A New Metric for Hurricane Destructive Potential

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Resources: 30 scientists and support staff from NOAA and University of Miami
Cooperative Institute for Marine and Atmospheric Studies, regional lab with
oceanographic expertise
• Motivation for a new metric

• Intensity is important but independent of size

• Wind radii are important but independent of intensity

• Destructive potential depends on both

• We need a metric to convey this to the public
• Outline:

• Risk perception

• Intensity and measures of destructive potential

• Integrated Kinetic Energy

• Wind and Surge Destructive Potential Scales

• Applications, advantages, limitations
• Risk Perception
Despite excellent forecasts and warnings, people act on perceived vulnerability

- Past experience influences perception (Baker 2006, Wilkinson and Ross 1970)

- Those who experienced significant loss are more likely to act in the future (Shulz et al. 2005, Miletti 1992)

- Experiences from Hurricane Camille of 1969 influenced actions taken in Katrina

- Camille and Katrina were very different storms
"It looks like Hurricane Camille killed more people yesterday than it did in 1969." Mr. Jim Holt of Biloxi on 30 August 2006

"Many officials and locals believed those like Nelson who had survived what was then the strongest recorded hurricane were lulled into a false sense of security that kept them in harm's way."

"...They, like many others, thought their homes would survive because they had withstood Hurricane Camille in 1969. They were wrong. Hurricane Camille killed more people last week than it did the first time," Amy Wilson said."
• **A New Metric:**

• Distinguish between a Katrina and a Camille

• Compare destructive potential of storms independent of local effects

• Evaluate the destructiveness of TC activity

• Evaluate the ability of a model to predict destructive potential
• Intensity, the Saffir–Simpson Scale, and alternative measures of destructive potential
• **Hurricane Intensity:**

  • “The highest one-minute average wind speed (at an elevation of 10 m with an unobstructed exposure) associated with that weather system at a particular point in time”

  • Difficult to measure

  • Estimates can vary by 30%

  • The max sustained wind determines the Saffir-Simpson Category
• **Saffir-Simpson Scale**

  • Widely used, very useful and understood by the public for over 30 years

  • Saffir: Engineering report winds in gusts (UN 1975)

  • Simpson added storm surge descriptors (Weatherwise 1974)

  • Reinterpreted to represent sustained winds
**Alternative Measures:**

- Accumulated Cyclone Energy (only uses Vmax... no size) Bell et al 2000,

- Inner and outer core strengths (mean wind over an annulus) Croxford and Barnes 2002, Weatherford 1988

- Energy dissipation or power (scales with Vmax\(^3\)) Emanuel 2005 (used only max wind), TKE Dissipation Businger and Businger 2001

- Hurricane Intensity Index (Kantha 2006) uses ratio square of Vmax to ref wind, Hazard index adds Rmax, storm motion, cube of Vmax

- Roof cladding fatigue index Mahendran 1998

- Damage as a power of the maximum wind speed (power ranging from 2 to 9) Howard 1972, Nordhaus 2006

- Destruction, Economic loss, Mortality: depend on population density and wealth
• Integrated Kinetic Energy

• Destructive Forcing:
  • Wind Stress
    • Wave damage
    • Storm Surge
  • Wind Loads
Wind stress on the ocean surface (force per unit area)

- scales with the square of the wind speed

\[ \tau = \rho C_d U_{10}^2 \]

- \( C_d \) levels, then decreases as winds increase above hurricane force
**Wave damage**

- Wind stress on the ocean, *size of wind field* determines extent of wave field

- Right rear quad waves move in direction of winds, highest waves, largest wave lengths

- Long waves travel very fast, land at coast well ahead of the storm

- Can cause beach erosion even if storm remains out at sea or landfalls elsewhere

- Shallow water slows, steepens waves $\rightarrow$ Breaking

- Breaking waves add to the storm surge 10-30% Weaver 2004, IPET 07
**Storm Surge Damage**

- Wind stress on the ocean, *size of wind field* determines extent of water pushed ashore by winds

- Local factors (coastline shape and bathymetry) determine storm surge elevation

- Combined surge with tide, wave setup and run-up determines high water

- Waves on the surge provide the battering ram for damage

- Pre storm water levels can go up several feet when a hurricane enters the Gulf (Cline 1920)
• **Wind Damage**

• Wind loading acts as a force that goes as the square of the wind speed (ASCE-7)

• Damage to homes depends on building design, workmanship, local building codes, code enforcement, and preparedness

• Roof suction pressures, buffeting, and debris load depend on structure of turbulence

• At ~110 kts the building envelope is compromised
- **Insured Loss**
  - Wind damage only (National Flood program handles storm surge damage)
  - Difficult to determine wind vs surge in some cases
  - Zip code loss data from Hurricanes Andrew, Hugo, and Opal were compared to winds based on H*Wind analyses projected along the storm track
Damage increases dramatically at ~ 55 m/s

% Damage claim/insured value

Threshold damages at 2%, 12%, 60%
• **Integrated Kinetic Energy (IKE)**

  • Kinetic energy/volume

  \[
  IKE = \int \frac{1}{2} \rho ws^2 dV
  \]

  • Scales with the square of the wind speed and the areal coverage of damaging winds

  • Contributions of IKE over various wind thresholds

  • Sum grid cell KE - 5 x 5 km, 1 m deep at 10 m

  • IKE range from H*Wind archive
**H*WIND** is an **global, interactive, graphical, tropical cyclone observing/analysis system**

**Data Collection**
- Satellite
- Air Force and NOAA Aircraft
- Ships, buoys
- + more

**Presentation Layer**
- Quality Control
- Analysis
- Products

**Database Layer**

**Winner of NOAAATech 2000 and 2002 awards**
**H*Wind: Hurricane Wind Field Analysis**

**Observing Platforms**

- Geostationary (GOES) satellite data
- Polar Orbiting OSCAT, TM/I, and SSM/I satellites data
- Air Force and NOAA Aircraft
- Stepped Frequency Microwave Radiometer (SFMR)
- Automated Surface Observing System (ASOS) Mesonets
- GPS dropwindsondes
- Coastal Marine Automated Network (CMAN)
- NOAA Buoys Drifting buoys
- Ship reports
Hurricane Isabel 2003 at landfall
The H*Wind Archive: http://www.aoml.noaa.gov/hrd/data_sub/wind.html

**Hurricane Isabel 1630 UTC 18 Sep 2003**
Max 1-min sustained surface winds (kt) for marine exposure
Analysis based on GOES from 1602 - 1602 z; TOWER, LD, TO from 1724 - 1800 z;
MOORED_BUOY from 1600 - 1429 z; GPSSONDE_SFC from 1706 - 1429 z;
SFMR from 1721 - 1800 z; APRES from 1721 - 1415 z; CMAN from 1705 - 1428 z;
GPSSONDE_WL150 from 1700 - 1429 z;
1630 z position interpolated from 1544 Vortex; mslp = 957.0 mb

**Hurricane Charley 1800 UTC 13 Aug 2004**
Max 1-min sustained surface winds (kt)
Valid for marine exposure over water; open terrain exposure over land
Analysis based on BACKGROUND_FIELD from 1800 - 1800 z; DRIFTING_BUOY from 1500 - 1700 z;
FCMP_TOWER from 1531 - 2055 z; CMAN from 1502 - 2100 z;
MAPS from 1500 - 2300 z; GPSSONDE_SFC from 1522 - 1833 z;
AFREC from 1500 - 2017 z; GPSSONDE_WL150 from 1522 - 1930 z;
GOES from 1602 - 1902 z; MOORED_BUOY from 1910 - 2024 z;
1800 z Army Corps fix; mslp = 951.0 mb
IKE$_{TS}$ Calculation:

1. 5 km gridded field
2. Square winds in $> 18$ m/s grid cells
3. Multiply by volume and sum
• IKE calculation sensitivity:

  • $<1\%$ change in IKE when resampling Andrew with $10\%$ random error

  • $0.2\%$ change in $IKE_{TS}$ when adding a $20\%$ bias in Andrew’s max wind

  • $8\%$ increase in $IKE_{TS}$ when adding $10\%$ bias to winds > hurricane force
Camille
Reconstructed:
Using data from NEW, BIX, TW50, blended with Shapiro model wind field:
Rmax 14 km, Pmin 909 mb,
Profile parameter 0.435
IKE_Ts = 63 TJ

Special Thanks to
David Levinson of NCDC
Kinetic energy from the wind field takes into account storm size

Katrina at landfall (Cat 3*) was as destructive as when a Cat 5

Cat 5 KE for winds > 34 kt = 124 TJ

Cat 3: KE for winds > 34 kt = 122 TJ

*Marine Exp
Camille

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 CMAN from 0909 - 1445 z, APRBC from 0907 - 1449 z,
QSCAT from 1115 - 1332 z, SHIF from 1132 - 1312 z,
PESONET from 1416 - 1456 z, CPSS/NOAA_WL150 from 0900 - 1456 z,
METAS from 0913 - 1400 z, ALOS from 0904 - 1100 z,
MOORED_BUOY from 0949 - 1459 z,
1200 z position interpolated from 1104 Army Corps, mslp = 950.0 mb

Observed Max. Surface Wind: 129 kt, 8 nm NE of center based on 0943 z
1 nautical measurement
Analysis Max. Wind: 127 kt, 7 nm NE of center
Experimental research product of NOAA / AOML / Hurricane Research Division

Katrina

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 0909 - 1445 z, APRBC from 0907 - 1449 z,
QSCAT from 1115 - 1332 z, SHIF from 1132 - 1312 z,
PESONET from 1416 - 1456 z, CPSS/NOAA_WL150 from 0900 - 1456 z,
METAS from 0913 - 1400 z, ALOPS from 0904 - 1100 z,
MOORED_BUOY from 0949 - 1459 z,
1200 z position interpolated from 1104 Army Corps, mslp = 950.0 mb

Observed Max. Surface Wind: 129 kt, 14 nm NE of center based on 1422 z
1 nautical measurement
Analysis Max. Wind: 129 kt, 14 nm NE of center
Experimental research product of NOAA / AOML / Hurricane Research Division

*Marine Exp

124 TJ

122 TJ
• **IKE -> Hurricane Destructive Potential**

  • Objective scale to allow comparison of different sized storms, independent of local susceptibility (coastline shape, bathymetry, building codes)

  • Dependent on IKE computed from damaging portion of analyzed or modeled wind field or wind radii

  • Similar numerical range to familiar Saffir-Simpson Scale, but continuous
Range of storms selected from the H*Wind Archive

SS Cat
IKE based on a 10 m/s threshold ignores compact but intense storms

Need separate scales for wind and surge/waves
• Surge / Wave Destructive Potential (SDP):

  • Depends on IKE from winds > tropical storm force

  • A large TS can be more destructive than small hurricane

  • Actual destruction depends on local effects
Surge / Waves Damage Potential IKETS

![Graph showing Surge-Wave Damage Potential Rating for various storms. The x-axis represents the storms, and the y-axis represents the damage potential rating. The graph indicates a general increasing trend in damage potential as the storms move from left to right.]
Wind Damage

Insurance loss by zip code vs 10 m open terrain wind speed

Damage Threshold Multipliers
Winds > 55 m/s - 30
Winds 41-54 m/s - 6
Winds 25-40 m/s - 1
• **Wind Destructive Potential (WDP):**

  • Depends on damage-weighted IKE contributed by three wind speed ranges: 25-40 m/s, 41-54 m/s, > 55 m/s

  • Cat 4 and 5 storms have > 55 m/s winds covering areas > 25 km² capable of compromising the building envelope

  • A large tropical storm can be more destructive than a small hurricane

  • Actual destruction depends on local effects like building design, codes, code enforcement, workmanship
Wind Destructive Potential
IKE Calculation:

1. 5 km gridded field
2. Square winds in threshold grid cells
3. Weight by contribution to damage
4. Multiply by volume and sum
Wind destructive potential < Cat 4

Cat 0-3
Winds > 25-40, 41-54

Storm
Katrina_FL_LF
Dennis_FL_LF
Keith_BZ_LF
Emily_MX_LF
Michelle_CU_LF
Jeanne_FL_LF
Ivan_AL_LF
Frances_FL_LF
Rita_TX_LF
Wilma_LF_FL
Isabel_NC_LF
Opal_FL_LF
Fabian_BD_LF
Katrina_LA_LF

W'td IKE (TJ) Winds < 55 m/s
Wind destructive potential > Cat 4

Cat 4-5
Winds > 55 m/s
Saffir-Simpson scale relationship to IKE from winds over tropical storm force (left) and damage-weighted IKE (right)
Hurricane Intensity Index (HII) relationship to IKE from winds over tropical storm force
Hurricane Intensity Index (HII) relationship to damage-weighted IKE
Challenge: Small intense storms with winds > 55 m/s can rate as WDP > 4 despite having smaller total weighted IKE than weaker storms.
• **Operational IKE, \( W_{DP} \), and \( S_{DP} \)**

- Operational \( V_{MS} \), radii of tropical storm \((R_{18})\), 26 m s\(^{-1}\) (50 kt or \( R_{26})\), and hurricane force \((R_{33})\) winds issued in advisories and forecasts every 6 h.

- Operational forecasts do not include \( R_{max} \), but the calculations could use CARQ value and assume persistence to produce forecasts of \( W_{DP} \) and \( S_{DP} \).

- A set of equations have been developed to compute IKE based on operational Rmax, Vmax, \( R_{33} \), \( R_{26} \), and \( R_{18} \).
- **Limitations**

  - Local factors determine the ultimate damage (bathymetry, coastline shape, building codes, debris load, workmanship, design, topography, roughness, etc.)

  - Additional physical processes not taken into account (Turbulence, duration, steadiness, air density variations)

  - Smaller grid needed to resolve small intense storms e.g. Iris, Charley

  - Functions to compute IKE, WDP, SDP from radii may not apply to TC basins outside the Atlantic
Wind and Surge Destructive Potential Rating

- Physically based on wind stress and wind loading
- Continuous, 0-5 range is familiar
- Apportions threat into surge and wind *(Weather Channel)*
- Comparing historical storms may help improve risk perception among public
• IKE, WDP, SDP Advantages

• Takes into account the area of damaging winds

• Can be computed from gridded fields or wind radii, analyzed or forecast

• Objective... Tropical cyclones of different sizes and intensities can be compared independent of local factors

• Alternative metric for forecast model verification... less dependent on a single number
Subtropical Storm Andrea

Subtropical Storm Andrea 1330 UTC 09 MAY 2007
Max 1-min sustained surface winds (kt)
Valid for marine exposure over water, open terrain exposure over land

Integrated Kinetic Energy > TS, 21TJ > Hurricane: 0.0 TJ
Destructive Potential Rating: 0-6 Wind: 0.0 Surge/Waves: 2.6

Observed Max. Surface Wind: 47 kts, 82 nm SE of center based on 1040 z QSCAT_HIRES
Analyzed Max. Wind: 47 kts, 78 nm NE of center

Experimental research product of NOAA / AOML / Hurricane Research Division
Tropical Storm Barry

Tropical Storm Barry 1330 UTC 02 JUN 2007
Max 1-min sustained surface winds (kt)

Valid for marine exposure over water, open terrain exposure over land
Analysis based on GOES from 1302 - 1302 z; CMAN from 1039 - 1259 z; MOORED_BUY from 1039 - 1320 z;
AFRC from 1116 - 1336 z; SHIP from 1100 - 1300 z;
1330 z position interpolated from 1220 Vortex; mslp = 1002.0 mb

Integrated Kinetic Energy > TS: 3 TJ > Hurricane: 0 TJ
Destructive Potential Rating(0-6) Wind: 0 Surge/Waves: 1

Observed Max. Surface Wind: 48 kts, 11 nm SE of center based on 1217 z AFRC
Analyzed Max. Wind: 48 kts, 17 nm SE of center

Experimental research product of NOAA / ACML / Hurricane Research Division
• Hurricane Ernesto Example

Hurricane Ernesto 1330 UTC 27 AUG 2006
Max 1-min sustained surface winds (kt)
Valid for marine exposure over water, open terrain exposure over land
Analysis based on GIPSSonde_MBL from 0745 - 0800 z; METAR from 0745 - 1200 z; HOBOED_SODY from 0730 - 1245 z;
QECAT from 1045 - 1545 z; AFRC / SPHL-Matrix adjusted from 0445 - 1155 z;
1330 z Vortex fix; mslp = 995.0 mb

Observed Max. Surface Wind: 64 kts, 6 nm NW of center based on 0838 z GIPSSonde_MBL
Analyzed Max. Wind: 62 kts, 7 nm NE of center
Experimental research product of NOAA / AOML / Hurricane Research Division
ESTIMATED MINIMUM CENTRAL PRESSURE 997 MB
MAX SUSTAINED WINDS 65 KT WITH GUSTS TO 80 KT.
64 KT...... 15NE 15SE 0SW 15NW.
50 KT...... 25NE 25SE 10SW 25NW.
34 KT...... 80NE 80SE 20SW 50NW.
12 FT SEAS 100NE 225SE 50SW 80NW.
WINDS AND SEAS VARY GREATLY IN EACH QUADRANT.
RADII IN NAUTICAL MILES ARE THE LARGEST RADII EXPECTED ANYWHERE IN THAT QUADRANT.

REPEAT..CENTER LOCATED NEAR 17.6N 73.7W AT 27/1500Z
AT 27/1200Z CENTER WAS LOCATED NEAR 17.3N 73.4W

FORECAST VALID 28/0000Z 18.6N 74.9W
MAX WIND 75 KT..GUSTS 90 KT.
64 KT...... 15NE 15SE 0SW 15NW.
50 KT...... 40NE 30SE 15SW 30NW.
34 KT...... 100NE 80SE 30SW 60NW.

FORECAST VALID 28/1200Z 20.0N 76.5W...INLAND
MAX WIND 85 KT..GUSTS 105 KT.
64 KT...... 20NE 20SE 15SW 15NW.
50 KT...... 50NE 40SE 25SW 30NW.
34 KT...... 110NE 90SE 40SW 60NW.

FORECAST VALID 29/0000Z 21.5N 78.3W...INLAND
MAX WIND 75 KT..GUSTS 90 KT.
64 KT...... 20NE 20SE 15SW 15NW.
50 KT...... 50NE 40SE 25SW 30NW.
34 KT...... 120NE 100SE 60SW 90NW.
• **Next Steps**

• **Tropical Cyclone Destructive Potential by Integrated Kinetic Energy, April issue of BAMS**

• IKE, WDP, SDP calculations will be added to the AOML H*Wind Experimental wind analysis products during 2007

• **Experiment with computing WDP and SDP from operational products**

• **Experiment with evaluating model forecasts in collaboration with forecast centers**