New Scales for the Destructive Potential of Tropical Cyclones[1]

by

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ABSTRACT

Tropical cyclone intensity defined by maximum wind speed in the storm fails to consider the area impact of damaging winds. A more appropriate intensity measure scales with the physical processes of ocean surface stress and structural wind loading and takes into account the spatial coverage of the wind field, thereby including the potential for a storm to create damage through wind, waves, or storm surge.

KEYWORDS: Hurricanes, IKE, Tropical Cyclones, Saffir-Simpson Scale

1. TROPICAL CYCLONE INTENSITY AND DAMAGE SCALES

Tropical cyclone intensity in the Atlantic Basin is defined by the maximum sustained wind[1]: the maximum 1 min mean wind that might be measured anywhere in the storm at a particular instant in time, and then classified by a 1-5 rating according to the Saffir-Simpson (SS) scale[2,3]. Determination of tropical cyclone intensity is subjective, and often depends on indirect estimates from visible satellite imagery[4], pressure-wind relationships[5], or empirical surface-reduction of flight-level reconnaissance wind measurements[6]. Coastal communities are warned for tropical cyclone wind, wave, and storm surge impacts based on intensity information with uncertainties of 10-20% (depending on the method and measurement platform[6,7]), and forecasts (24 h) with ~5 m/s mean absolute intensity errors[8], or ~ one half an SS category. Here we propose an alternative measure of intensity that may be produced from an integrated system of aircraft- space-, land- and marine-based observing platforms. The integrated kinetic energy (IKE) is more physically linked to the damage process than the maximum wind speed or Saffir-Simpson Scale, and provides a measure of intensity forecast accuracy that is less sensitive to uncertainty in the maximum wind speed. Furthermore the IKE provides an intensity measure that is equivalent to earthquake energy release.

The potential of a tropical cyclone to inflict damage is currently described by the SS scale, originally defined according to peak 3 s wind gusts[2]. Subsequently, SS has been interpreted to be associated with the maximum sustained wind[9]. While the SS scale has been used extensively to convey storm intensity to the public, it is subjective and can be misleading especially applied to storms of different sizes. Alternative measures to assess hurricane intensity or damage potential include Hurricane Destructive Potential and Accumulated Cyclone Energy (ACE)[10], Hurricane Outer and Inner core Strengths,[11,12] and kinetic energy dissipation or Power[13]. Each of these measures have limitations related to the lack of consideration for the spatial extent of damaging winds. For example ACE and Power are computed from the square or cube of the maximum sustained wind speed alone. Since experts often disagree on measured or estimated maximum sustained wind speeds, we seek an alternative intensity metric less sensitive to a single wind value.

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[1] Portions of this paper were published in Powell and Reinhold, 2007: Tropical cyclone destructive potential by integrated kinetic energy. Bulletin of the American Meteorological Society, 87, 513-526. Portions will be also presented at the 11th ACWE Conference and proceedings.

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2. IKE

As numerical modeling of tropical cyclones progresses, it is important to validate model forecasts objectively based on observations. It is also important that critical natural hazard information be based on an objective assessment of the available observations. The recent development of air-, space-, land-, and sea-based measurement systems now provide sufficient observations to depict the horizontal distribution of tropical cyclone wind fields in the Western Atlantic and Caribbean basin. The Integrated Kinetic Energy (IKE), takes into account the destructive potential of the wind field. IKE is computed from the surface wind field by integrating the kinetic energy per unit volume (V) over the storm domain (or the contribution over specific wind speed (ws) thresholds) for a 1 m thick air layer of unit density centered at the 10 m level.

$$IKE = \int \frac{1}{2}\rho ws^2 dV \qquad (1)$$

Kinetic energy scales with wind loads on structures[14] since it correlates with the wind pressure acting on a vertical structure. However, weighting of IKE is generally necessary for assessing wind damage potential because damage to most of the built environment at risk increases almost exponentially with increased wind speed once damage is initiated. Waves and storm surge are generated by shear stress of the wind on the ocean surface, which also scales with IKE. While the initial dependence of sea surface drag coefficient is linear with wind speed, supporting a cubic dependence for stress, recent analysis of wind profiles in hurricanes[15] find that the drag coefficient levels off or slightly decreases at winds above 33 m/s, suggesting a continued dependence on the square of the wind speed. It is clear from recent storms such as Opal, Ivan, Katrina and Rita that the potential for storm surge is correlated with the size and intensity of the storm in the hours and days before landfall as well as the actual wind field characteristics during landfall. Consequently, the history of IKE components in the hours and days before landfall are likely to provide a robust estimate of surge damage potential.

3. H*Wind GRIDS and IKE

Measurement of IKE in a hurricane requires sufficient observations for an analysis of the wind field. The NOAA Hurricane Research Division Hurricane Wind Analysis System[16,17] (H*Wind) provides an objective analysis of all available observations and since 1999, these have been available in a gridded format to facilitate research and experimental use in storm surge and wave models, as well as for validation of remotely sensed winds and numerical weather prediction models. Analyses are conducted on an experimental basis when a tropical cyclone is monitored by reconnaissance aircraft. Uncertainty of the analysis maximum sustained wind speed depends on data coverage and the quality of the individual platforms contributing to the peak wind measurement, but is estimated at 10% when the peak wind is sampled at the surface[8], or 20% if the peak wind is estimated by a simple flight level reduction factor[6]. Outside the eyewall where radial gradients are weaker, more plentiful in-situ observations are available and wind uncertainty is probably closer to 10%. While estimates of the maximum sustained wind in a landfalling hurricane can vary by agency, the IKE depends on the spatial characteristics of the tropical cyclone and is not very sensitive to changes in the maximum wind.

In order to better differentiate between intense but small tropical cyclones such as Camille and Andrew and broader but less intense storms such as Hugo and Katrina it is necessary to further refine the IKE analysis. Analysis options were explored by evaluating several threshold wind speed values for a selection of 22 hurricanes comprising large and small wind fields in the H*Wind archive[4] over an 8 degree latitude domain. A wind speed of 10 m/s was selected for the low end ($IKE_{>10}$), with additional thresholds chosen to relate to storm surge and wave damage (V_{MS} > 18 m s^{-1}: IKE_{TS}, > 33 m/s: IKE_H), light (25-40 m/s, IKE_{25-40}) and moderate (41-55 m/s, IKE_{41-55}) wind damage and severe building envelope wind damage ($IKE_{>55}$) for winds > 55 m/s. After experimenting during the 2006 and

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[4] www.aoml.noaa.gov/hrd/data2.html

2007 hurricane seasons, the IKE_{TS} was the most relevant quantity for assessing Surge and Wave Damage Potential (SDP) and continuous multiplier approach was formulated for Wind Damage Potential (WDP).

4. SURGE DESTRUCTIVE POTENTIAL

Based on the largest and most intense hurricanes observed since 2000, a continuous spline fit relationship was assigned between IKE_{TS} and SDP (Fig. 1) based on the familiar 0-5 range of the SS scale.

Ultimately the damage scale should be based on an objective measure of damage realized but such depends on the infrastructure and population of an affected area and the difficulty of attributing damage to wind, wave or surge. The SDP is an objective measure of the forcing available from the wind field. Based on simple scaled storm surge modeling results (private communication, Jennifer Irish, Texas A&M) the SDP has a strong relationship to the extent of coastal inundation greater than 1 m, but a poor relationship to peak surge. Given that bathymetric and coastline orientation details are missing from SDP, the relationship to inundation is useful for emergency management and storm preparedness applications. The strength of the SDP scale is that it provides an objective means to compare a current storm to historical storms in the same area based on a level playing field. When decisions need to made regarding evacuation and warnings 1-2 days before expected landfall, forecast uncertainty is such that the precise landfall location (and associated local bottom slope and coastline shape factors that ultimately affect surge) is unknown. Although peak surge is important, it usually covers a very small area so the extent of inundation levels known to threaten safety or encumber evacuation take on an increased importance. Its practical to base the damage potential rating on an integrated wind forcing rather than some peak value that can misrepresent the severity of the event.

5. WIND DESTRUCTIVE POTENTIAL

From a direct wind damage perspective, it is important to develop a meaningful way to relate the IKE values to damage experience. The response of residential structures to wind is a highly non-linear process, as evidenced by residential insurance losses[19] (by zip code) compared to H*Wind analyses of open terrain wind speeds in Hurricanes Andrew, Hugo, and Opal (Fig. 2). The kinetic energy per unit volume (KE_V in Joules) for a wind field analysis grid cell was related to the co-located damage data (Fig. 3). A multiplier was fit based on a reference value corresponding to the kinetic energy per unit volume associated with the initiation of light structural damage in winds of ~ 25 m s^{-1} (Fig. 4).

$$M_G = 3.45 \, (49.785 * [1+ \mathrm{TanH} (0.002469 * (KE_V - 1602.94))])$$

The weighted IKE for a tropical cyclone (IKE_{WT}) is found by summing each grid cell's product of MG * KE_V, for all grid cells with winds in excess of 25 m s^{-1}.

Since the concept of a damage scale with a 1-5 range is familiar to the public, we evaluated IKE threshold contributions and assigned a 1-5 rating scale. For wind damage, categories 4-5 are based on a prerequisite of winds > 55 m s^{-1}.

The Wind Damage Potential (WDP) is defined as:

$WDP>4$: $V_{MS} >= 55.0$ m s^{-1}

$$WDP>4 = 3.974 -0.0002\, IKE_{WT} + 0.0373\, (IKE_{WT})^{.5} + 0.085\, \mathrm{Log}_{10} (IKE_{WT})$$

where IKE_{WT} is in TJ.

$WDP<4$: $V_{MS} > 55.0$ m s^{-1}

$$WDP<4 = .8828 + 0.0183\, (IKE_{WT})^{.5} + 0.802\, \mathrm{Log}_{10} (IKE_{WT})$$

6. HURRICANES KATRINA AND IKE

As an example, consider two stages of Hurricane Katrina's wind field as depicted in post-storm analysis of all available observations during two ~ 6 h periods on 28 and 29 August, 2005. When considered to be a SS Category (Cat) Five (Fig. 5a) the day before landfall, Katrina's wind field contained maximum winds estimated at 71 m/s with an IKE of 117 TJ over an 8 degree domain. At landfall in Southern Louisiana and Mississippi, Katrina had weakened to Cat 3 status (52 m/s) but the wind field had expanded (Fig.

5b) with an IKE of 112 TJ. Therefore, based on the IKE, Katrina at landfall was of similar destructive capacity to when it was an SS Cat 5 in the central Gulf of Mexico, and about twice as destructive as the prior standard of destruction for the Gulf of Mexico coast (SS Cat 5 Hurricane Camille of 1969 with max winds near 67 m s^{-1} and IKE of ~ 63 TJ). The tremendous wave and storm surge related destruction of Katrina at landfall was not well represented by the SS scale[5].

In 2008 Hurricane Ike passed over western Cuba and emerged into the Gulf of Mexico as a marginal hurricane. Ike gradually developed a huge wind field despite maximum winds < 50 m s^{-1}. The day before landfall Ike's IKE_{TS} values (Fig 5c) were comparable to those for Katrina (Fig. 5a,b) despite being rated as an SS Category 2 storm. There is some evidence that the relatively low SS rating of Hurricane Ike, during this critical period for undertaking evacuation and preparation activities, may have influenced some coastal residents to stay rather than evacuate, with catastrophic results in the vicinity of the Bolivar Peninsula.

7. DISCUSSION

An advantage of using an IKE-based approach is that it makes no distinction on whether a tropical cyclone is classified as a hurricane or tropical storm (a large, strong tropical storm could have more damage potential than a small, weak hurricane), the scale could also be applied to non tropical storms. IKE_{TS} may be compared to objective measures of earthquake Seismic Moment Magnitude (SMM)[20, 21], which conveys earthquake size in terms of radiated energy. A SSM 7.0 earthquake corresponds to an energy release of 2000 TJ. However, unlike SMM, with 10^3 increases in energy between two integer gradations, the entire range in IKE_{TS} between a selection of the smallest and largest hurricanes in the H*Wind archive is on the order of 200 TJ. Considering that we are focusing here on a 1 m thick layer of air near the surface, the IKE_{TS} values would increase by a factor of ~ 10^3-10^4 if we integrated to the top of the tropical cyclone, which would approach the energy release of severe earthquakes[6]. The influence of bathymetry, coastline shape, surface topography, and roughness could be used as modifiers for the surge estimation, much the same as soil modification factors are used to estimate site specific ground motions. A limitation of IKE as a damage potential indicator include the inability to account for localized areas susceptible to storm surge and waves due to coastline shape and bathymetry. During the 2009 Hurricane Season we will continue to issue wind field analysis research products containing IKE_{TS}, IKE_{H}, SDP, and WDP as shown in Fig. 5c. With future advances in satellite and airborne monitoring of ocean surface wind vectors, we envision that all tropical cyclone basins will eventually contain sufficient observations for global assessments of tropical cyclone intensity by IKE, and more meaningful measures of basin wide tropical cyclone destructiveness from one season to the next.

Acknowledgements

This research was supported by NOAA 2005 hurricane supplemental and the U.S. Army Corps of Engineers IPET Project.

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[5] Many people on the Mississippi coast based their evacuation plans on comparing Katrina to 1969 Cat 5 Hurricane Camille, a destructive but much smaller storm.

[6] The energy release associated with the Magnitude 9.2 Alaska earthquake of 1964 has been estimated at 3.9 x 10^6 TJ.

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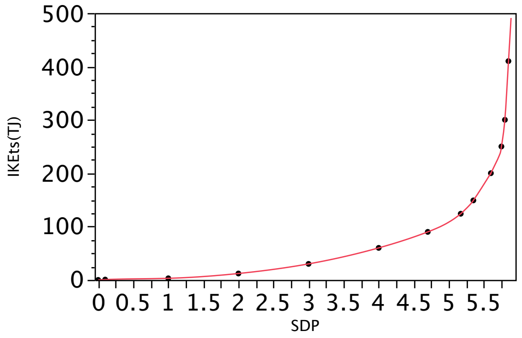

Fig. 1 Spline fit of $\mathrm{IKE}_{\mathrm{TS}}$ (in TJ) vs. SDP.

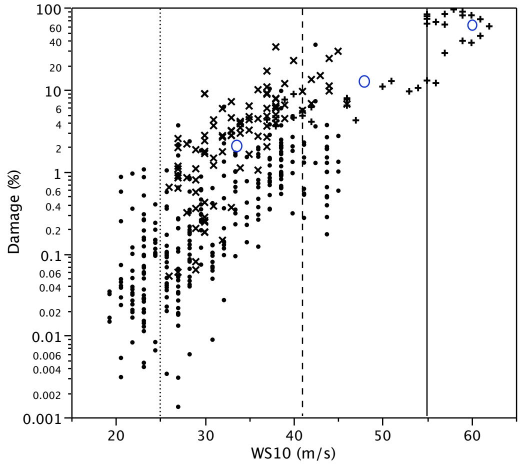

Fig. 2 Residential damage (claim to insured value ratio) as a function of 10 m open -terrain maximum sustained wind speed in Hurricanes Andrew, Hugo, and Opal. The 25-41, 42-55, and >55 m/s thresholds are shown by vertical lines and mean damage by blue circles.

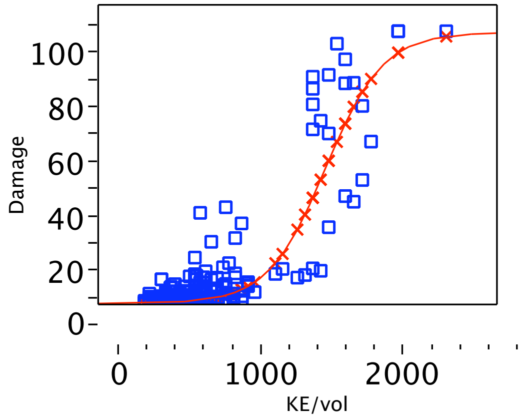

Fig. 3 Fit of damage ratio to grid cell kinetic energy per unit volume.

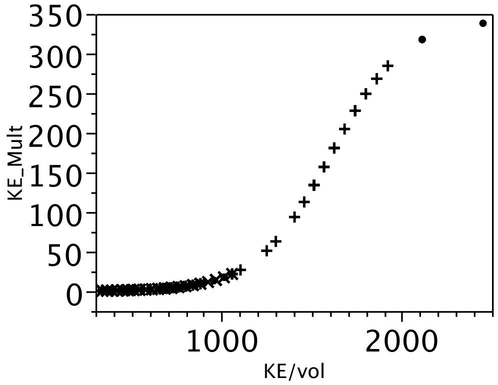

Fig. 4 Grid cell multiplier factor for computing weighted IKE in the WDP calculation.

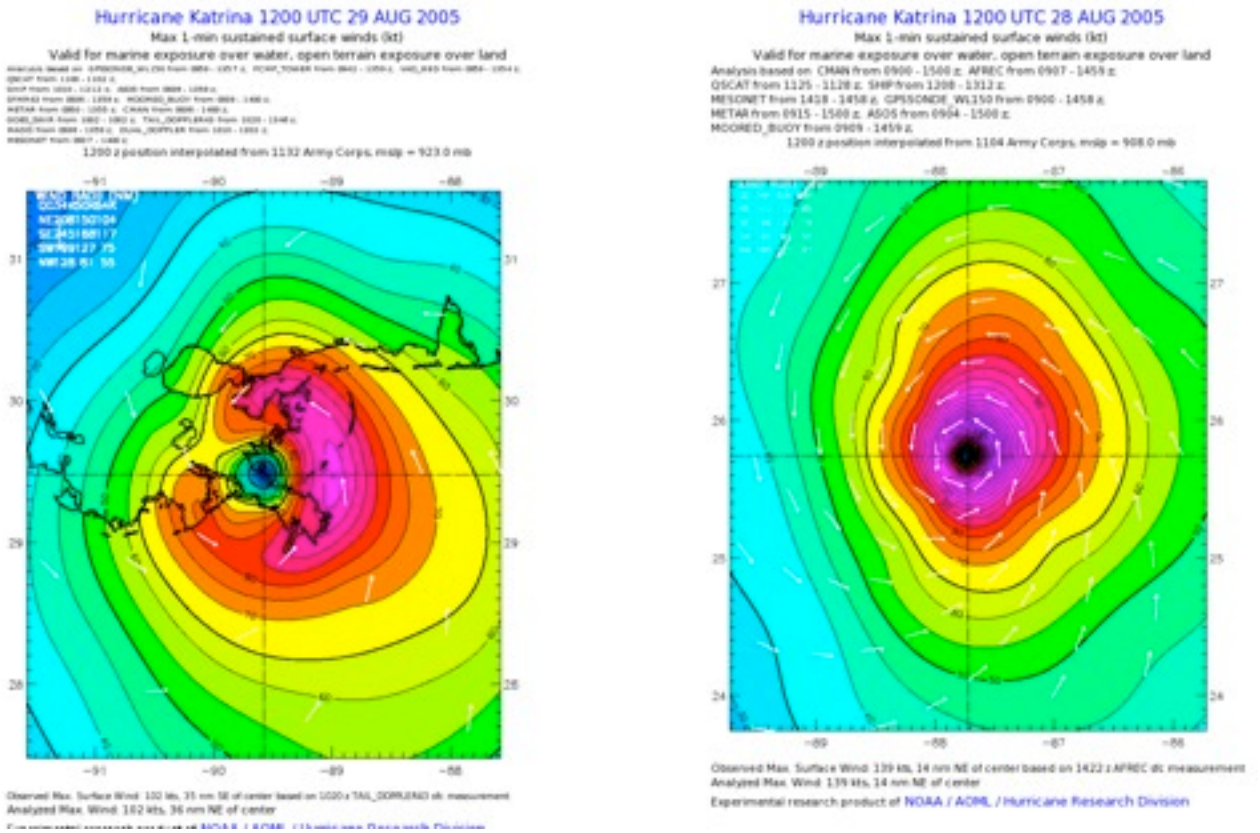

Fig. 5 H*Wind analysis of Hurricane Katrina's surface wind field at a) peak maximum wind speed, b) landfall, c) Hurricane Ike 24 h before landfall.