TROPICAL CYCLONE DESTRUCTIVE POTENTIAL BY INTEGRATED KINETIC ENERGY

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The maximum sustained surface wind speed and the Saffir–Simpson scale are poor indicators of a hurricane's destructive potential; integrated kinetic energy is more relevant to damage by wind, storm surge, and waves.

The Hurricane Katrina disaster and recent studies examining hurrcanes and global climate change have generated discussion on tropical cyclone intensity and its relevance to destructive potential. Climate scientists are trying to determine whether hurricanes are becoming more frequent or destructive (e.g. Webster et al. 2005; Emanuel 2005), with resulting impacts on increasingly vulnerable coastal populations. People who lived in areas affected by Hurricane Katrina are wondering how a storm weaker than Hurricane Camille at landfall, could have contributed to so much more destruction. While intensity provides a measure to compare the maximum sustained surface winds (V_{MS}) of different storms, it is a poor measure ▶

H*Wind analysis of Hurricane Camille at landfall. See figure 1 on page 4 for more information.

of the destructive potential of a storm since it does not account for storm size. The Saffir–Simpson scale (SS) is currently used to communiate the disaster potential of hurricanes in the Western Hemisphere. It serves a useful purpose for communicating risk to individuals and communities, but is a poor measure of the destructive potential of a hurricane because it depends only on intensity.

Destruction can be quantified in terms of mortality and economic loss, but these measures cannot easily be associated with hurricanes of a given size and intensity, because they also depend on population density and coastal vulnerability in the affected area. Mortality is complicated by direct and indirect causes (Combs et al. 1996; Shultz et al. 2005), while total insured or estimated economic loss additionally depends on the wealth of the impacted area. Therefore mortality and insured losses do not necessarily scale with hurricane intensity. For example, the south Florida landfall of Hurricane Andrew (1992) contributed to insured losses of $22 billion (in 2006 dollars) with 40 deaths in Miami–Dade County while SS3 Hurricane Katrina (2005) is associated with insured losses of over $42 billion and over 1,400 deaths in Louisiana and Mississippi.

The purpose of this paper is to broaden the scientific debate on how best to describe a hurricane's destructive potential. Kantha (2006) initiated debate on the subject when he suggested retiring the SS. We suggest a metric relevant to the physical forces that contribute to damage, based on the size of the wind field and magnitude of the winds. From this we take a first step toward defining scales to help distinguish between potential wind and wave/surge impacts while retaining the concise range of the SS. The destructive potential is suggested as an objective starting point to estimate the impact of the wind field, before the coastal vulnerability, infrastructure, and affected populations are taken into account.

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First, we review current measures of hurricane destructive potential and discuss risk perception. In the second section we introduce integrated kinetic energy and justify its relevance to wind and storm surge and wave destructive potential. We describe the H*Wind analysis fields and compare kinetic energy calculations for Hurricanes Camille and Katrina, and discuss the sensitivity of the calculations to biases in the measurements or methods used to estimate surface winds. The third section presents the kinetic energy calculations relevant to wind and storm surge for a variety of large and small hurricanes, and introduces the wind and surge destructive potential scales, along with methods to compute them from wind radii information available in advisories and forecasts. Finally, in the fourth section we discuss the advantages, limitations, and new applications for the destructive potential metrics.

Hurricane intensity. Tropical cyclone intensity in the Atlantic Basin is currently defined (NWS 2006) by the maximum sustained wind, "the highest one-minute average wind, V_{MS}, (at an elevation of 10 m with an unobstructed exposure) associated with that weather system at a particular point in time," and a 1–5 damage potential rating is assigned by the Saffir–Simpson scale (R. H. Simpson 1974; Saffir 1975; more information available at www.nhc.noaa.gov/aboutsshs.shtml). From a practical standpoint we interpret the V_{MS} as a marine exposure wind. Determination of tropical cyclone intensity often depends on indirect estimates from visible satellite imagery (Dvorak 1975), pressure–wind relationships (e.g., Kraft 1961), or empirical reduction of flight-level reconnaissance wind measurements to produce surface level estimates (Franklin et al. 2003). Coastal communities are warned for tropical cyclone impacts based on intensity information with uncertainties of 10%–20% [depending on the method and measurement platform (Franklin et al. 2003; Uhlhorn and Black 2003)], and forecasts (24 h) with ~5 m s^{-1} mean absolute intensity errors (www.nhc.noaa.gov/verification/index.shtml?), or ~one-half an SS category.

Measures of hurricane destructive potential. The potential of a tropical cyclone to inflict damage is currently described by the SS, originally defined according to peak 3-s wind gusts (Saffir 1975), and subsequently interpreted to be associated with V_{MS}. Alternative measures to assess hurricane destructive potential include accumulated cyclone energy (ACE; Bell et al. 2000), hurricane outer- and inner-core strengths (Weatherford and Gray 1988;

Croxford and Barnes 2002), roof cladding fatigue damage index (Mahendran 1998), turbulence kinetic energy dissipation (Businger and Businger 2001), power (Emanuel 2005), and hurricane intensity and hazard indices (Kantha 2006). Most of these measures have limitations related to the lack of information on the spatial extent of damaging winds. For example ACE and power are computed from the square or cube of V_{MS} without considering storm structure.

Mahendran (1998) was the first to call attention to the need for a damage index based on quantities other than V_{MS}. He modeled fatigue damage to metal roofing panels and found that the damage depended on the radius of maximum wind, storm translation speed, central pressure, and maximum wind gust. Kantha (2006) was the first post-Katrina paper to question the SS. He acknowledged the importance of dynamic pressure associated with the wind and proposed a continuous hurricane intensity index (HII) based on the square of the ratio of V_{MS} to a reference wind of 33 m s^{-1}. A 6.0 HII rating would represent a maximum sustained surface wind speed of 81 m s^{-1}. Kantha also recognized the need to account for storm size and proposed a hurricane hazard index (HHI), which brought in the radius of hurricane-force winds, the storm motion, and the cube of V_{MS} [based on Emanuel's (2005) claim that damage scales with the third power of V_{MS}]. The HHI has the advantage of being a continuous scale; but it is not bounded. The HHI also fails to consider that wind damage can begin at winds less than hurricane force, that the wind field of a hurricane can be asymmetric with different wind radii in each quadrant, and becomes exceedingly large when a storm stalls. Dependence on the cube of V_{MS} also makes the HHI overly sensitive to a single wind speed value in a very small part of the storm, which is difficult to sample and measure.

Additionally, the damage process is too complex to simply state that it depends on some power of V_{MS}. While wind loading on a structure is related to the square of the wind speed (ASCE-7 2005), interactions of a structure with the wind depend on the structure of the turbulence, the cycling between gusts and lulls, and the debris loading. A given building component may have a wind resistance or a wind vulnerability curve that depends on the strength of the local building code, code enforcement, and workmanship, and that varies greatly from other components. The ultimate wind resistance of the structural system depends on the interaction of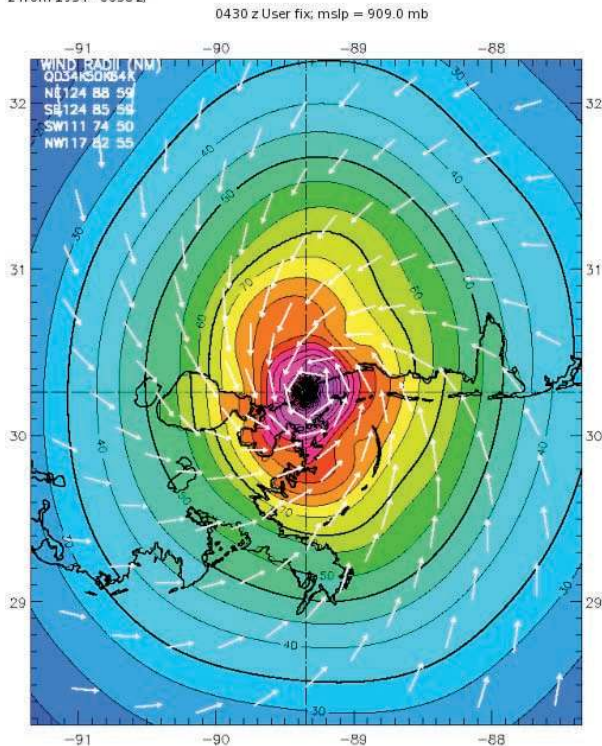 the various components. Economic loss estimates can include indirect effects beyond the physical interactions between structures and wind, such as loss of use, living expenses, food spoilage, etc., resulting in loss relationships to as high as the ninth power of V_{MS} (Nordhaus 2006). However, attempts to match economic loss to some power of V_{MS} (e.g. Howard et al. 1972; Nordhaus 2006) fall prey to the same limitation as the SS in that they ignore the fact that loss also depends on the wealth and population density of the impacted area such that a large but relatively weak storm in a well-populated area (e.g., Frances 2004; SS2, $4.4 billion) can result in higher losses (based on estimates from the American Insurance Services Group) than a smaller, more intense storm hitting a less populated area (e.g., Dennis 2005; SS3, $1.1 billion).

Risk perception. People who decide to leave or stay in response to a hurricane warning make decisions based on perceived vulnerability, and past hurricane experience is one of several influences on this perception (J. Baker 2006, personal communication; Wilkinson and Ross 1970). Those who have experienced significant loss from disasters are more likely to have realistic risk perceptions and respond to future warnings (Schultz et al. 2005; Milletti and O'Brien 1992). In the case of Hurricane Katrina (2005) on the Mississippi coast, regardless of warnings well in advance, some people did not evacuate because their location was known not to have been flooded by Hurricane Camille, an SS5 storm that devastated the area in 1969. However, despite having the same SS5 rating the day before landfall, and a lower (SS3) rating at landfall, Katrina's landfall wind field was much larger than Camille's (Fig. 1). Without storm size information in the SS classification, some people may have perceived the risk of Katrina to be the same or even lower than Camille. In Katrina's aftermath many people in coastal Mississippi have repeated a quote attributed to Mr. Jim Holt of Biloxi on 30 August 2006: "It looks like Hurricane Camille killed more people yesterday than it did in 1969" (A. Lee, *Biloxi Sun Herald,* 2006, personal communication). Better risk perception is an important goal for any new metric of hurricane destructive potential.

INTEGRATED KINETIC ENERGY. As an indicator of destructive potential, we propose integrated kinetic energy (IKE), which is computed from the surface wind field by integrating the 10-m-level kinetic energy per unit volume over portions of the storm domain volume (V) containing sustained

a) Hurricane Camille 0430 UTC 18 AUG 1969
Max 1-min sustained surface winds (kt)
Valid for marine exposure over water, open terrain exposure over land
Analysis based on 1 from 0430 - 0430 z; 4 from 0000 - 0600 z; 3 from 2115 - 2330 z;
2 from 1954 - 0658 z;
0430 z User fix; mslp = 909.0 mb

Observed Max. Surface Wind: 129 kts, 8 nm NE of center based on 0430 z 1 sfc measurement
Analyzed Max. Wind: 127 kts, 7 nm NE of center
Experimental research product of NOAA / AOML / Hurricane Research Division

b) Hurricane Katrina 1200 UTC 28 AUG 2005
Max 1-min sustained surface winds (kt)
Valid for marine exposure over water, open terrain exposure over land
Analysis based on CMAN from 0900 - 1500 z; AFREC from 0907 - 1459 z;
QSCAT from 1125 - 1128 z; SHIP from 1208 - 1312 z;
MESONET from 1418 - 1458 z; GPSSONDE_WL150 from 0900 - 1458 z;
METAR from 0915 - 1500 z; ASOS from 0904 - 1500 z;
MOORED_BUOY from 0909 - 1459 z;
1200 z position interpolated from 1104 Army Corps; mslp = 908.0 mb
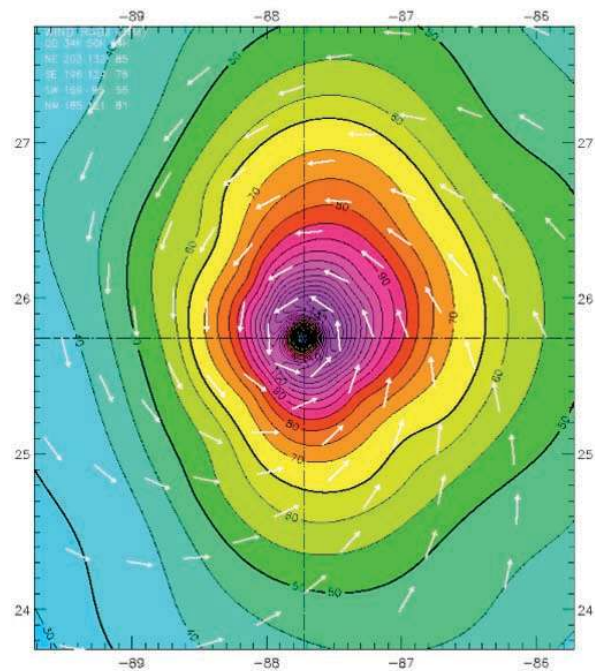
Observed Max. Surface Wind: 139 kts, 14 nm NE of center based on 1422 z AFREC sfc measurement
Analyzed Max. Wind: 139 kts, 14 nm NE of center
Experimental research product of NOAA / AOML / Hurricane Research Division

FIG. 1. H*Wind isotach analysis (in knots) of (a) Hurricane Camille at landfall based on model and blended observations, (b) Hurricane Katrina's surface wind field at peak H*Wind V_{ms},(c) Hurricane Katrina at landfall. For IKE calculations, portions of the wind field over land are converted to marine exposure.

surface wind speeds (U) within specific ranges, assuming an air density (ρ) of 1 kg m^{-3},

$$\text{IKE} = \int_v \frac{1}{2}\rho U^2 dV. \qquad (1)$$

Here the wind speeds and volume elements (dV) are taken from an objectively analyzed, gridded wind field over a storm-centered 8° latitude domain having grid cells ~6 km on a side and 1 m in the vertical (centered at the 10-m level), and we ignore the contribution of turbulent wind fluctuations to the total kinetic energy of the flow.

Relevance to wind destructive potential. Kinetic energy is relevant to the wind destructive potential because it scales with the wind pressure (wind load) acting on a structure (ASCE 2005). However, much of the built environment consists of structures characterized by brittle failures of components and systems that lead to rapid escalation in damage and loss once a part of

the structure or building envelope fails. To account for this process, IKE is segregated into low, moderate, and high wind speed ranges, and multiplied by a representative damage factor.

Relevance to storm surge and wave destructive potential. Storm surge and waves generated by the shear stress of the wind on the ocean surface also scale with kinetic energy. While the initial dependence of sea surface drag coefficient is linear with wind speed, supporting a cubic dependence for stress, recent investigations (Powell et al. 2003; Donelan et al. 2004) suggest that the drag coefficient levels off or even decreases at winds above 33 m s^{-1}, suggesting a continued dependence on the square of the wind speed. Cline (1920) noted several cases of elevated water levels associated with waves propagating from distant tropical cyclones entering the Gulf of Mexico. These waves generate a shoreward flux of momentum known as radiation stress (Longuet-Higgins and Stewart 1964), which contributes to wave setup and elevated water levels

c) Hurricane Katrina 1200 UTC 29 AUG 2005
Max 1-min sustained surface winds (kt)
Valid for marine exposure over water, open terrain exposure over land
Analysis based on GPSSONDE_WL150 from 0959 - 1357 z; FCMP_TOWER from 0942 - 1359 z; VAD_88D from 0959 - 1354 z;
QSCAT from 1100 - 1102 z;
SHIP from 1010 - 1212 z; ASOS from 0936 - 1359 z;
SFMR43 from 0936 - 1359 z; MOORED_BUOY from 0939 - 1400 z;
METAR from 0950 - 1355 z; CMAN from 0936 - 1400 z;
GOES_SWIR from 1002 - 1002 z; TAIL_DOPPLER43 from 1020 - 1346 z;
MADIS from 0936 - 1359 z; DUAL_DOPPLER from 1010 - 1302 z;
MESONET from 0937 - 1400 z;
1200 z position interpolated from 1132 Army Corps; mslp = 923.0 mb
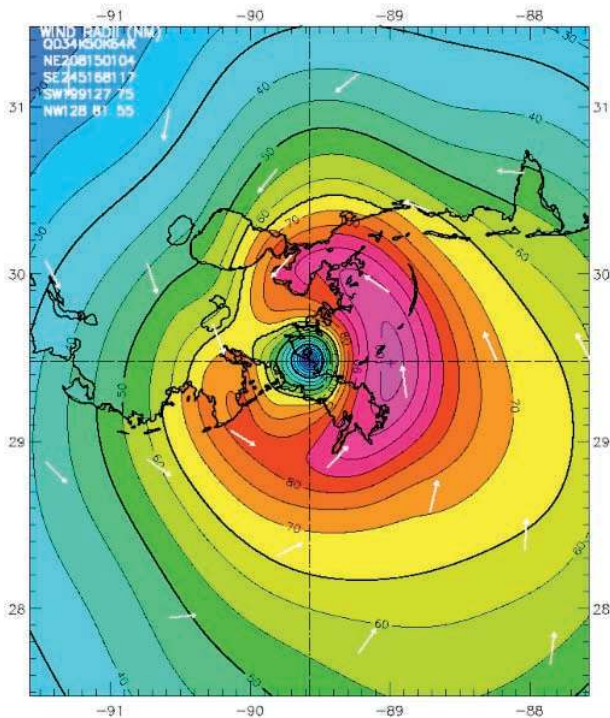
Observed Max. Surface Wind: 102 kts, 35 nm SE of center based on 1020 z TAIL_DOPPLER43 sfc measurement
Analyzed Max. Wind: 102 kts, 36 nm NE of center

long before landfall, and that can add significantly to the ultimate high water levels during landfall. A study of Hurricane Georges (1998) by Weaver (2004) estimated that wave forcing contributed 25%–33% of the total rise in water levels, and the recent post-Katrina study (IPET 2006) indicated wave setup contributing to ~1.4-m water level increases at levees in the vicinity of New Orleans. Indeed, recent hurricanes such as Opal, Georges, Isabel, Ivan, Katrina, Rita, and Wilma indicate that wave and storm surge heights are 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 values in the hours and days before landfall are likely to provide a robust estimate of wave and surge destructive potential. However, the ultimate surge actually experienced depends on additional factors such as bathymetric topography, bottom and surface roughness, storm motion, and coastline shape, while the surge- and wave-related destruction depends on the infrastructure at risk.

*H*Wind objective wind field analysis.* Measurement of IKE in a hurricane requires sufficient observations for an analysis of the wind field. Air-, space-, land-, and sea-based measurement systems now provide sufficient observations to depict the horizontal distribution of tropical cyclone winds in the western Atlantic and Caribbean basin. The National Oceanic and Atmospheric Administration (NOAA)–Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Wind Analysis System (H*Wind; Powell et al. 1996, 1998) provides an objective analysis of all available quality-controlled 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-based V_{MS} depends on data coverage and the quality of the individual platforms contributing to the wind measurement, but is estimated at 10% when the peak wind is sampled at the surface, or ~20% if winds are estimated from a simple flight-level wind speed reduction factor. Outside the eyewall where radial gradients are weaker, more plentiful in situ observations are available and wind uncertainty is probably closer to 10%. Landfalling hurricanes contain large sections of the wind field influenced by land friction. To allow for comparison of destructive potential near landfall to earlier offshore stages of the storm, all winds over land are converted to marine exposure using methods described in Powell et al. (1996).

Storm surge and wave destructive potential in Hurricane Katrina compared to Camille. As an IKE example for storm surge destructive potential, consider a reconstruction of Hurricane Camille's landfall wind field (Fig. 1a) as compared with two analyses of Hurricane Katrina's wind field at different times. The IKE for marine winds > tropical storm force (18 m s⁻¹, IKE_{TS}) is used as a proxy for storm surge and wave destructive potential. Blending the Shapiro (1983) wind model (using 909-mb central pressure, 14-km radius of max wind, and a pressure profile parameter of 0.435) with the few available marine observations leads to an estimated IKE_{TS} of 63 TJ contributed by Camille's marine winds > 18 m s⁻¹ (all winds have been converted to a marine exposure). We compare this to 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. A day before landfall, when an SS5 (Fig. 1b),

Katrina's marine wind field contained V_{TS} estimated at 71 m s^{-1} with an IKE$_{TS}$ of 124 TJ. At landfall in southern Louisiana and Mississippi, Katrina had weakened to SS3 status (52 m s^{-1}), but the marine-equivalent wind field in the storm core expanded (Fig. 1c) resulting in a respective IKE$_{TS}$ of 122 TJ. Therefore, based on IKE$_{TS}$, Katrina at landfall had destructive potential for storm surge similar to that attained a day earlier when it had stronger V_{MS}. Both analyses suggest Katrina had much more destructive potential than Camille. The tremendous wave- and storm surge–related destruction of Katrina at landfall was not well represented by the SS rating; SS3 Katrina at landfall (122 TJ) was more destructive than SS5 Camille (63 TJ) and similar to SS5 Katrina (124 TJ). This is especially pertinent when considering designs for flood protection systems; a system designed for a small SS5 hurricane might not survive a large SS3 hurricane.

Sensitivity of IKE calculations to wind bias. While landfall estimates of V_{MS} in a hurricane can vary by scientist, engineer, or agency, experiments suggest that IKE is not sensitive to bias in the V_{MS} estimate. To simulate a case in which a bias might be present, for example a high bias in the reduction factor used to estimate V_{MS} from reconnaissance flight-level winds, a 20% bias was added to the Andrew grid point containing V_{MS}, resulting in a 0.18% increase in IKE$_{TS}$ and a 0.49% increase in IKE contributed by winds above hurricane force (IKE$_{H}$). To simulate a biased reduction factor affecting all observations in the inner core, a 10% bias was added to all grid points containing surface winds above hurricane force, resulting in a 7.6% increase in IKE$_{TS}$ and a 21% increase in IKE$_{H}$. In practice, any bias evident in a reduction method is minimized by the H*Wind analyst choosing the reduction method that best agrees with available surface observations (typically GPS sondes are available for comparison). When the Stepped-Frequency Microwave Radiometer (SFMR) instrument transition to the Air Force Reserves Hurricane Hunter fleet is completed, the use of reduction factors should cease except for retrospective analyses of historical storms. It is possible that the observations used for an H*Wind analysis might not sample the maximum

wind region due to radial reconnaissance flight legs typically covering four azimuths over the 4–6-h period required for a H*Wind analysis. However, this should not be a systematic error and the magnitude of the error would be on the order of one half the storm translation speed. If a major, nontransient convective burst was not sampled by the aircraft, the error could be larger, but subsequent sampling would provide updated calculations.

WIND AND STORM SURGE/WAVE IMPACTS. A variety of IKE calculation options were explored by summing IKE contributions over several wind speed thresholds for a selection of gridded wind fields from 23 hurricanes comprising large and small wind fields available from the H*Wind archive (www.aoml.noaa.gov/hrd/data_sub/wind.html) over an 8° latitude domain (Table 1). A wind speed of 10 m s^{-1} was selected for the low end (IKE$_{>10}$), with additional thresholds for tropical storm force (> 18 m s^{-1}, IKE$_{TS}$) and hurricane force (> 33 m s^{-1}, IKE$_{H}$) chosen to relate to storm surge and wave destructive potential. Wind destructive potential thresholds include light (25 to <41 m s^{-3}, IKE$_{25-40}$), moderate (41 to <55 m s^{-1}, IKE$_{41-54}$), and severe (>= 55 m s^{-1}, IKE$_{55}$).

First we examine the storm-scale energy in the wind field using IKE$_{>10}$ (Fig. 2). While the range in values shown in Fig. 2 gives some idea of the energy differences between large [Hurricane Isabel (2003)] and small storms [Hurricanes Andrew (1992), Charley (2004), Camille (1969)], it is not well suited as a general indicator of damage potential since it fails to convey the potential for either wave and storm surge, or wind damage by small storms like Camille and Andrew.
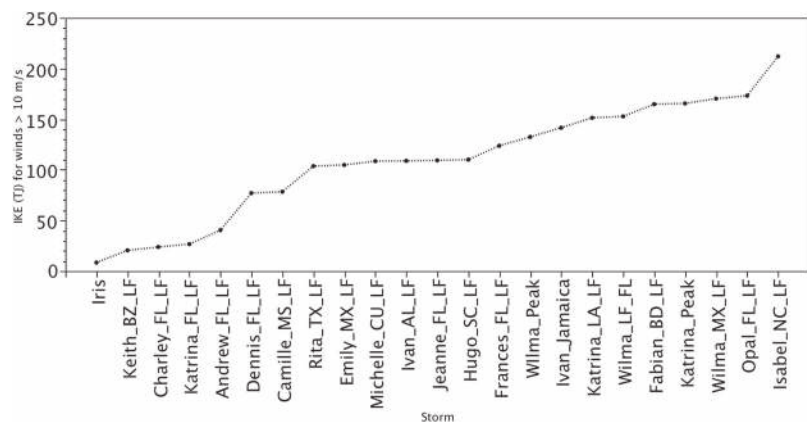
FIG. 2. Storm-scale integrated kinetic energy for winds >10 m s^{-1}. Letters refer to state or country abbreviations and landfall (LF) status or peak H*Wind intensity follow each storm name.

TABLE 1. H*Wind analysis cases, associated wind field structure quantities, IKE calculations (TJ), W_{DP}, S_{DP}, SS, and HII. H*Wind V_{MS} represents the maximum wind speed in the gridded file, which is usually smaller than the maximum wind speed depicted in the H*Wind graphic; P_{min} is from best track, SS and HII are based on best track V_{MS} (not shown).

Storm	Year	Month-day	Time (UTC)	R_{max} (km)	P_{min} (hPa)	V_{ms} (m s^{-1})	R_{18} (km)	R_{26} (km)	R_{33} (km)	W_{DP}	S_{DP}	IKE_{10}	IKE_{TS}	IKE_H	IKE_{25-40}	IKE_{41-54}	IKE_{55}	SS	HII
Andrew	1992	8-24	0900	19	922	68	191	142	77	5.0	2.5	40	20	7	7	3	2	5	5.2
Camille	1969	8-18	0430	15	909	65	230	163	109	5.2	4.0	78	63	31	32	14	3	5	5.0
Charley	2004	8-13	1930	7	941	63	156	81	40	4.1	1.9	24	11	2	5	1	0	4	4.1
Dennis	2005	7-10	1930	9	946	51	296	77	33	0.3	3.4	77	40	2	7	1	0	3	2.7
Emily	2005	7-20	0130	24	948	54	291	168	86	1.7	4.2	105	70	14	38	4	0	3	3.0
Fabian	2003	9-05	1330	67	941	51	380	241	138	3.7	5.1	165	123	40	61	21	0	3	3.0
Frances	2004	9-05	0130	52	960	46	319	217	139	2.5	4.7	124	94	29	53	8	0	2	2.0
Hugo	1989	9-22	0400	37	934	58	317	235	146	4.7	4.7	110	95	25	51	9	1	4	3.5
Iris	2001	10-09	0130	8	948	43	165	93	37	0.1	1.3	8	5	1	2	0	0	4	3.8
Isabel	2003	9-18	1630	87	957	47	532	322	214	3.4	5.6	212	174	42	93	12	0	2	1.9
Ivan (AL)	2004	9-16	0730	35	946	49	326	206	128	2.2	4.4	109	81	26	46	7	0	3	2.7
Ivan (Jamaica)	2004	9-11	1330	17	925	70	314	196	121	5.6	4.7	142	95	32	43	11	6	4	3.8
Jeanne	2004	9-26	0330	48	950	46	317	201	131	1.9	4.3	109	73	21	39	6	0	3	2.7
Katrina (FL)	2005	8-25	2230	15	984	33	115	44	28	0.1	1.3	27	5	0	2	0	0	1	1.2
Katrina (LA)	2005	8-29	1200	65	920	52	454	311	217	3.7	5.1	151	122	49	68	21	0	3	3.0
Katrina peak H*Wind	2005	8-28	1200	26	909	71	349	218	139	5.8	5.1	166	124	45	58	16	7	5	5.2
Keith (Belize)	2000	10-01	2230	19	959	50	154	62	44	0.5	1.9	20	11	4	4	2	0	3	2.4
Michelle	2001	11-04	1930	28	949	50	335	120	80	1.7	4.0	109	61	14	17	8	0	4	3.5
Opal	1995	10-04	2235	98	942	50	353	191	169	3.5	5.0	173	119	38	46	21	0	3	2.4
Rita	2005	9-24	0730	30	937	49	357	230	174	2.6	4.3	104	74	32	42	12	0	3	2.4
Wilma peak H*Wind	2005	10-19	1930	7	892	62	326	97	53	4.6	4.2	132	70	7	13	4	1	5	4.8
Wilma (FL)	2005	10-24	1030	72	951	51	380	268	179	2.8	4.8	153	104	29	48	12	0	3	2.5
Wilma (Mexico)	2005	10-22	0130	20	930	59	394	220	121	4.7	5.1	170	121	28	49	13	1	4	3.2

TABLE 2. A wind and storm surge/wave destructive potential rating for hurricanes based on integrated kinetic energy (TJ).

| Wind destructive potential rating	Wind damage-weighted IKE	Surge/waves destructive potential rating	Storm surge and waves IKE$_{TS}$
0.1	0.5	0.1	0.7
1.0	34.5	1.0	2.7
2.0	78.0	2.0	11.7
3.0	135.0	3.0	29.5
4.0	30 IKE$_{55}$ 1.1	4.0	61.0
5.0	30 IKE$_{55}$ 50	5.0	119.5
5.9	30 IKE$_{55}$ 298	5.9	260.0

Wind destructive potential. Since the concept of a damage potential rating with a 1–5 range is familiar to the public, we investigated the range of various IKE measures computed from a variety of storms in the H*Wind archive (Table 1). With the exception of Hurricanes Iris, Keith, and Michelle (in which grid points over land reflect open terrain winds), the gridded fields represent marine winds throughout the analysis domain. A rating system for wind destructive potential was assigned according to Table 2. We limit

the rating to <6.0 and follow the recommendation of Kantha (2006) for a continuous scale to prevent discrete jumps in category.

To convey the potential for wind damage, we take into account the nonlinear nature of the interaction of wind with structures. Residential structures respond to wind in a highly nonlinear process, as evidenced by residential insurance losses at zip codes (Fig. 3) compared to H*Wind open terrain wind speeds in Hurricanes Andrew, Hugo, and Opal (Powell 2000). Light, moderate, and severe wind damage thresholds correspond to loss levels of ~2%, 12%, and 60% of insured value. The respective IKE wind damage thresholds were weighted by multipliers of 1.0, 6.0, and 30.0 to account for the relative contribution to losses (e.g., winds ≥55 m s^{-1} (IKE$_{55}$) produce about 30 times more loss, and winds from 41 to <55 m s^{-1} (IKE$_{41-54}$) produce 6 times more loss than winds 25 to <41 m s^{-1} (IKE$_{25-40}$)]. However, describing impacts of small, intense storms within the context of larger, less intense storms remains a challenge. The weighted IKE values obtained from this analysis did not appear to do justice to the dramatic damage potential associated with a small, intense storm with winds >55 m s^{-1}. Consequently, we segregate storms with winds ≥=55 m s^{-1} from the population and reserve a scale rating >4 for these storms using a different empirical fit. Very small, intense storms are also a challenge for gridding an analysis. Several of the gridded field V_{MS} values for storms listed in Table 1 show differences from V_{MS} depicted in the H*Wind online graphical product (not shown). The H*Wind analysis is continuous and constrained to match the observed V_{MS}; depending on the grid resolution, the maximum gridded V_{MS} will typically be less. As described in the second section, the V_{MS} value has little effect on the IKE calculations, but grid resolution should be adjusted to better resolve grid cells in which V_{MS} ≥= 55 m s^{-1}. For example, the online H*Wind analysis graphic for Hurricane Iris (not shown) depicts a V_{MS} of 66 m s^{-1} but the largest value in the 1.5-km resolution gridded field was 43 m s^{-1}. A smaller grid size would be needed to resolve V_{MS} and compute IKE$_{55}$ for this tiny storm.
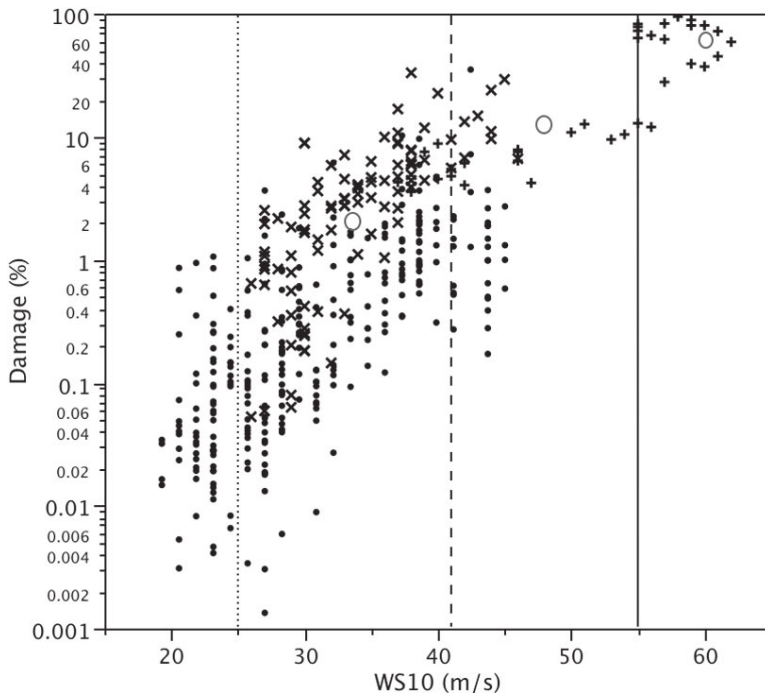
FIG. 3. Residential wind damage (claim to insured value ratio) as a function of 10-m open-terrain V_{ms} for zip code locations in Hurricanes Andrew, Hugo, and Opal. The 25–40, 41–54, and ≥=55 m s^{-1} thresholds are shown by vertical lines and mean damage by open circles.
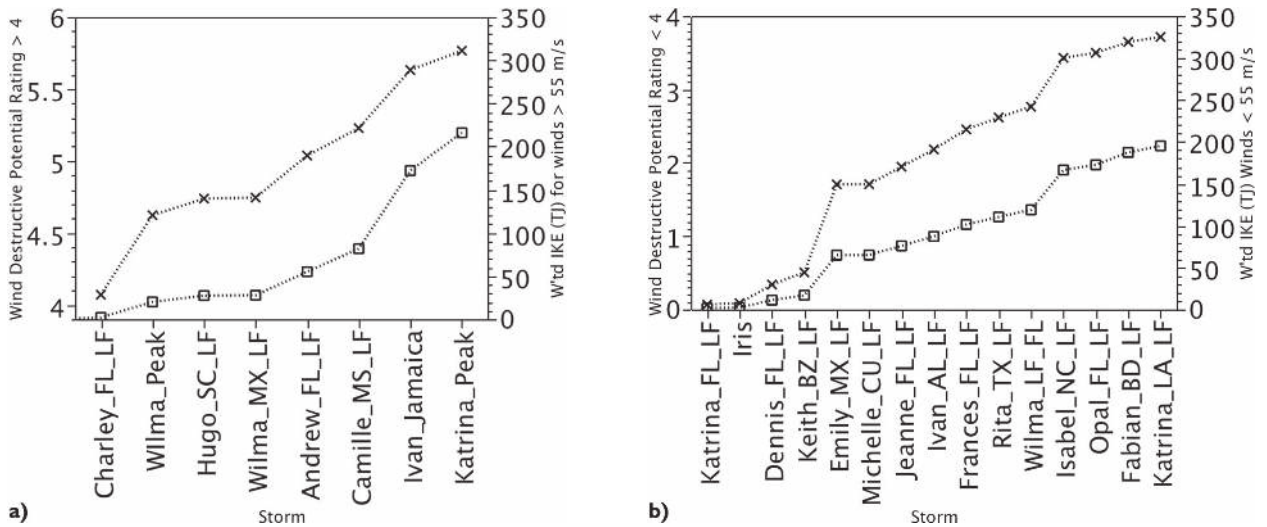
Fig. 4. Wind damage potential category assigned to storms from the H*Wind archive: (a) Assignment of storms to categories 4 and 5 (x's) based on weighted IKE (squares) for winds ≥55 m s⁻¹. (b) Categories 1–3 (x's) based on weighted IKE (squares) for winds of 25–41, and 41–54 m s⁻¹. Letters refer to state or country abbreviations and LF status or peak H*Wind intensity follow each storm name.
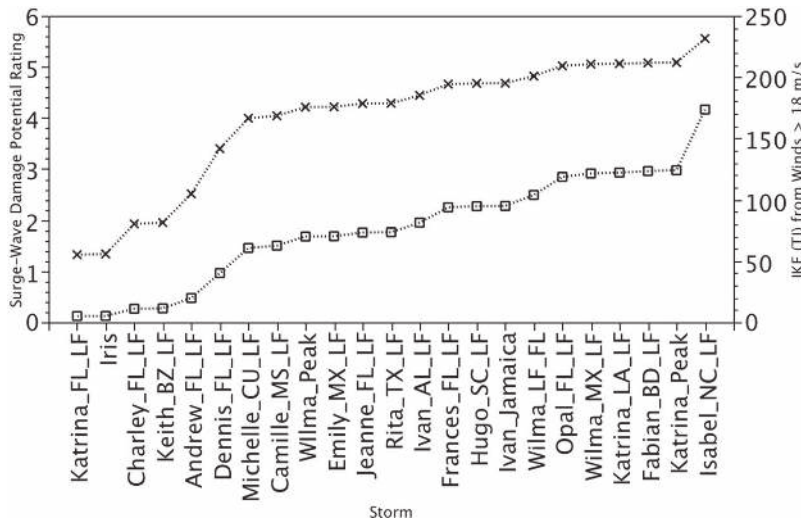
Storms with winds <55 m s⁻¹ are assigned a wind destructive potential (W_{DP}) rating <4 (Fig. 4a), based on the sum of the damage-weighted IKE values ($IKE_{25-40} + 6\ IKE_{41-54}$) in (TJ). As indicated in Table 2, a storm need not be a hurricane to be rated for W_{DP},

$$W_{DP} < 4 = 0.67 + 0.017(IKE_{25-40} + 6\ IKE_{41-54}) \\ - 5.4 \times 10^{-5}[(IKE_{25-40} + 6\ IKE_{41-54}) - 109.6]^2; \quad (2)$$

W_{DP} ratings >4 (Fig. 4b) are assigned to storms with winds ≥55 m s⁻¹, and are based on the contribution of the damage-weighted IKE value, $30\ IKE_{55}$ alone:

$$W_{DP} > 4 = 3.28 + 1.007 \times Log_{10}(30\ IKE_{55}) \\ + 0.271 \times [Log_{10}(30\ IKE_{55}) - 1.629]^2. \quad (3)$$

A W_{DP} rating of 3.5 was assigned to Katrina at landfall in Louisiana and Mississippi with a weighted IKE of 195 TJ for winds <55 m s⁻¹ (Fig. 4a). For storms with winds ≥55 m s⁻¹, a W_{DP} rating of 5 was assigned to an $30\ IKE_{55}$ value of 50 TJ and the upper limit of 5.99 is reached if $30\ IKE_{55}$ values reach 298 TJ. For example, Hurricanes Camille (Mississippi), Andrew (Florida), Ivan (near Jamaica), and Katrina the day before landfall received W_{DP} ratings >5 but Charley (Florida), Hugo (South Carolina), and Wilma (near the Yucatan of Mexico) rate $4 < W_{DP} < 5$ (Fig. 4b).

Storm surge and wave destructive potential. As an indicator of storm surge and wave destructive potential (S_{DP}) we evaluated IKE_{TS} and IKE_H. IKE_{TS} (Fig. 5; Table 1) was selected because it covered the possibility of a large, strong tropical storm posing a larger surge and wave threat than a small, weak hurricane. In contrast to W_{DP}, we have not applied damage multipliers or weights so the IKE_{TS} energy levels in Fig. 5 are not comparable to Fig. 4, but they do represent a contribution to the IKE_{10} values in Fig. 3.

Fig. 5. As in Fig. 4, but for storm surge and wave damage potential categories (x's) related to IKE for winds >33 m s⁻¹ (squares).

A continuous S_{DP} rating was assigned according to

$$S_{DP} = 0.676 + 0.43\sqrt{IKE_{TS}} - 0.0176(\sqrt{IKE_{TS}} - 6.5)^2. \quad (4)$$

For storm surge and waves Hurricanes Katrina (Louisiana and at peak H*Wind intensity), Wilma (Mexico), Fabian, Isabel, and Opal all rate $S_{DP} > 5$, while Camille, Jeanne, Frances, Rita, Ivan (Alabama and Jamaica), Wilma (peak H*Wind intensity and Florida), Hugo, and Emily all receive $4 < S_{DP} < 5$.

Comparison of IKE to SS and HII. The IKE_{TS} was compared to SS and HII (Fig. 6) computed from the best track V_{MS} closest to the times of the H*Wind analyses contained in the NHC storm report (for cases near landfall) or HURDAT (official NHC historical data on storm position, surface pressure, and intensity at the 6h intervals) file (www.nhc.noaa.gov/pastall.shtml). No relationship is evident and the HII yields only five values >4.0. The total wind damage–weighted IKE is computed as the sum ($IKE_{25-40} + 6\,IKE_{41-54} + 30\,IKE_{55}$) and compared

Fig. 6. Comparison of IKE$_{TS}$ to (a) SS and (b) HII based on best track V_{ms}.

to SS, HHI, and W_{DP} in Fig. 7. The SS (Fig. 7a) and HII (Fig. 7b) show a small dependence (r^2 of 10% and 12%, respectively) on wind damage–weighted IKE.

Ideally an IKE measure of wind damage potential should be continuous. However, despite weighting IKE by damage, a discontinuity is apparent in Fig. 7c, caused by the different empirical fit (3) we chose to account for small storms with strong ($\geq$55 m s^{-1}) winds. These storms have smaller values of total wind damage–weighted IKE than larger storms with weaker winds. Using IKE to describe potential impacts of small, intense storms within the context of larger, but less intense storms remains a challenge, and we welcome suggestions for improving the scale and the concepts behind it. Improvement of damage–wind relationships will likely require further research concerning the escalation of damage and loss as winds begin to generate large amounts of airborne debris and buildings begin to disintegrate.

Estimating W_{DP} and S_{DP} wind radii. From a practical point of view, to estimate W_{DP} and S_{DP}, surface wind fields should be available to compute IKE. H*Wind fields are limited geographically and are not always available. H*Wind analyses are experimental research products generated when sufficient observations are available for analysis (typically when named tropical cyclones are within reconnaissance aircraft range in the Atlantic basin and also occasionally in the eastern and central Pacific basins if aircraft sortie there). Gridded surface wind fields from numerical weather prediction models such as the Geophysical Fluid Dynamics Laboratory (GFDL) model are available in gridded binary (GRIB) format, so IKE, W_{DP}, and S_{DP}, could be routinely computed from model forecast fields. Operational estimates of wind radii can be used to estimate IKE, W_{DP}, and S_{DP}, values in the absence of a gridded wind field. Operational estimates of the V_{MS}, and outermost radii of tropical storm (R_{18}), 26 m s^{-1} (50 kt or R_{26}), and hurricane-force (R_{33}) winds are issued in operational tropical cyclone advisories and forecasts every 6 h.

To develop relationships between wind radii and IKE, W_{DP}, and S_{DP}, H*Wind radii were recorded from text information provided on each of the graphical analysis products listed in Table 1. Here, R_{max} was determined from the location of the maximum observed wind measurement from each analysis. Least squares regression resulted in a series of relationships (appendix) for estimating various IKE quantities, W_{DP}, and S_{DP} from wind radii. These relationships may be
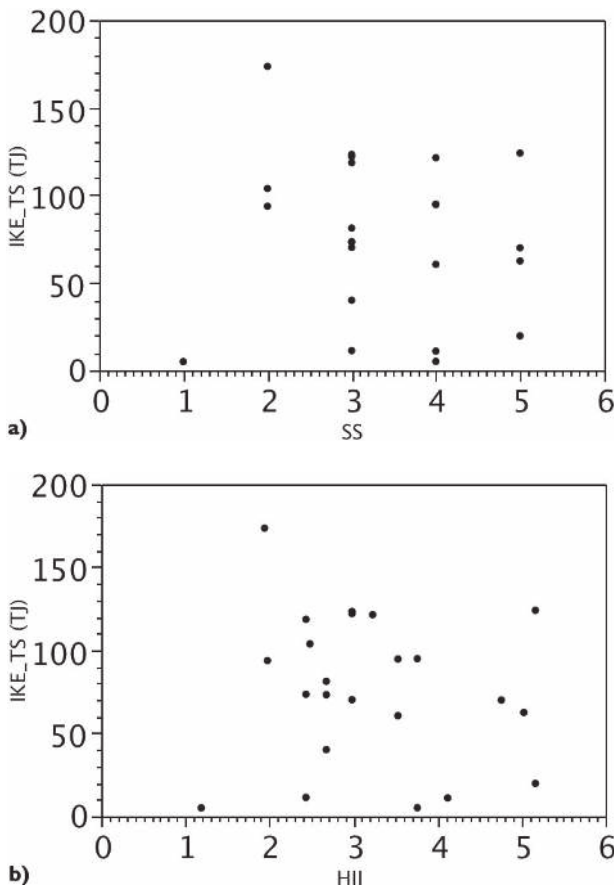
used to estimate IKE, W_{DP}, and S_{DP} from operational advisory information. Operational forecasts do not include radius of maximum wind speed (R_{max}), but the calculations could use the Rmax information contained in the CARQ (Combined Automated Response to Query) "cards" available from the NHC archive of public aids (A decks) and assume persistence so that forecasts of W_{DP} and S_{DP} could be generated. The relationships listed in the appendix should be considered preliminary estimates; a larger selection of H*Wind analyses could further refine the expressions and take into account wind field asymmetry. Tropical cyclones in basins outside the Atlantic may have different wind averaging specifications and different wind field radii characteristics, necessitating wind radii relationships tailored to the basin of interest. For basins outside the Atlantic, satellite remote sensing of ocean vector winds are sufficient to determine IKE_{TS} in weak tropical cyclones, but improvements are needed to sample stronger storms and relate wind radii to additional IKE values. Of special interest would be whether improved satellite remote sensing of larger storms in the western Pacific basin can eventually help establish IKE values associated with the upper limits of W_{DP} and S_{DP}.

With wind radii information available in historical tropical cyclone databases, W_{DP} and S_{DP} computations could be made for retrospective analysis of historical storms with sufficient radii data. For studies involving tropical cyclone climate variability and global climate change, accumulated IKE_{TS} and IKE_{55} could be computed over the 6-h periods of storms over a season (similar to the current ACE and power calculations). Accumulated IKE should better convey tropical cyclone severity and destructive potential than the ACE or power calculations currently conducted.

DISCUSSION. We have proposed W_{DP} and S_{DP} ratings based on IKE computations from 23 objectively analyzed hurricane wind fields. The W_{DP} ratings >5 include Hurricanes Katrina (on 28 August), Andrew, Camille, and Ivan (near Jamaica). Storms with S_{DP} ratings >5 include Katrina at landfall in Louisiana, Isabel at landfall in North Carolina, Opal at landfall in Florida, and Wilma at landfall in Mexico. Camille received an S_{DP} rating of 4. The S_{DP} ratings >4 for Hurricanes Frances, Jeanne, Hugo, Ivan, Rita, and Wilma suggest that these storms were capable of surge and wave impacts similar to Camille had they followed the same track. The variability in storm size and intensity leads to interesting combinations in destructive potential.
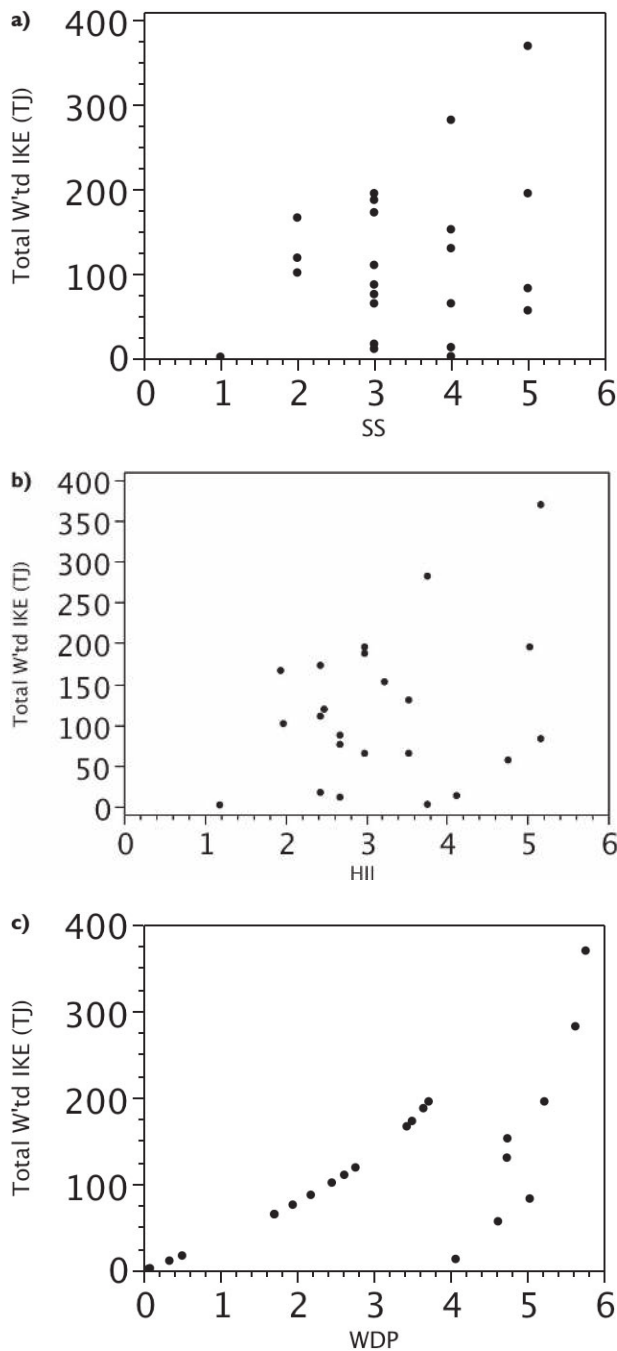
Fig. 7. Comparison of (a) SS, (b) HII, and (c) W_{DP} to total wind damage–weighted IKE; SS and HII are based on best track V_{MS}. IKE values are computed from H*Wind gridded fields. Total wind damage–weighted IKE is the sum: $IKE_{25–40} + 6\ IKE_{41–54} + 30\ IKE_{55}$.

For example, Andrew and Charley's Florida landfalls were more wind threats with W_{DP} of 5.0 and 4.1, respectively, than surge threats (S_{DP} of 2.5 and 1.9), while Isabel (North Carolina) and Opal (Florida) were more surge (S_{DP} of 5.6 and 5.0) than wind (W_{DP} of 3.4 and 3.5) threats.

Ultimately the damage potential rating should be based on an objective measure of damage realized but such depends on the infrastructure, population, and wealth of an affected area; the susceptibility of the area to surge and waves; and the difficulty of attributing damage to wind, wave, or surge. An IKE-based approach to destructive potential provides an objective means to compare historical storms and makes no distinction on whether a tropical cyclone is classified as a hurricane or tropical storm (a large, strong tropical storm could have a larger destructive potential than a small, weak hurricane); the rating could also be applied to nontropical storms. IKE values can be routinely computed from gridded surface wind field output from numerical weather prediction models. Comparisons of model and analysis IKE computations would supplement model performance evaluations. With the provided relationships, IKE quantities may be forecast and estimated through a storm's life cycle from wind radii information available from operational advisories, forecasts, and historical databases. IKE values can be summed to provide a cumulative index applicable to global climate change assessments of tropical cyclone destructiveness. IKE values or their associated wind fields can at some point be combined with bathymetric topography, storm motion, and infrastructure at risk to produce more realistic estimates of expected damage and disruption at specific locations.

The IKE-based W_{DP} and S_{DP} calculations are more complex than the current SS, and there may be some resistance to any new metric if there were any chance it might confuse the public. By using the familiar numerical range covered by the SS, our new metrics simply apportion the destructive potential between wind and surge similar to the qualitative graphics of wind versus surge threats effectively presented to the public by The Weather Channel. The W_{DP} and S_{DP} convey destructive potential from a physical basis in terms of wind loading and sea surface stress. By considering the importance of storm size and wind strength, when computed and compared among historical storms that have affected a geographic area, W_{DP} and S_{DP} could help to improve risk perception among the public.

Some limitations of IKE as metric of destructive potential include the inability to account for 1) localized areas susceptible to storm surge and waves due to coastline shape and bathymetric topography, 2) storm motion contributions to surge, 3) duration- and wind direction steadiness–related wind damage (Powell 2000), 4) variations in air density (~5%) over the area of winds >25 m s⁻¹, and 5) the contribution of the turbulence kinetic energy in generating roof suction pressures and debris missiles.

Revisions of the destructive potential scales could incorporate the factors above, the duration of the storm within the basin, and new findings on the interaction of winds with structures and with the ocean surface. The influence of storm motion, bathymetric topography, coastline shape, surface topography, and roughness could be used as modifiers for the IKE quantities, much the same as soil modification factors are used to estimate site-specific ground motions in earthquakes. During the 2007 hurricane season we will add IKE calculations and the IKE damage potential ratings to experimental H*Wind analyses on our Web site and work toward improving the relationship between the IKE intensity metrics and wind radii. At present, the IKE calculations are best suited to the western Atlantic basin where regular aircraft reconnaissance is available, but the relationships of IKE to wind radii will allow experimentation with IKE in forecasts and analyses in tropical cyclone basins outside the Atlantic.

We encourage scientists and engineers from multiple disciplines to build on our approach to help us reach an improved understanding of tropical cyclone impacts. Gridded wind fields are available for experimentation toward refining measures of the wind and surge destructive potential.

APPENDIX: COMPUTING IKE, W$_{DP}$, AND S$_{DP}$ FROM OPERATIONAL WIND RADII AND INTENSITY.

IKE quantities (TJ) are estimated from the H*Wind V_{MS} (m s⁻¹) and the quadrant average of reported wind radii (km) listed in H*Wind graphical products (Table 1). Quadrants without wind radii or quadrants over land were not included in the radii averages. Any negative IKE, W_{DP}, or S_{DP} computations should be constrained to zero.

If $V_{MS} >= 18$ m s^{-1}

$\text{IKE}_{TS} = -46.42 + 0.352\ R_{18} + 0.0007\ (R_{18} - 305.97)^2 + 0.187\ R_{33} - 0.004\ (R_{33} - 113.15)^2$ ($r^2 = 0.93$, $n=23$)   (A1)

If $V_{MS} >= 25$ m s^{-1}

$\text{IKE}_{25-40} = -23.3 + 0.05\ R_{18} + 0.245\ R_{26}$ ($r^2 = 0.91$, $n=23$)   (A2)

If $V_{MS} >= 33$ m s^{-1}

$\text{IKE}_{H} = -25.2 + 0.238\ V_{MS} + 0.023\ (V_{MS} - 55.87)^2 + 0.235\ R_{33}$
$\quad - 5.5 \times 10^{-4}\ (R_{33} - 113.15)^2 + 0.025\ R_{18}$ ($r^2 = 0.90$, $n=23$)   (A3)

If $V_{MS} >= 41$ m s^{-1}

$\text{IKE}_{41-54} = -25.7 + 0.4\ V_{MS} - 0.022\ (V_{MS} - 56.9)^2 + 0.085\ R_{33} + 0.097\ R_{max}$ ($r^2 = 0.73$, $n=22$)   (A4)

If $V_{MS} >= 55$ m s^{-1}

$\text{IKE}_{55} = -28.96 + 0.43\ V_{MS} + 0.036\ (V_{MS} - 64.9)^2 + 0.024\ R_{33}$ ($r^2 = 0.98$, $n=10$)   (A5)

W_{DP} and S_{DP} estimated from wind radii and V_{MS} as described above.

If $V_{MS} < 55$ m s^{-1};

$W_{DP<4} = 0.047 + 0.015\ R_{33} - 5.98 \times 10^{-5}(R_{33} - 119.74)^2 + 0.008\ R_{max}$ ($r^2 = 0.91$, $n=15$)   (A6)

If $W_{DP<4} > 4.0$, set $W_{DP<4} = 3.99$

If $V_{MS} >= 55$ m s^{-1};

$W_{DP>4} = -0.778 + 0.078\ V_{MS} + 0.008\ R_{33} - 9.01 \times 10^{-5}\ (R_{33} - 100.79)^2$ ($r^2 = 0.99$, $n=8$)   (A7)

If $W_{DP>4} < 4.0$, set $W_{DP>4} = 4.0$; If $W_{DP>4} > 6.0$, set $W_{DPs} = 5.99$

$S_{DP} = 0.959 + 0.009\ R_{18} - 8.88 \times 10^{-6}\ (R_{18} - 305.98)^2 + 0.005 R_{33}$
$\quad - 1.04 \times 10^{-4}\ (R_{33} - 113.15)^2$ ($r^2 = 0.95$, $n=23$)   (A8)

If $S_{DP} > 6.0$, set $S_{DP} = 5.99$.

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