Quantifying hurricane destructive power, wind speed, and air-sea material exchange with natural undersea sound

Joshua D. Wilson[1,2] and Nicholas C. Makris[1]

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[1] Passive ocean acoustic measurements may provide a safe and inexpensive means of accurately quantifying the destructive power of a hurricane. This is demonstrated by correlating the underwater sound intensity of Hurricane Gert with meteorological data acquired by aircraft transects and satellite surveillance. The intensity of low frequency underwater sound measured directly below the hurricane is found to be approximately proportional to the cube of the local wind speed, or the wind power. It is shown that passive underwater acoustic intensity measurements may be used to estimate wind speed and quantify the destructive power of a hurricane with an accuracy similar to that of aircraft measurements. The empirical relationship between wind speed and noise intensity may also be used to quantify sea-salt and gas exchange rates between the ocean and atmosphere, and the impact of underwater ambient noise on marine life and sonar system performance. **Citation:** Wilson, J. D., and N. C. Makris (2008), Quantifying hurricane destructive power, wind speed, and air-sea material exchange with natural undersea sound, *Geophys. Res. Lett.*, *35*, L10603, doi:10.1029/2008GL033200.

1. Introduction

[2] Satellite technology makes it possible to detect and track hurricanes. Expensive aircraft, however, are typically required to accurately quantify [*Holland*, 1993] hurricane destructive power. They do this by measuring peak wind speed while flying through a hurricane's center [*Holland*, 1980]. Here we show that passive ocean acoustic measurements, from sensors deployed in waters deep below a passing hurricane, may provide a safe and inexpensive alternative to aircraft measurements. This is done by correlating underwater sound generated by Hurricane Gert [*Lawrence*, 2000], recorded by a single autonomous underwater acoustic hydrophone [*Smith et al.*, 2002], with meteorological data acquired by in situ aircraft transects and satellite surveillance. We find the intensity of low frequency underwater sound directly below the hurricane to be approximately proportional to the cube of the local wind speed, or the wind power. From this relationship, we show that passive underwater acoustic intensity measurements may be used to estimate wind speed and quantify the destructive power of a hurricane with an accuracy similar to that of aircraft measurements. This relationship may also be used to help (1) quantify the rate of sea salt injection into the atmosphere from sea spray, which has important implications for global climate, (2) quantify the rate of gas exchange between the ocean and atmosphere, which has important implications for ocean ecosystem health, (3) distinguish natural ambient noise levels from those due to ocean shipping, which may have implications for the behavior of marine species that rely on sonar, and (4) quantitatively assess the impact of natural noise levels on the performance of sonar systems used in ocean remote sensing and communication.

[3] Hurricane destructive power was recently demonstrated by Katrina which caused over 1700 fatalities [*Kornblut and Nossiter*, 2006] and an estimated economic loss of roughly 100 billion dollars [*Bayot*, 2005]. Prior to Katrina, the United States Commission on Ocean Policy emphasized the need for more accurate quantification of hurricane destructive power to improve disaster planning [*Watkins et al.*, 2004]. Inaccurate classification can lead to unnecessary and costly evacuations, or missed evacuations which can result in loss of life [*Emanuel*, 1999]. Current classification and warning systems save $2.5 billion a year on average in the United States [*Watkins et al.*, 2004]. More accurate systems could save even more.

[4] The standard technique for hurricane quantification by satellite remote sensing is the *Dvorak* [1975] method. Destructive power, an absolute measure proportional to the cube of the maximum wind speed [*Holland*, 1980], is inferred by human interpretation of hurricane cloud features in satellite images. This approach can have significant errors. Of the eight North Atlantic hurricanes of 2000, the Dvorak errors for three [*Pasch*, 2000; *Franklin*, 2000; *Beven*, 2000] were over 40% of the 'ground truth' wind speed measured in situ by specialized aircraft. While new microwave techniques show promise for measuring hurricane wind speed [*Katsaros et al.*, 2002], resolution and accuracy issues still make the Dvorak method the standard for satellite hurricane quantification [*Franklin et al.*, 2003].

[5] The far more accurate method for quantifying hurricane destructive power achieved in situ through the direct wind speed measurements of specialized hurricane-hunting aircraft is prohibitively expensive for routine use outside of the North Atlantic and the Gulf of Mexico [*Holland*, 1993; *Federal Coordinator for Meteorological Services and Supporting Research (FCMSSR)*, 2003; *Wilson and Makris*, 2006].

[6] Empirical power-law relationships between underwater noise intensity and wind speed have been observed in the oceans at low wind speeds (<20 m/s), from which underwater noise measurements have been used to estimate wind speed [*Shaw et al.*, 1978; *Evans et al.*, 1984; *Nystuen and Selsor*, 1997]. To our knowledge this has not been done at

[1]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

[2]Now at Applied Physical Sciences Corp., Groton, Connecticut, USA.

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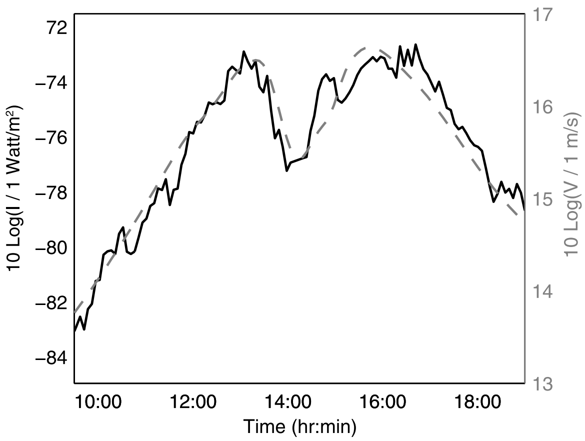

Figure 1. Underwater acoustic intensity level $L = 10\log(I/\text{Watt/m}^2)$ (black line), in the 10 to 50 Hz band, received by the NOAA hydrophone on 15 Sept., with 5 minute averaging. The expression $10\log(V/\text{m/s})$ (gray dashed line) is based on aircraft measurements of the wind speed V. The maxima at 13:30 and 15:30 GMT correspond to the powerful winds of the hurricane's eye-wall, and the minimum at 14:30 GMT corresponds to the hurricane's eye.

hurricane wind speeds due to the difficulty in conducting experiments at sea in hurricane conditions. These power law relationships are believed to arise from the entrainment of oscillating bubbles by wind-generated waves, which serves as a natural source mechanism for sound in the ocean at frequencies between 10 Hz and 10 kHz [*Knudsen et al.*, 1948; *Wenz*, 1962; *Piggott*, 1964; *Cato*, 1997]. While the entrainment of bubbles may also play a role in the attenuation of sound in the ocean at high frequencies and wind speeds [*Farmer and Lemon*, 1984], this attenuation is expected to be negligible at low frequencies (<100 Hz) even for hurricane wind speeds [*Wilson and Makris*, 2006].

2. Methods

[7] To investigate the relationship between undersea noise intensity and wind speed in hurricane conditions, we obtained a record of the underwater sound generated by Hurricane Gert [*Lawrence*, 2000] in the 10 to 50 Hz frequency band as it passed over a NOAA hydrophone [*Smith et al.*, 2002] in 1999 near the mid-Atlantic ridge at 17.7°N 49.5°W. The hydrophone was suspended at 800 m depth from the 4.7 km deep sea-floor. The measured acoustic intensity, shown in Figure 1, exhibits a temporal pattern marked by an initial maximum, followed by a minimum, and then a final maximum. This variation is consistent with advection of the characteristic morphology of a hurricane over the hydrophone, with the first sound-intensity maximum corresponding to the high leading-edge eye wall winds, the minimum to the low wind speeds of the eye, and the final maximum to the high trailing edge winds of the eye wall.

[8] Measurements of the spatial distribution of wind speed within Gert were made by U.S. Air Force hurricane-hunting aircraft [*Hurricane Research Division*, 1999], normalized to 10 m altitude [*Powell et al.*, 1996] and with an accuracy of ±5 m/s [*FCMSSR*, 2003], roughly 24 hours after Gert's eye passed over the NOAA hydrophone. Successive aircraft-based hurricane location estimates [*Hurricane Research Division*, 1999], with error radii of ±11 km [*FCMSSR*, 2003], provide an estimate of Gert's track. By extrapolating this track we find that the closest point of approach to the hydrophone occurred on 15 September at 13:49 GMT with the hurricane passing 32 km to the South of the sensor. Independent satellite estimates provide a similar track.

[9] To obtain the wind speed time series at the NOAA sensor (Figure 1), the aircraft-measured wind velocity field was advected backwards in time along the hurricane's track. This was accomplished by minimizing the linear-regression error between the log of the measured acoustic intensity [*Makris*, 1995] and the log of the estimated wind speed time series at the location of the acoustic sensor, with respect to the along-track hurricane speed, and the hurricane center's along and across-track offsets. This minimization led to a hurricane speed of 12.5 ± 0.6 m/s, an across track offset of 3.0 ± 4.0 km and an along track offset of 6.0 ± 3.6 km, which fall within the error ranges set by the aircraft and satellite measurements.

3. Results

[10] From regression analysis on the data measured during Hurricane Gert, we find that wind speed V and undersea noise intensity I follow a power law relationship

$$I(V) = V^n W \tag{1}$$

where W is a waveguide propagation factor [*Wilson and Makris*, 2006].

[11] Taking the logarithm of both sides of equation (1) transforms it into an equation where the logarithm of sound intensity is linearly related to the logarithm of the wind speed. A strong linear relationship between the time series of the logarithm of undersea noise intensity and the logarithm of local wind speed is evident in Figure 1. This is quantitatively verified by the high correlation coefficient of 0.97 found between the two time series. Linear regression analysis between the two logarithmic time series yields the equation

$$10\log\left(\frac{I(V)}{1\ \text{Watt/m}^2}\right) = 10n\log\left(\frac{V}{1\ \text{m/s}}\right) + b \tag{2}$$

where $n = 3.35 \pm 0.03$ and $b = -128.6 \pm 0.5$ in the 10 to 50 Hz measurement band. This linear relationship can be seen directly from Figure 2. Here, the slope n is believed to be universal and independent of measurement position while the intercept b is a constant that depends on the local waveguide environment [*Wilson and Makris*, 2006].

[12] Equation (2) may be used to estimate wind speed from undersea noise intensity. The linear regression error in this wind speed estimate is only 5% of the actual wind speed where percent error in wind speed is defined as

$$\nu = \frac{100\sqrt{\left\langle |\hat{V} - V|^2 \right\rangle}}{V}, \tag{3}$$

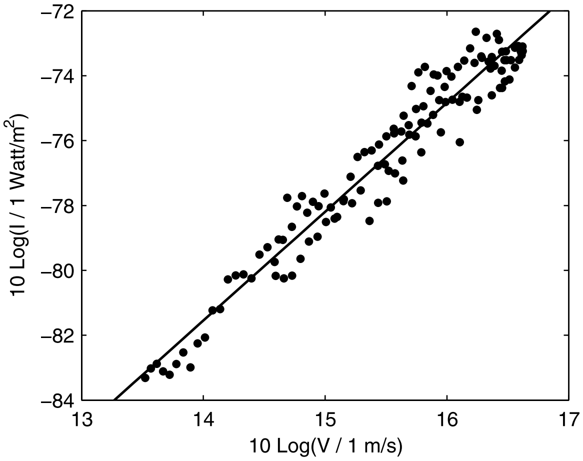

Figure 2. Underwater acoustic intensity level L = 10 log(I/ Watt/m^2) as a function of 10 log(V/m/s) (circles) where V is the estimated wind speed in m/s at the NOAA hydrophone based on the best fit hurricane track. The best fit linear regression shows a 10 log[I/(1 Watt/m^2)] = 10n log[V/(1 m/s)] + b relationship between intensity and wind speed where n = 3.35 ± 0.03 and b = −128.6 ± 0.5.

in terms of $\hat{V}$ the estimated wind speed from undersea acoustic measurements and V the actual wind speed. This is similar to the 5 m/s error typical of aircraft estimates [*FCMSSR*, 2003], and is likely dominated by uncertainties in the aircraft measurements in the regression analysis.

[13] The error component from the acoustic measurements should be much smaller given the temporal and frequency averaging employed [*Wilson and Makris*, 2006]. To see this, note that the time series of underwater sound intensity (Figure 1) was obtained by averaging intensity over consecutive time windows of 5 minute duration in the 10–50 Hz band. Each sample in the average intensity time series was then generated from roughly μ = 12000 independent samples of instantaneous intensity, where μ is the time-bandwidth product of the average. Since underwater sound intensity generated by the hurricane can be well described as a stationary random process [*Goodman*, 2000; *Makris*, 1997; *Pierce*, 1991], within a 5 minute time interval, the standard deviation σ_L of the log of the averaged intensity, L = 10 log(I/Watt/m^2), may be given as $\sigma_L = 10\log(e)\sqrt{1/\mu}$ for $\mu \gg 1$ [*Makris*, 1996] which for this analysis becomes σ_L = 0.04. Thus the temporal variations of sound intensity level shown in Figure 1 should be overwhelmingly dominated by variations in the wind source mechanisms driving the underwater sound. The error of estimated wind speed due solely to fluctuations in averaged underwater sound intensity should be roughly 0.27% of the actual wind speed, which in this case is as much as 0.13 m/s, based on *Wilson and Makris* [2006, equation (33)]. This is much smaller than the roughly 5 m/s error of aircraft wind speed measurements and highlights the potential for using undersea acoustic sensors as anemometers for estimating both the wind speed and the total destructive power of a hurricane, which is proportional to the cube of the maximum wind speed [*Holland*, 1997].

4. Quantifying Hurricane Destructive Power

[14] Theoretical calculations [*Wilson and Makris*, 2006] show that the hydrophone at 800 m depth effectively measures the wind generated noise within a horizontal radius of roughly 2 km, which is smaller than the typical length scale of spatial features in a hurricane. Several hydrophones could be scattered from aircraft or ships in the path of an oncoming hurricane. Each sensor would then measure wind speed as it cuts a swath through the storm passing overhead. This is analogous to the swaths cut by hurricane-hunting aircraft, which typically fly a single "X-pattern" centered on the eye, to measure wind speed in the eye wall and assess destructive power [*FCMSSR*, 2003].

[15] An advantage to acoustic hurricane quantification is that hydrophones could be safely deployed well in advance of an approaching hurricane from ships or aircraft that would never need to enter the storm. They are also orders of magnitude less expensive to purchase and operate than the specialized hurricane-hunting aircraft used today.

[16] The ocean-acoustic method described here for quantifying the destructive power of a hurricane could then provide a safe, practical and inexpensive monitoring capability for the many areas of the world where specialized hurricane-hunting aircraft are not available. This includes both the Pacific and Indian Oceans, where severe tropical cyclones frequently intersect inhabited areas, often with devastating consequences. In the North Atlantic where specialized aircraft are already in use, the ocean acoustic method may make it possible to reduce the number of aircraft flights necessary.

5. Quantifying Sea-Salt and Gas Exchange With Undersea Sound

[17] The empirical law described in equation (2) also provides quantitative knowledge about the air-sea boundary layer and its role in ocean-atmosphere exchanges of salt, gas, heat and momentum, which are important in determining global climate and regulating weather. Bubble bursting through mechanical agitation of the sea surface in wind forced white cap formation is a primary mechanism for sea spray, which is the largest source of aerosol mass injection into the atmosphere besides dust [*Hoppel et al.*, 2002]. The same wind-driven process generates underwater sound as a by product with intensity proportional directly to the bubble population in the upper ocean boundary layer [*Wilson and Makris*, 2006]. Sea salt injected into the atmosphere by bursting bubbles significantly impacts global climate because it is a dominant scatterer of solar radiation which regulates cloud cover [*Haywood et al.*, 1999]. Climate modelers deduce sea salt aerosol emission rates from wind speed estimates, since wind drives the sea spray formed from bursting bubbles in white caps [*Monahan et al.*, 1986; *Hoppel et al.*, 2002]. These models rely on empirical relationships between wind speed and sea salt emissions, measured at low (<15 m/s) wind speed and then extrapolated to higher wind speeds [*Monahan et al.*, 1986].

[18] It may be possible to better quantify salt aerosol emission rates and so enhance global climate models by measuring the intensity of underwater sound. Together with the analysis of *Wilson and Makris* [2006], the empirical relationship of equation (2) and Figure 2 show that the number of air bubbles in the upper ocean boundary layer, which determines aerosol salt flux, is nearly proportional to both wind power and underwater noise intensity, and that these relationships are maintained up through hurricane wind speeds. Combining our equation (1) with equation (6) of *Monahan et al.* [1986], aerosol flux density dF_0/dr (in *particles* $\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mu\mathrm{m}^{-1}$) due to wind-driven bubble bursting leads to an approximately linear function of undersea noise intensity I

$$\frac{dF_0}{dr} = 1.373\frac{V^{3.41}}{r^3}10^{1.19e^{-B^2}} = 1.373\frac{I^{\frac{3.41}{3.35}}}{W^{\frac{3.41}{3.35}}r^3}10^{1.19e^{-B^2}} \approx 1.373\frac{I}{Wr^3}10^{1.19e^{-B^2}} \quad (4)$$

where r is the bubble radius and $B = (0.380 - \log(r))/0.650$.

[19] Sea spray from breaking bubbles transfers not only salt to the atmosphere, but also water mass, dissolved gasses and heat, which regulate the intensity of hurricanes, as well other climactic and biologic processes. With the empirical relationship of equation (2), it may be possible to quantitatively determine mass, gas or heat flux from measurements of undersea noise intensity. For example combining our equation (1) with the equations (1) and (4) of *Wanninkhof and McGillis* [1999] for the CO_2 flux across the air-sea interface as a function of wind speed leads to

$$\begin{aligned} F &= 0.0283V^3(Sc/660)^{-1/2}s(p_w - p_a) \\ &= 0.0283W^{-3/3.35}I^{3/3.35}(Sc/660)^{-1/2}s(p_w - p_a) \\ &\approx 0.0283W^{-1}I(Sc/660)^{-1/2}s(p_w - p_a) \end{aligned} \quad (5)$$

where F is the number of mols of CO_2 that cross the interface per unit area per unit time. The sign of F indicates the direction of flux with positive values indicating flux from water to air. The variable s is the solubility, p_w and p_a are the partial pressures of CO_2 in water and air respectively, and Sc is the Schmidt number.

6. Effect of Noise on Marine Life and Man-Made Acoustic Systems

[20] Many fish and marine mammals rely on acoustics for navigation, sensing and communication but are limited in these activities by ambient noise levels in the ocean [*Miller et al.*, 2000]. Comparison of the empirical power law in equation (2) with measurements of shipping noise [*Wenz*, 1962] shows that only when wind speeds approach gale force (for $V > 15$ m/s) conditions does ambient noise in the ocean reach the level of noise pollution from moderate (76 dB re $\mu\mathrm{Pa}^2$/Hz at 10–50 Hz) shipping. So noise levels that in the past only occurred under gale conditions have become more common within the last century with the advent of engine-propelled shipping. Many species likely had to adapt to this pressure.

[21] In the ocean, modern sensing systems also rely on acoustics to explore and transfer information, whether it be for underwater archeology, marine geophysics, marine biology, petroleum exploration, or Naval operations. Acoustic sensing systems, however, are limited by ambient noise. The relationship of equation (1) makes it possible to quantitatively predict performance of underwater acoustic sensing or communication systems from wind measurements or weather forecasts.

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J. D. Wilson, Applied Physical Sciences Corp., 475 Bridge Street, Groton, CT 06340, USA.

N. C. Makris, Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave 5-212, Cambridge, MA 02139, USA. (makris@mit.edu)