A New Metric for Hurricane Destructive Potential

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Photo: Brad Smull

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Atlantic Oceanographic and Meteorological Laboratories
Virginia Key, Miami FL (about 20 miles east of the Tropical Prediction Center)

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

Camille vs Katrina accounts:

- *"It looks like Hurricane Camille killed more people yesterday than it did in 1969." Mr. Jim Holt of Biloxi on 30 August 2006* *Anita Lee, Biloxi Sun Herald*
- *“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

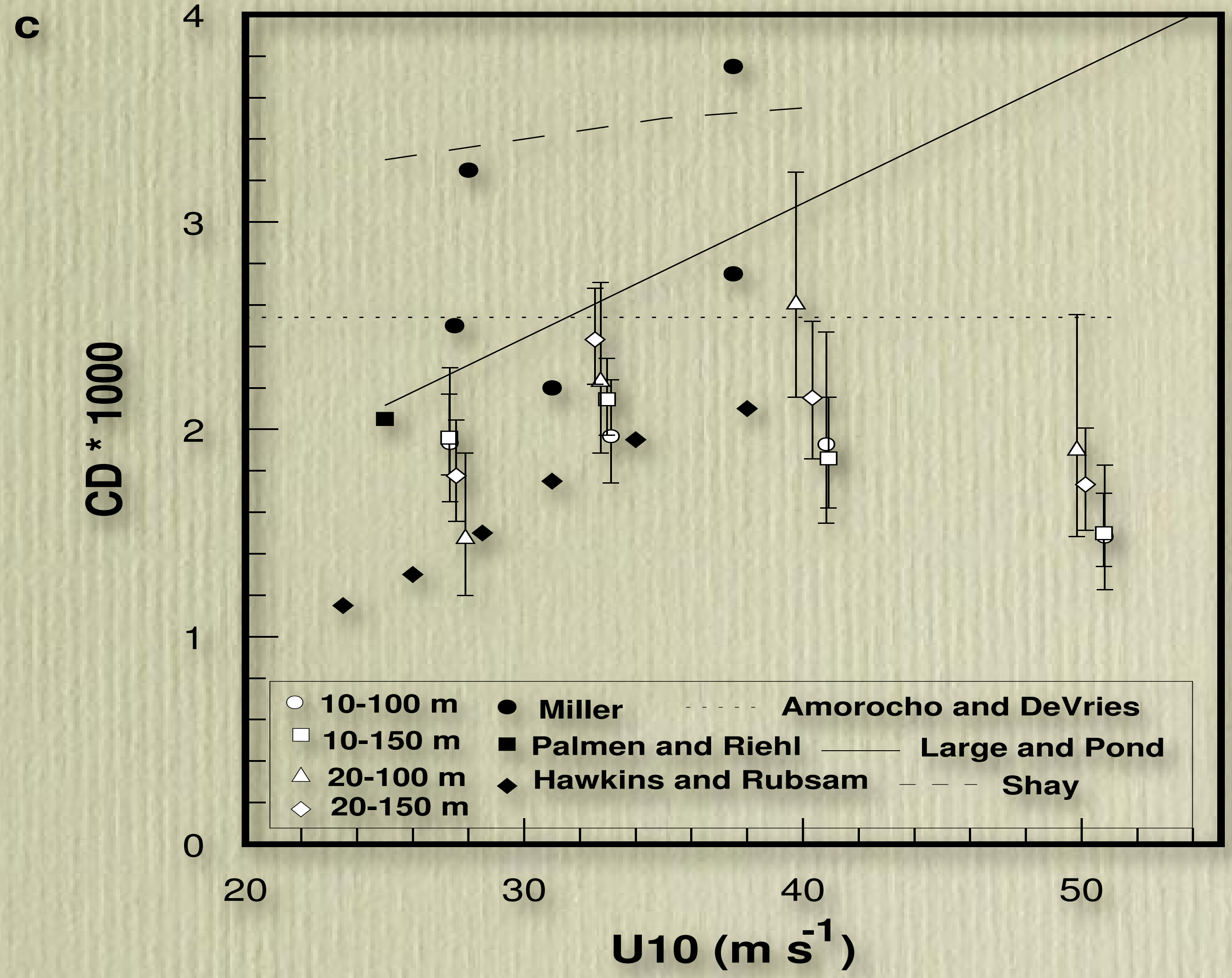
- **Integrated Kinetic Energy**
  - **Destructive Forcing:**
    - *Wind Stress*
      - Wave damage
      - Storm Surge
    - *Wind Loads*

- ***Wind stress on the ocean surface (force per unit area)***

  - **scales with the square of the wind speed**

  - **Cd levels, then decreases as winds increase above hurricane force**

$$\tau = \rho C_d U_{10}^2$$



- ***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 -> 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***

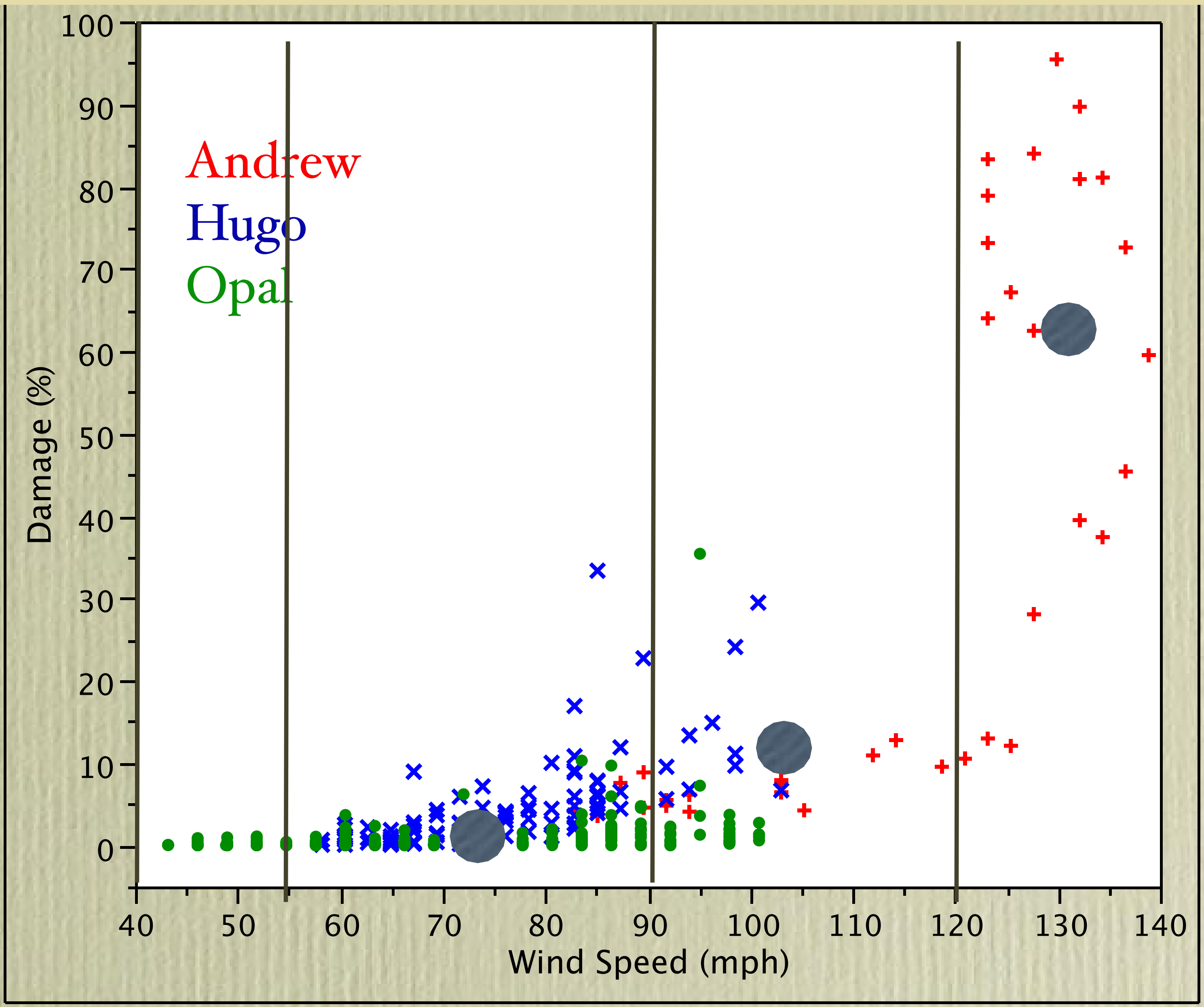
- Wind loading acts as a force that goes as the square of the wind speed (ASCE-7)
- Damage to homes depends on building design, workmanship, local building codes, code enforcement, and preparedness
- Roof suction pressures, buffeting, and debris load depend on structure of turbulence
- At ~110 kts the 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%



Wind Speed

- # Integrated Kinetic Energy (IKE)

  - Kinetic energy/ volume

$$IKE = \int \frac{1}{2}\rho w s^2 dV$$

  - 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

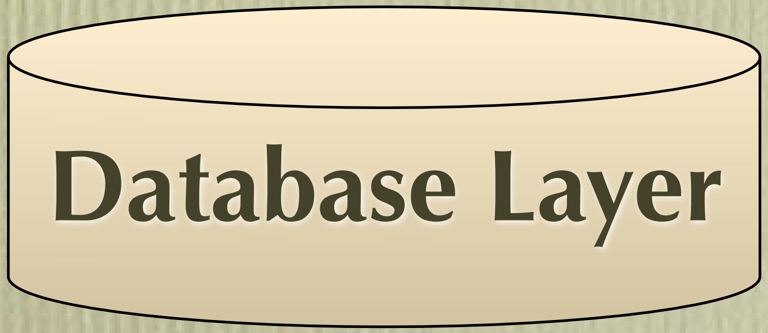
Database Layer ⟷

Presentation Layer

Quality Control →

Analysis →

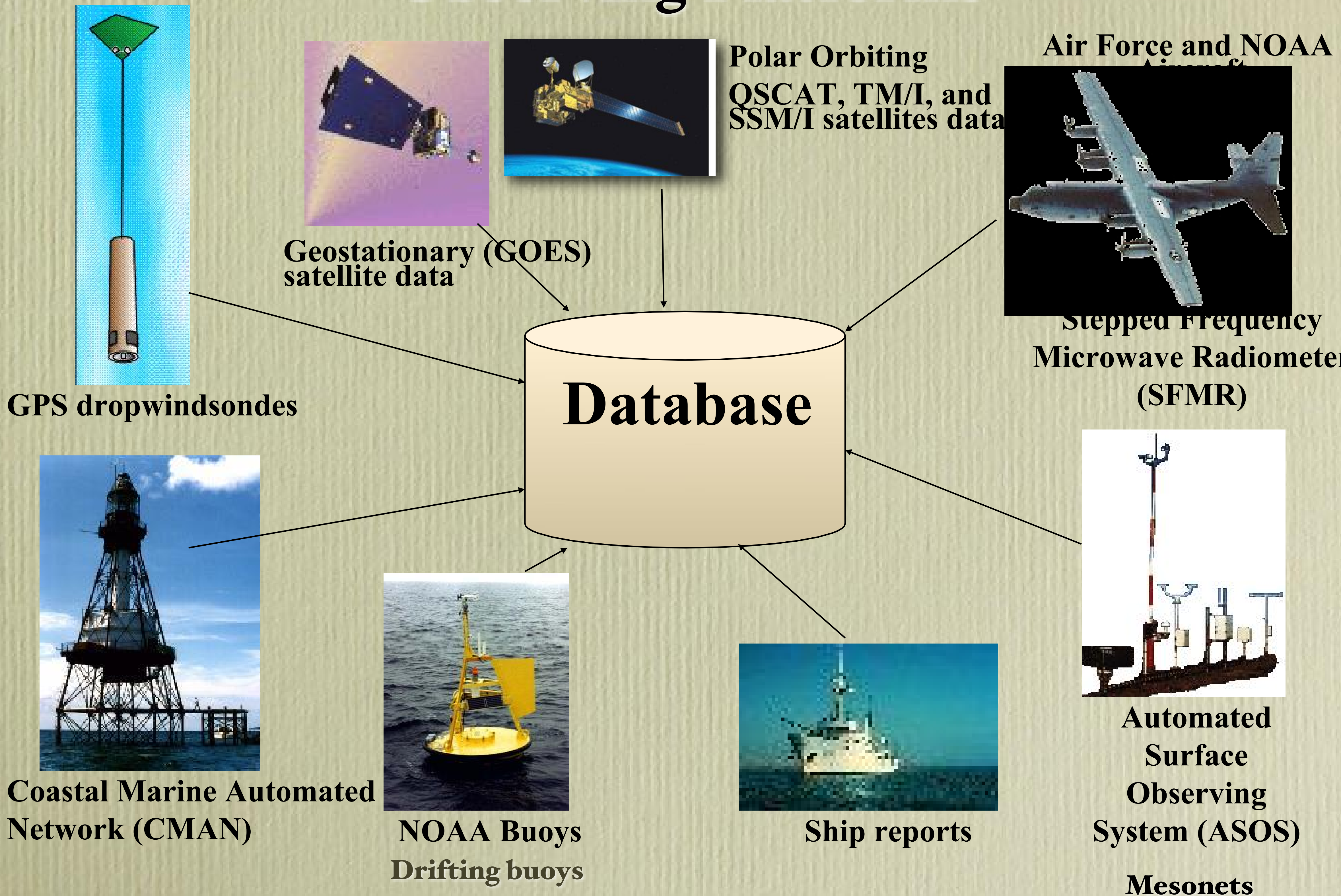
Products



Winner of NOAATech 2000 and 2002 awards

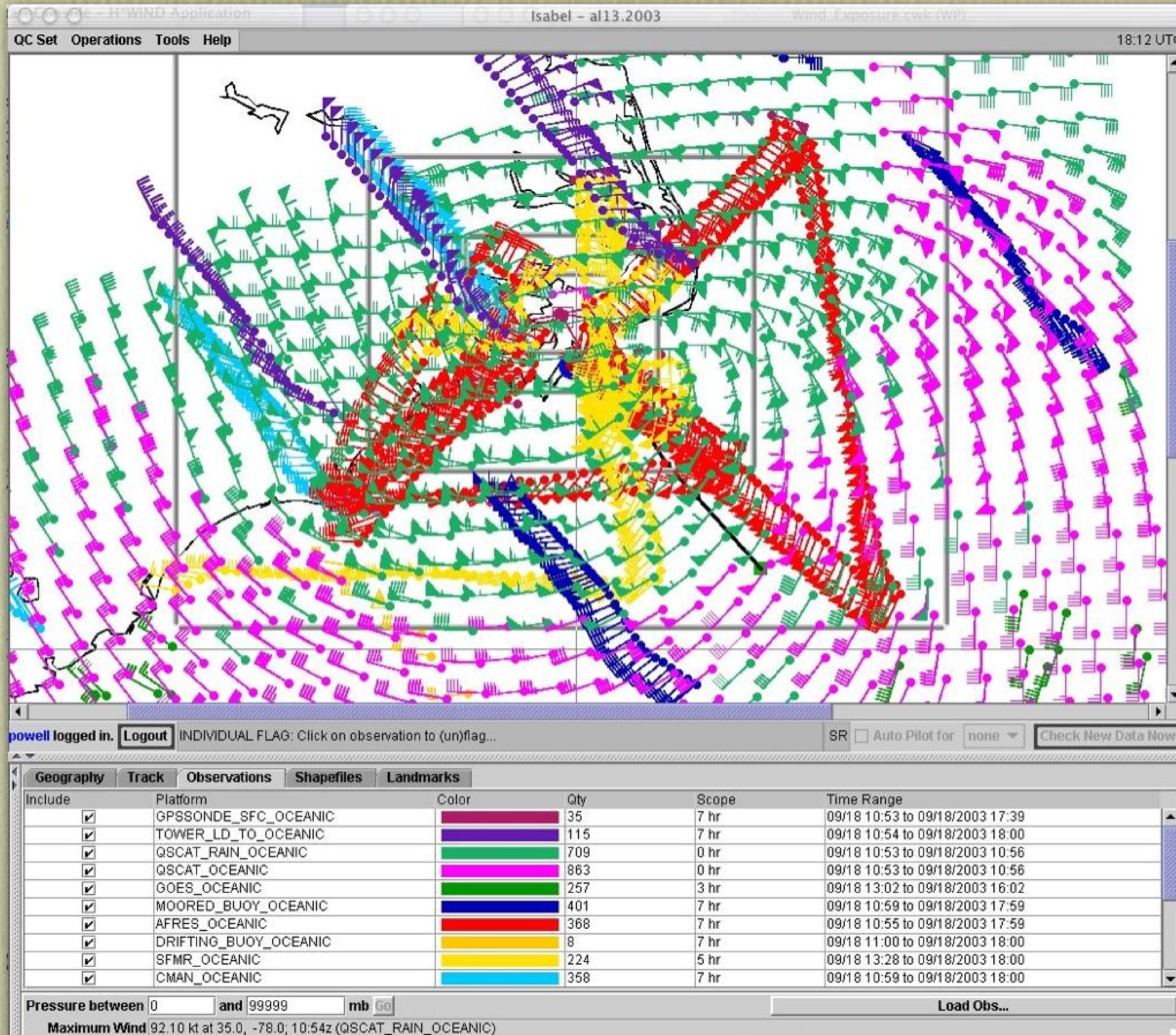
H*Wind: Hurricane Wind Field Analysis

Observing Platforms

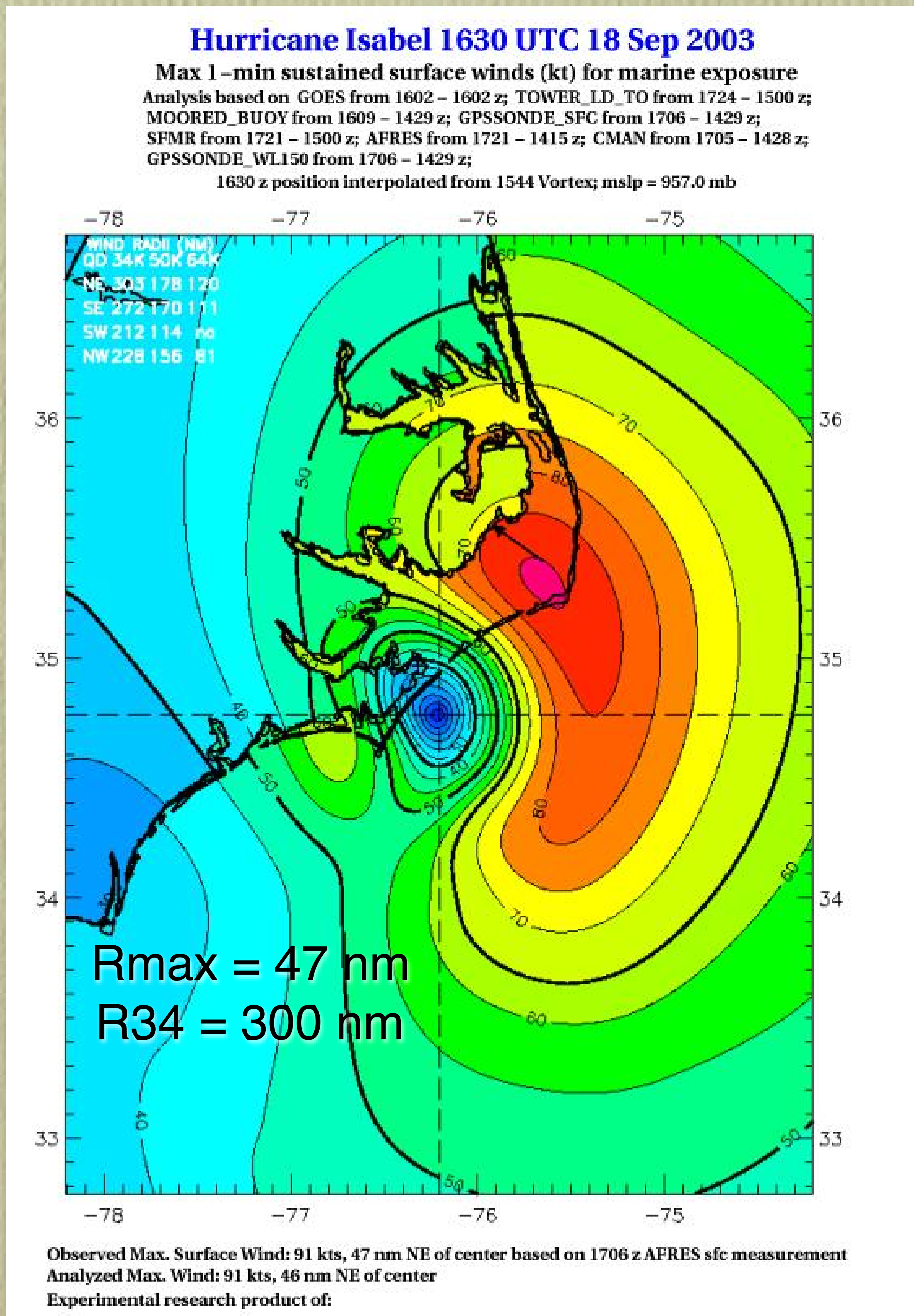


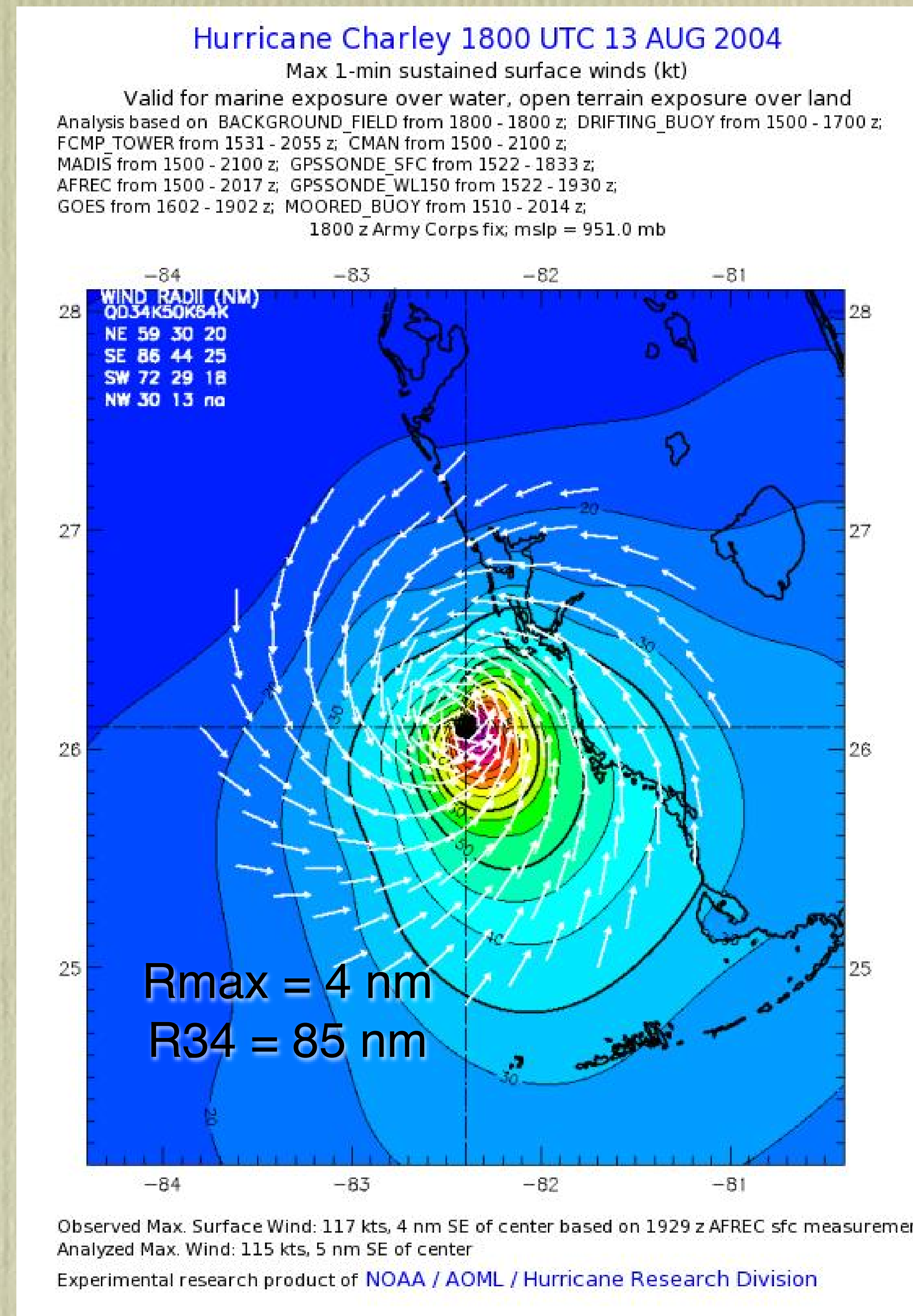
Sample Data coverage

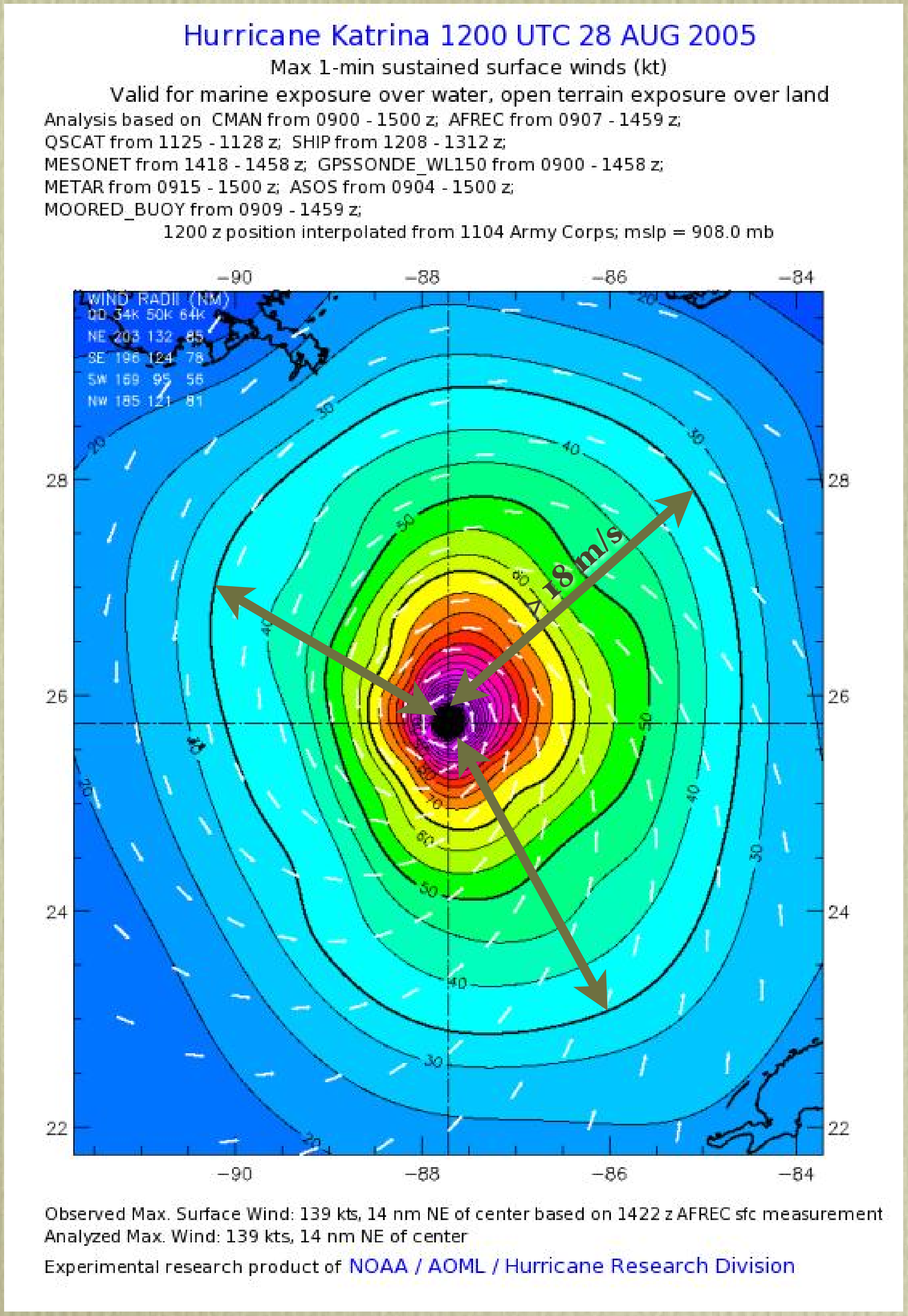
Hurricane Isabel 2003 at landfall



The H*Wind Archive: http://www.aoml.noaa.gov/hrd/data_sub/wind.html



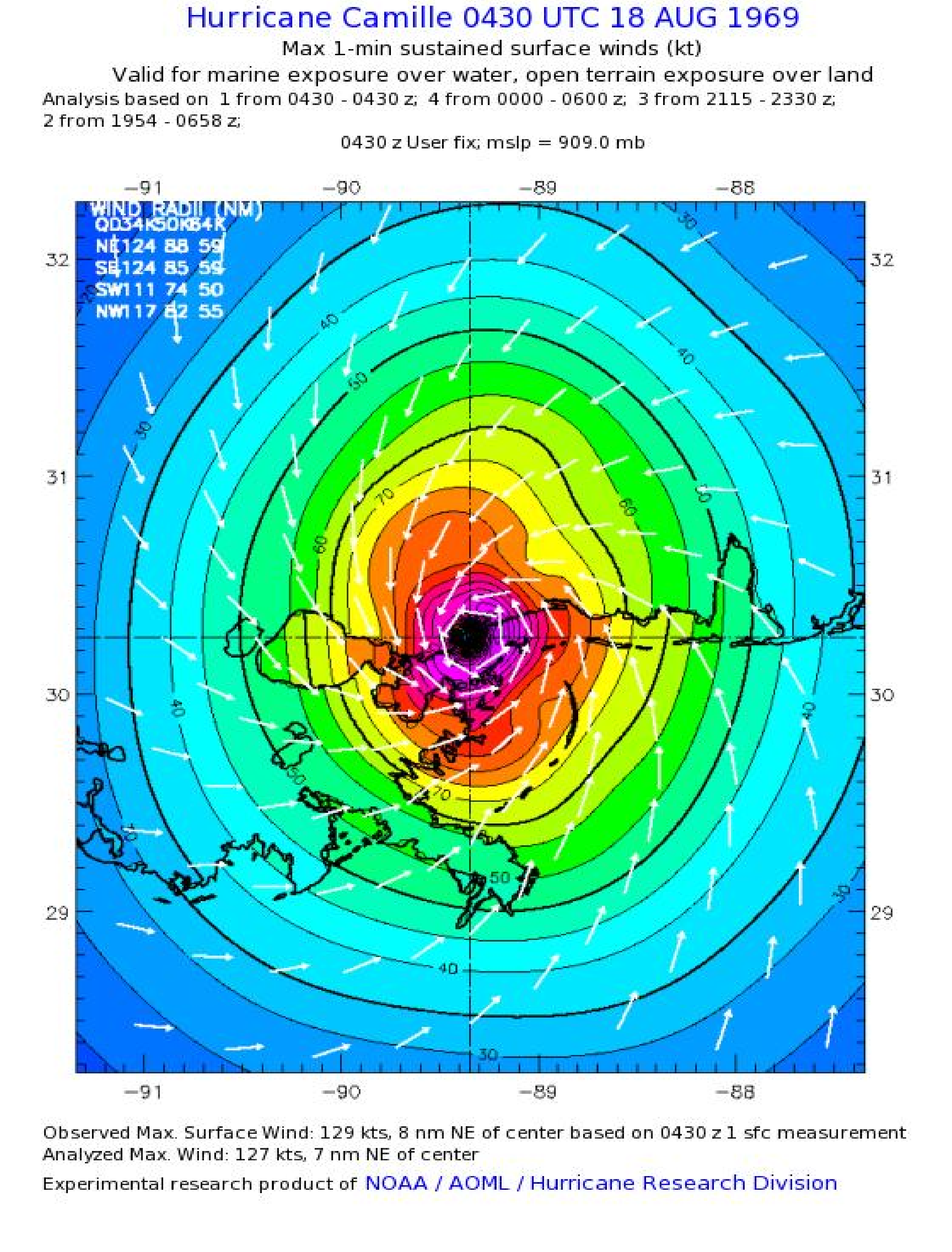




IKE_{TS} Calculation:

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

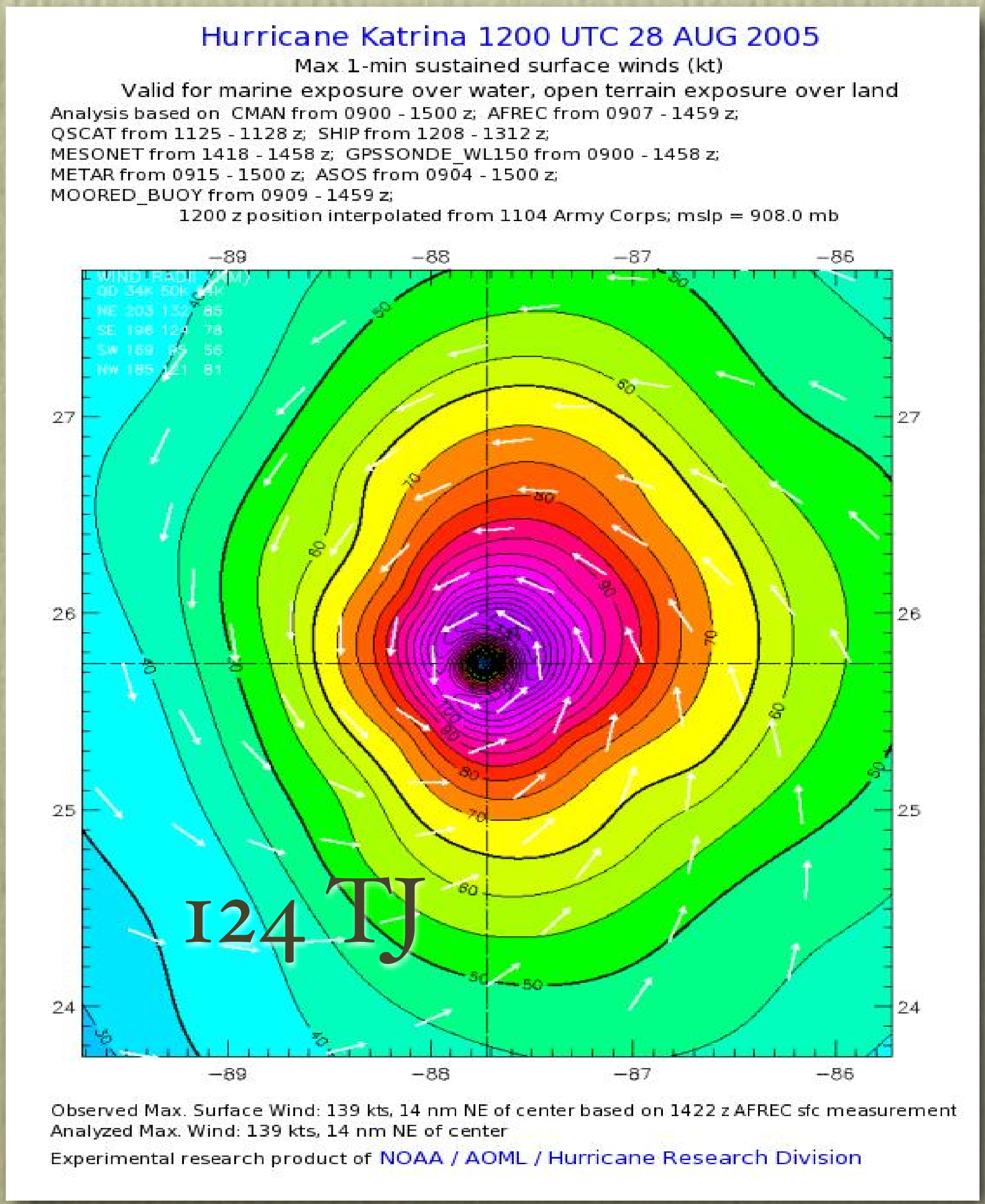
IKE_{TS} = 63 TJ

Special Thanks to
David Levinson of NCDC

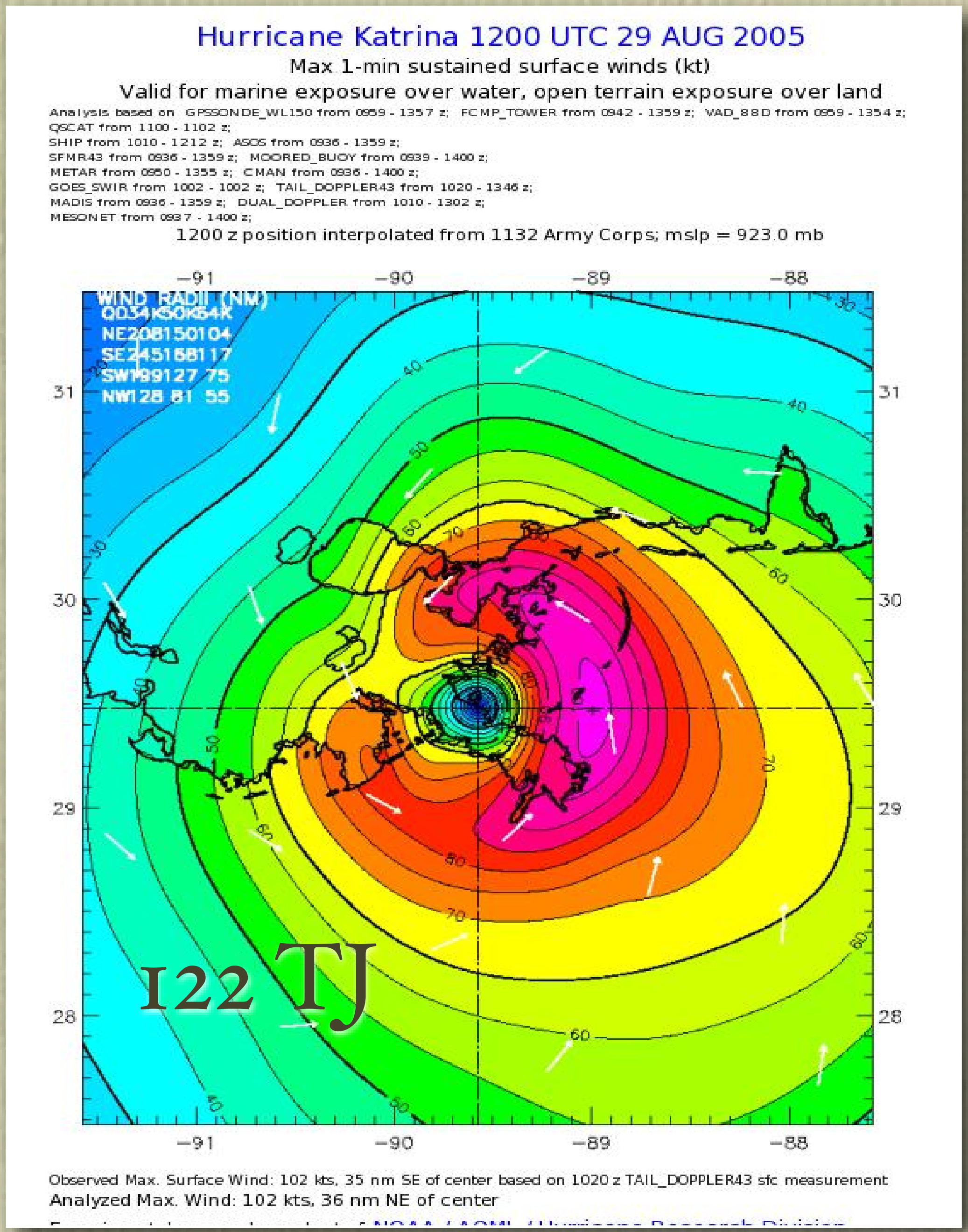
Kinetic energy from the wind field takes into account storm size

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

*Marine Exp



Cat 5 KE for winds > 34 kt = 124 TJ

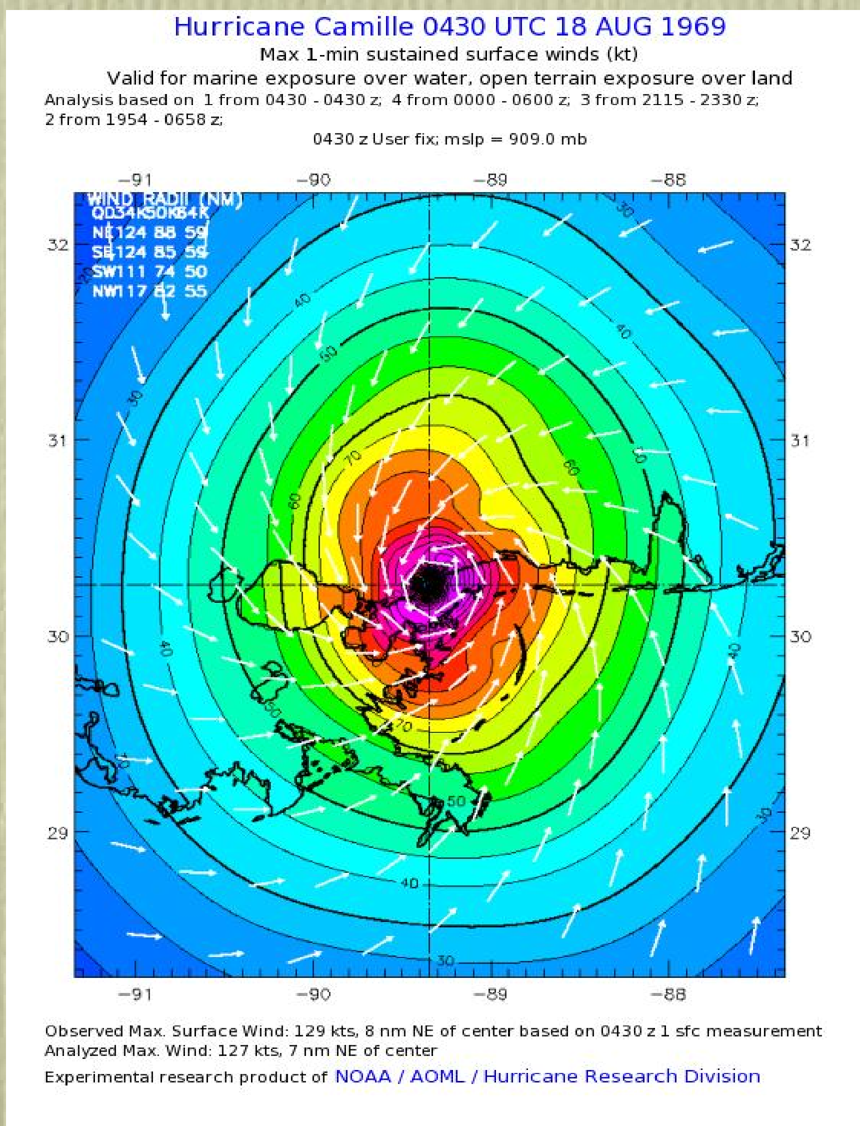


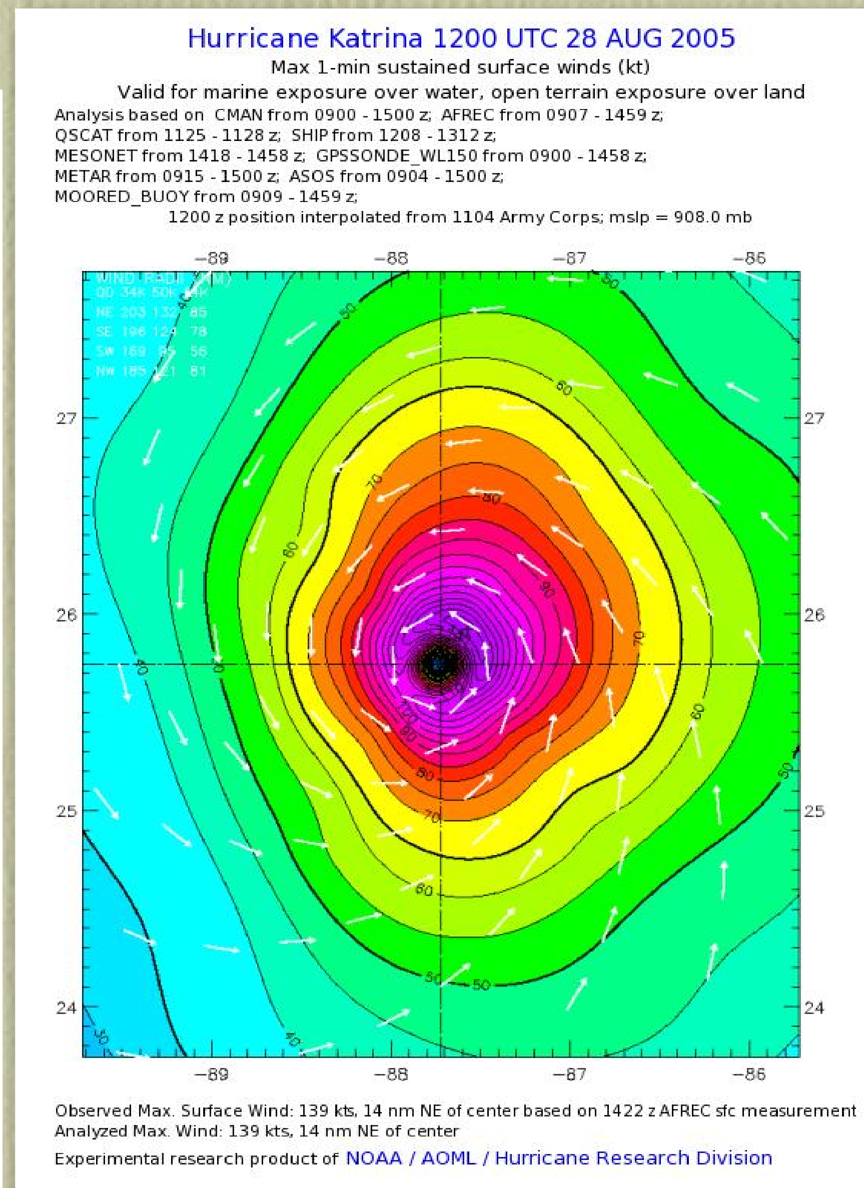
Cat 3: KE for winds > 34 kt = 122 TJ

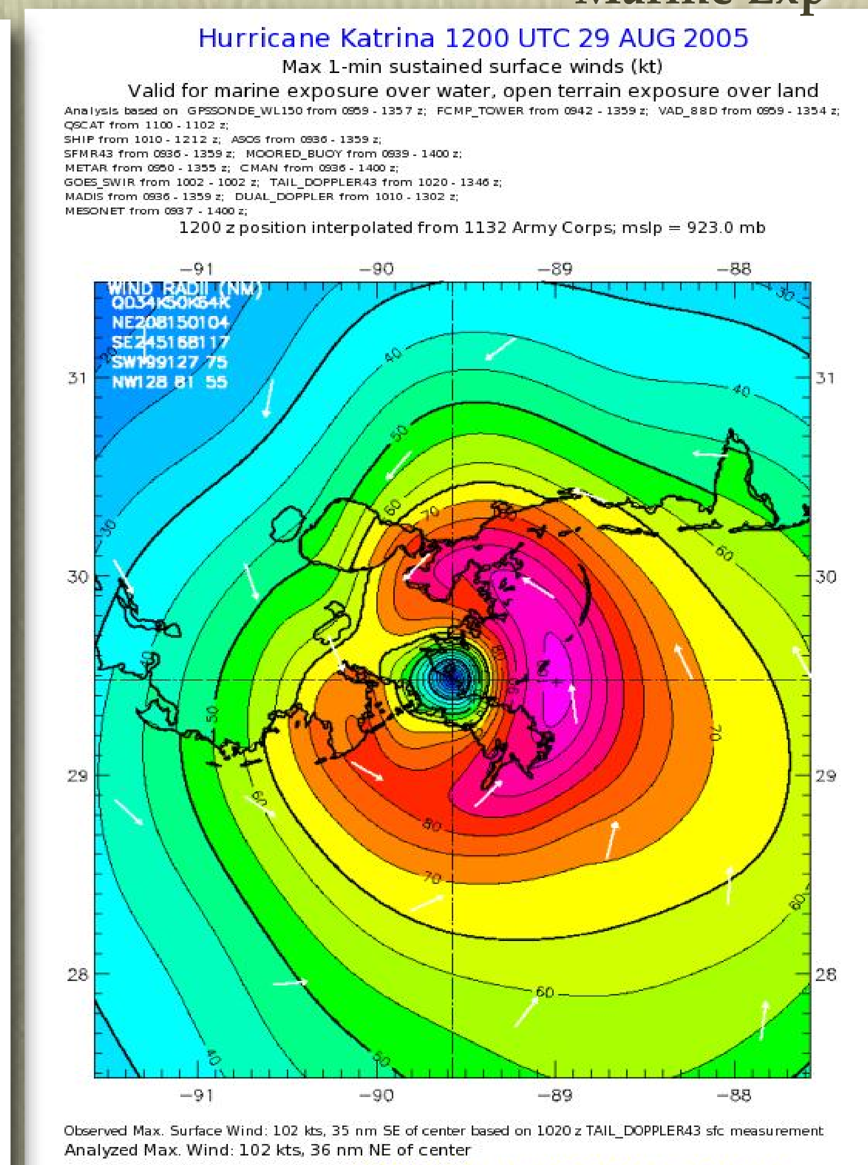
Camille

Katrina

*Marine Exp







63 TJ

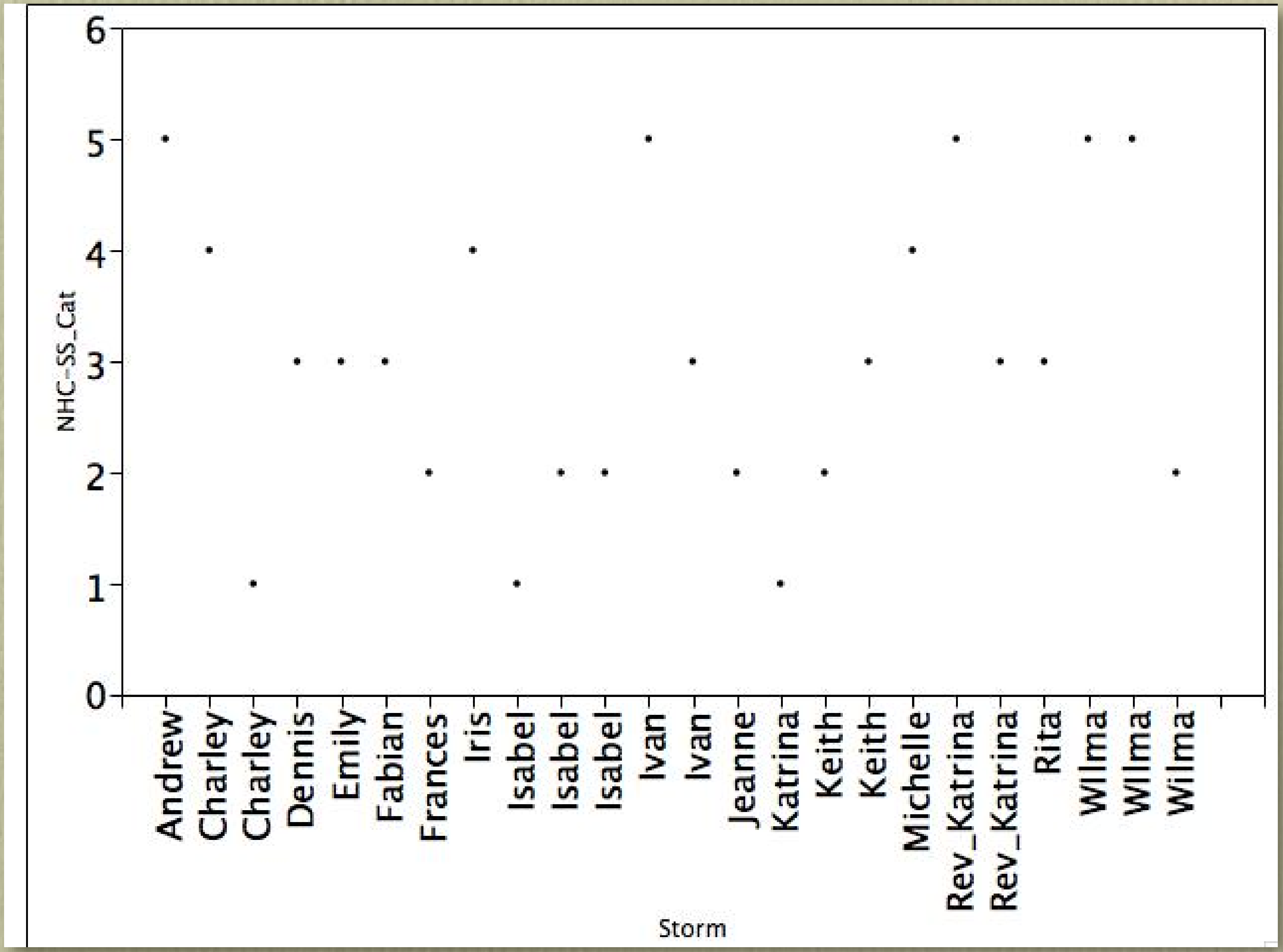
124 TJ

122 TJ

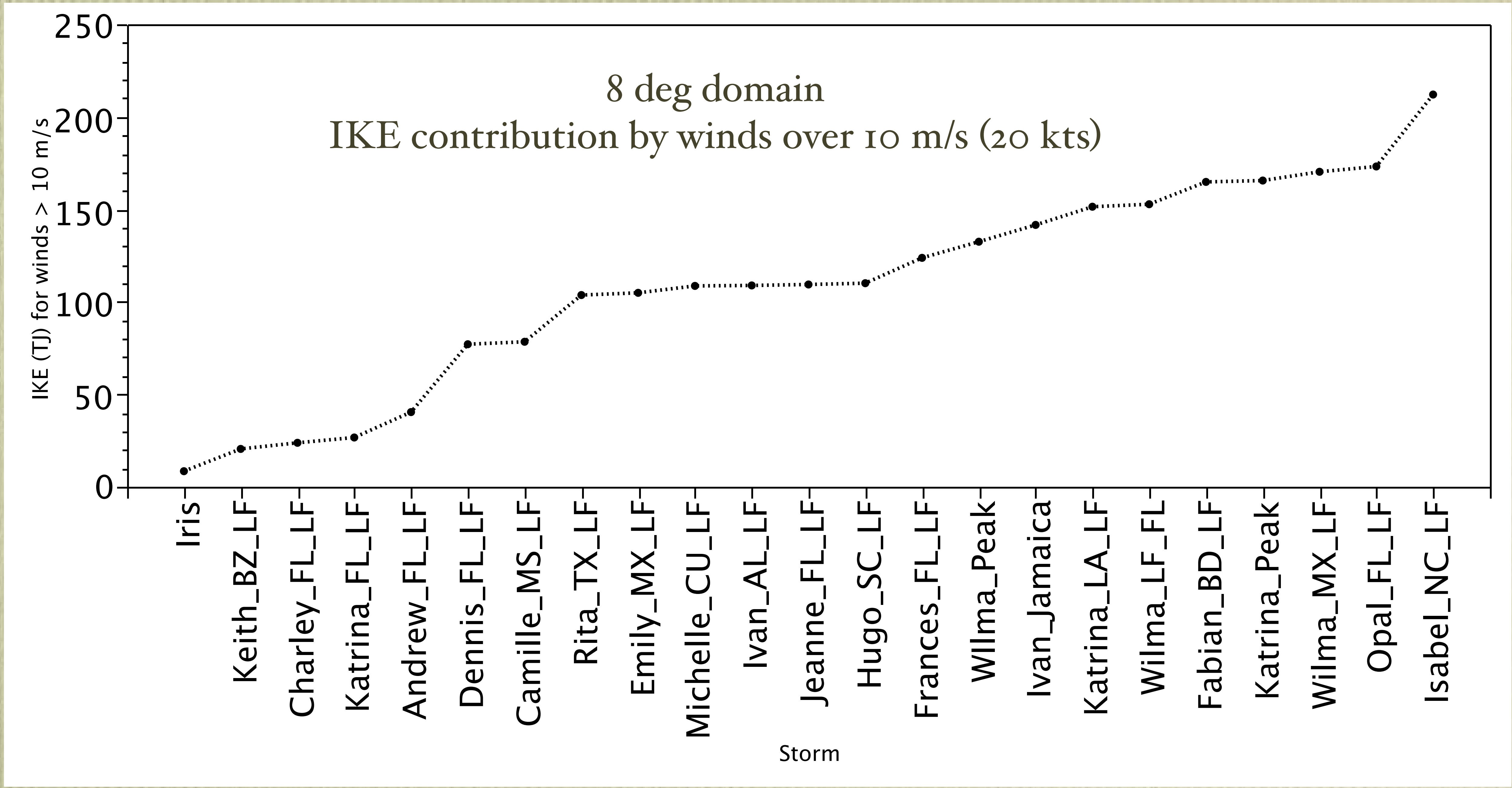
- **IKE -> Hurricane Destructive Potential**
  - Objective scale to allow comparison of different sized storms, independent of local susceptibility (coastline shape, bathymetry, building codes)
  - Dependent on IKE computed from damaging portion of analyzed or modeled wind field or wind radii
  - Similar numerical range to familiar Saffir-Simpson Scale, but continuous

Range of storms selected from the H*Wind Archive

SS Cat



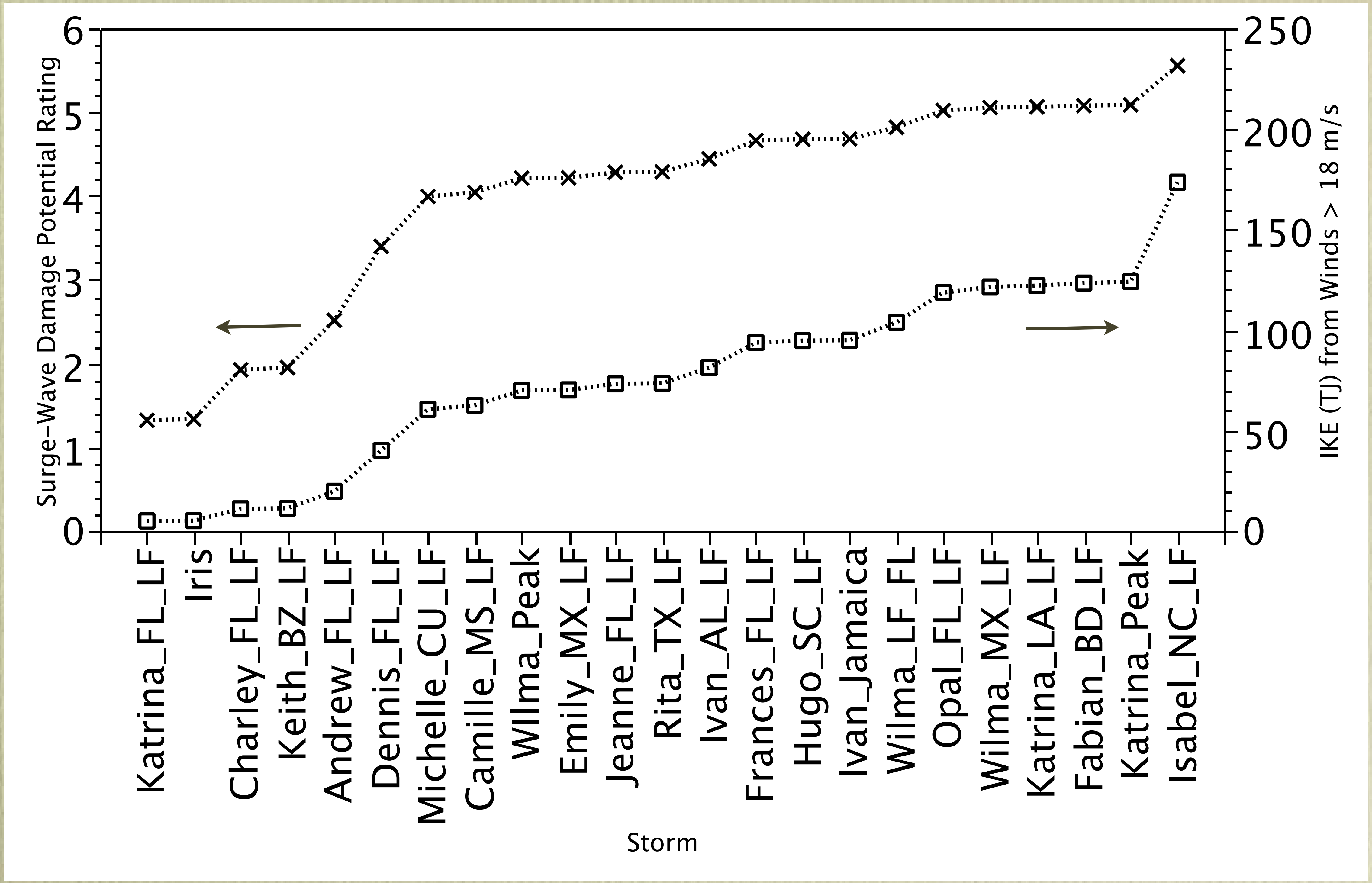
IKE based on a 10 m/s threshold ignores compact but intense storms

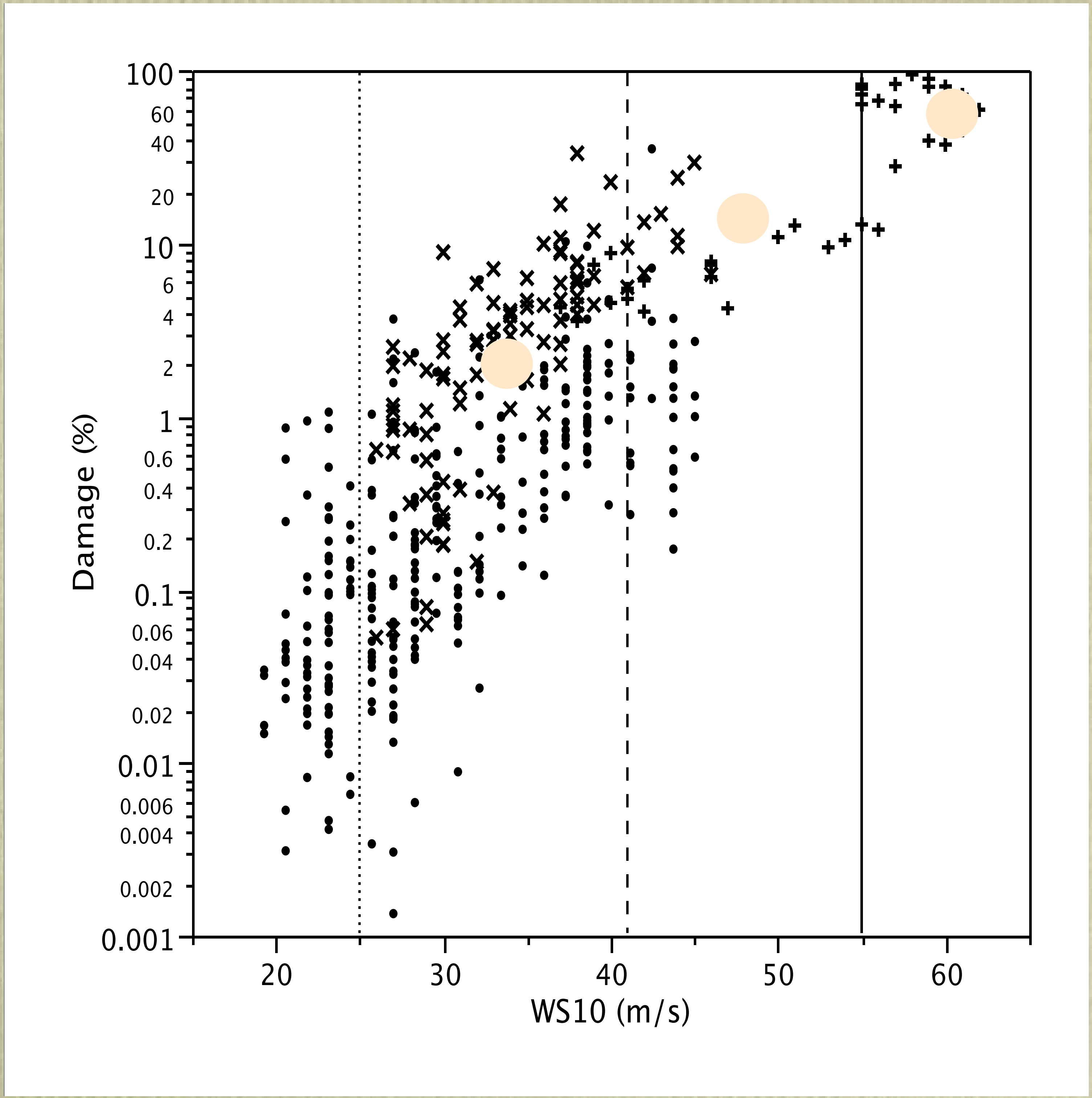


Need separate scales for wind and surge/waves

- **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 IKE TS



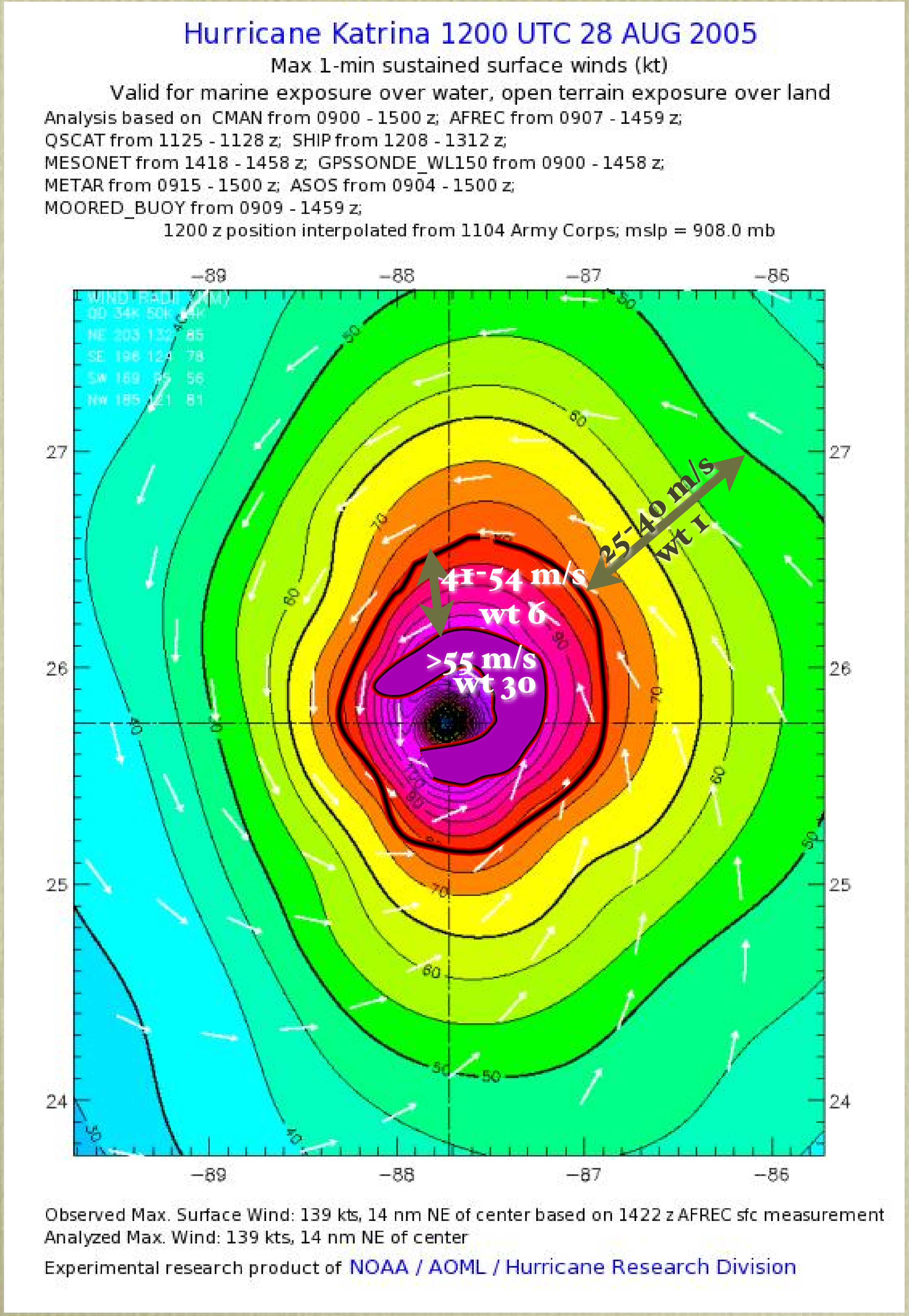


Wind Damage

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

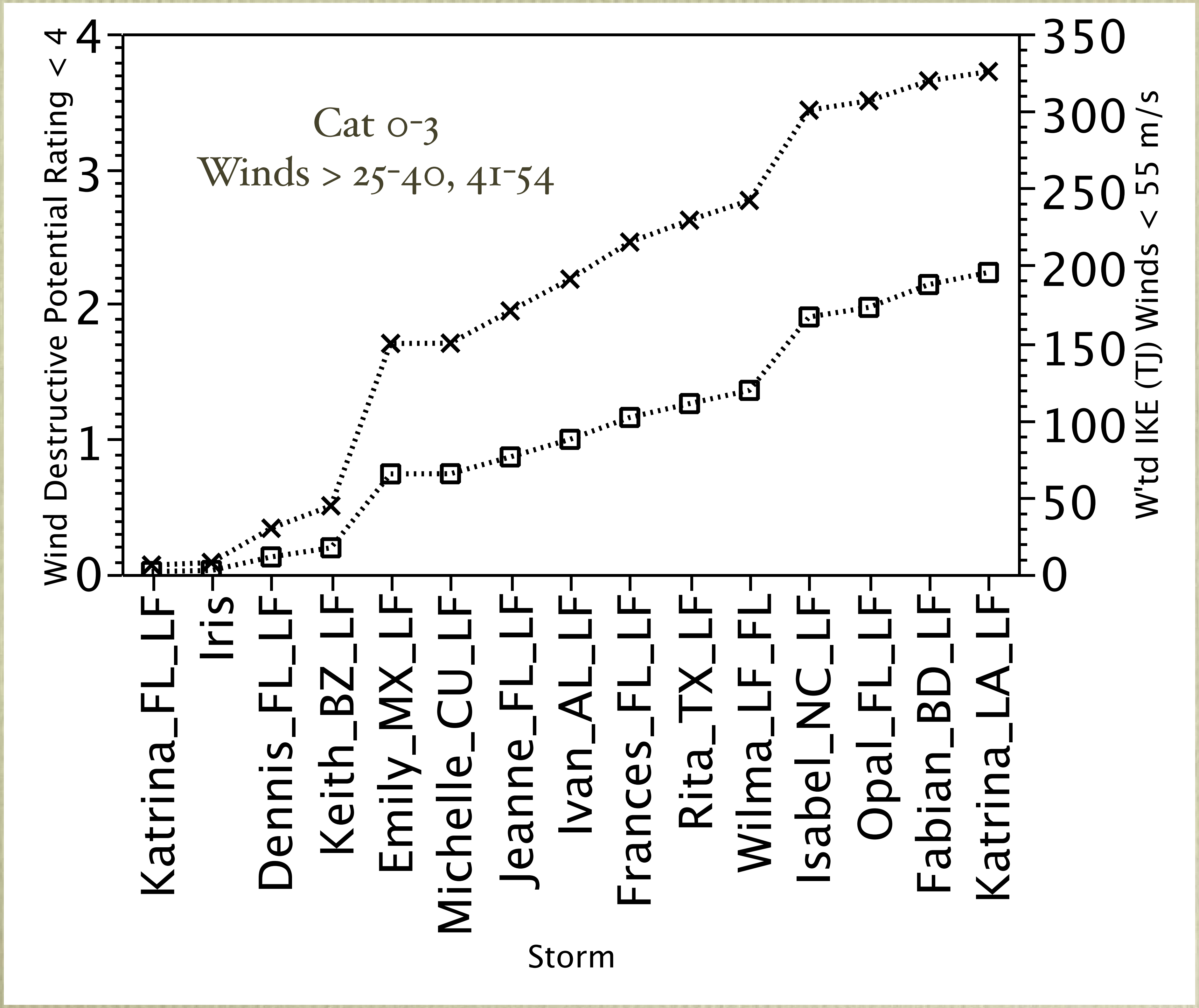
- **Wind Destructive Potential (WDP):**
  - Depends on damage-weighted IKE contributed by three wind speed ranges: 25-40 m/s, 41-54 m/s, > 55 m/s
  - Cat 4 and 5 storms have > 55 m/s winds covering areas > 25 km^2 capable of compromising the building envelope
  - A large tropical storm can be more destructive than a small hurricane
  - Actual destruction depends on local effects like building design, codes, code enforcement, workmanship



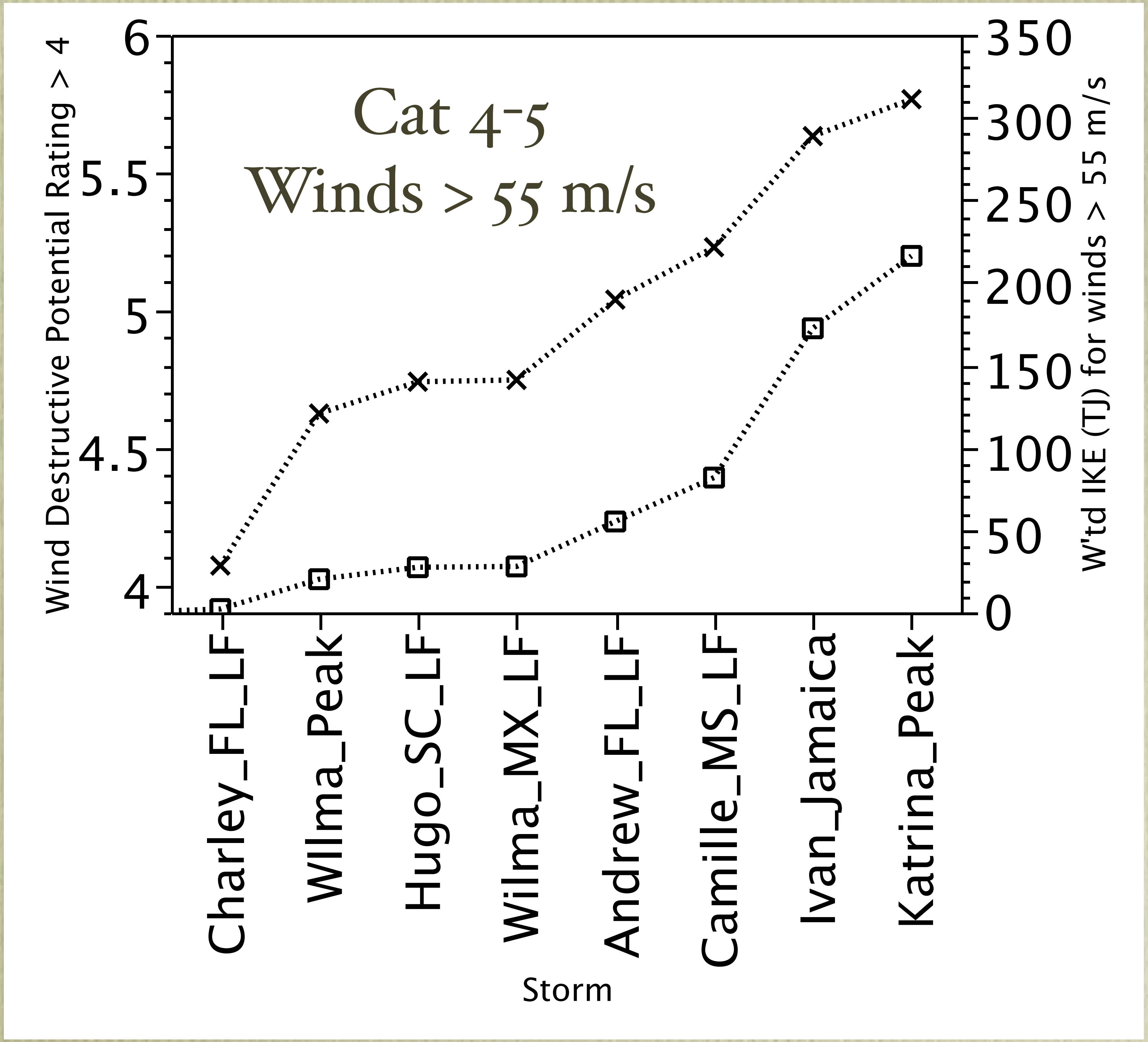
Wind Destructive Potential IKE Calculation:

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

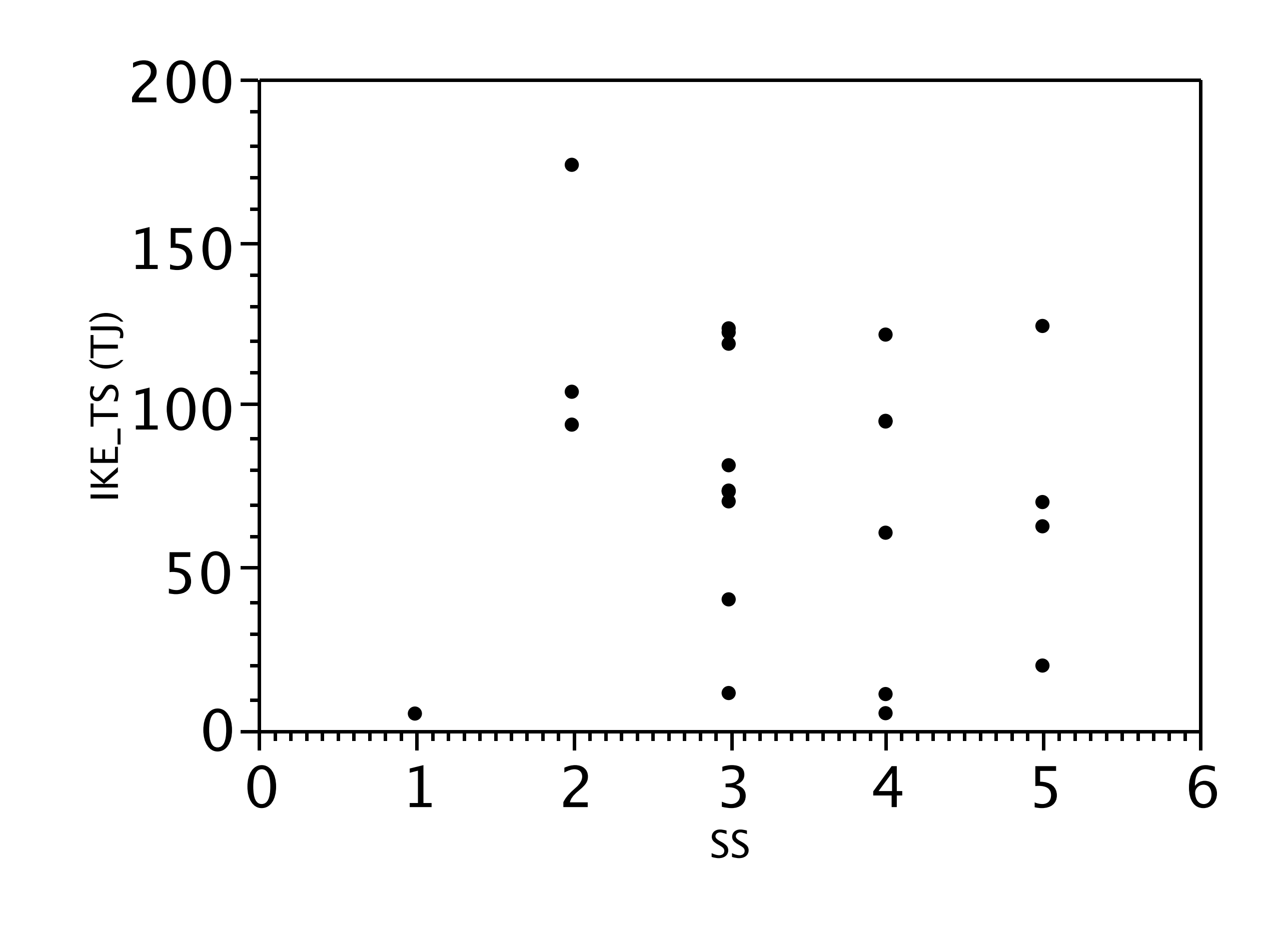
Wind destructive potential < Cat 4

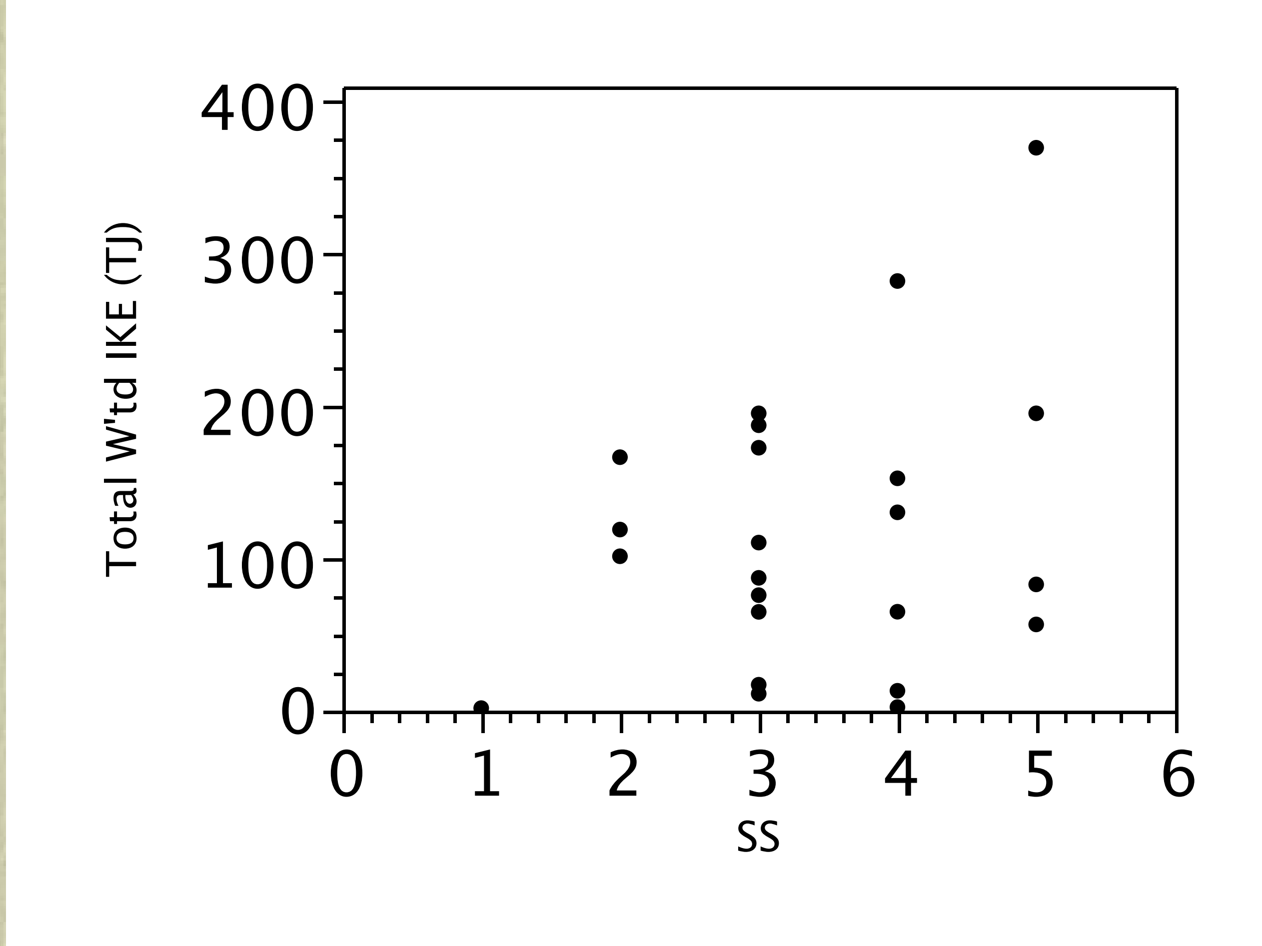


Wind destructive potential > Cat 4

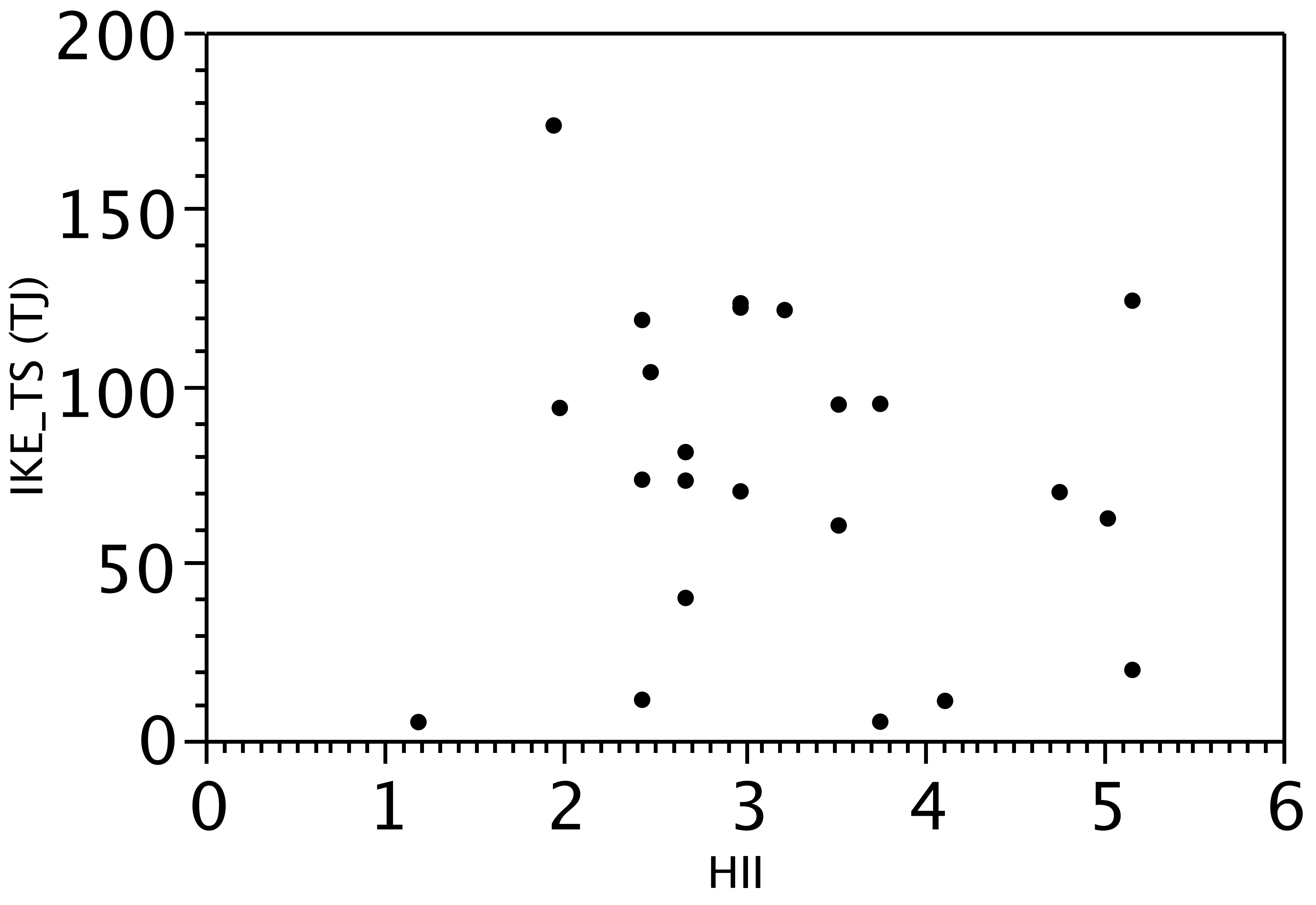


Saffir-Simpson scale relationship to IKE from winds over tropical storm force (left) and damage-weighted IKE (right)

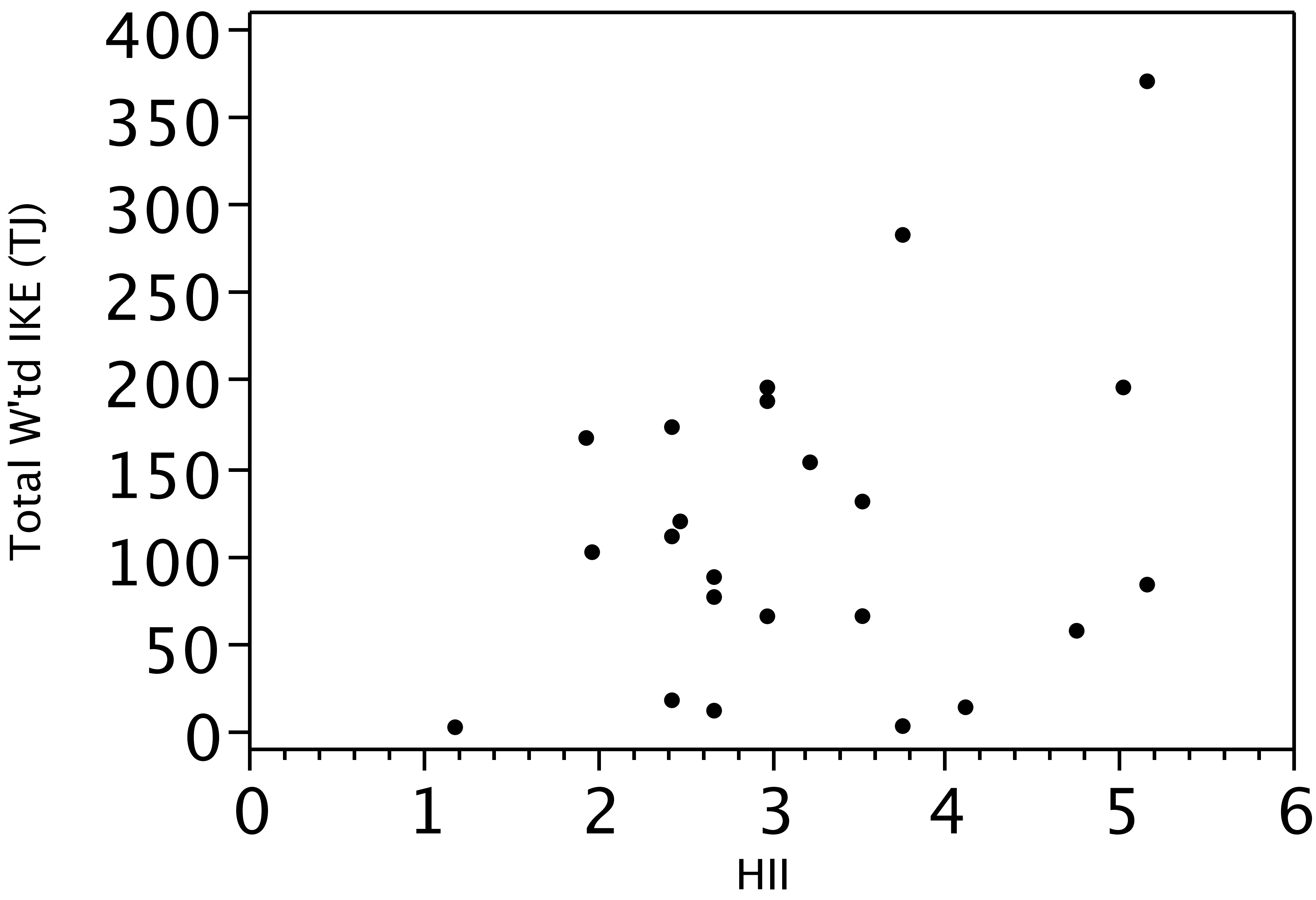




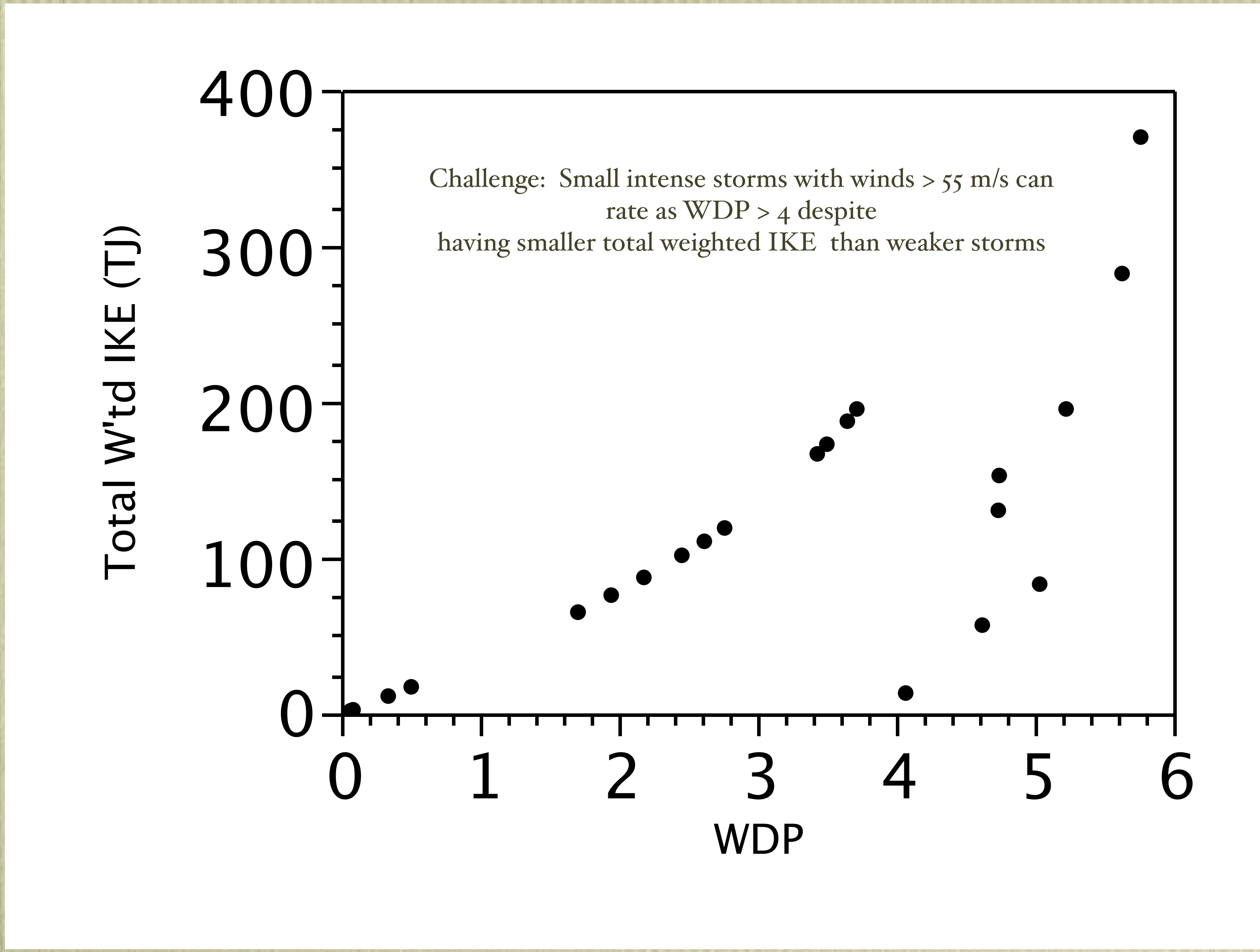
Hurricane Intensity Index (HII) relationship to IKE from winds over tropical storm force



Hurricane Intensity Index (HII) relationship to damage-weighted IKE



Damage-weighted IKE vs Wind Destructive Potential Scale



- **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}.

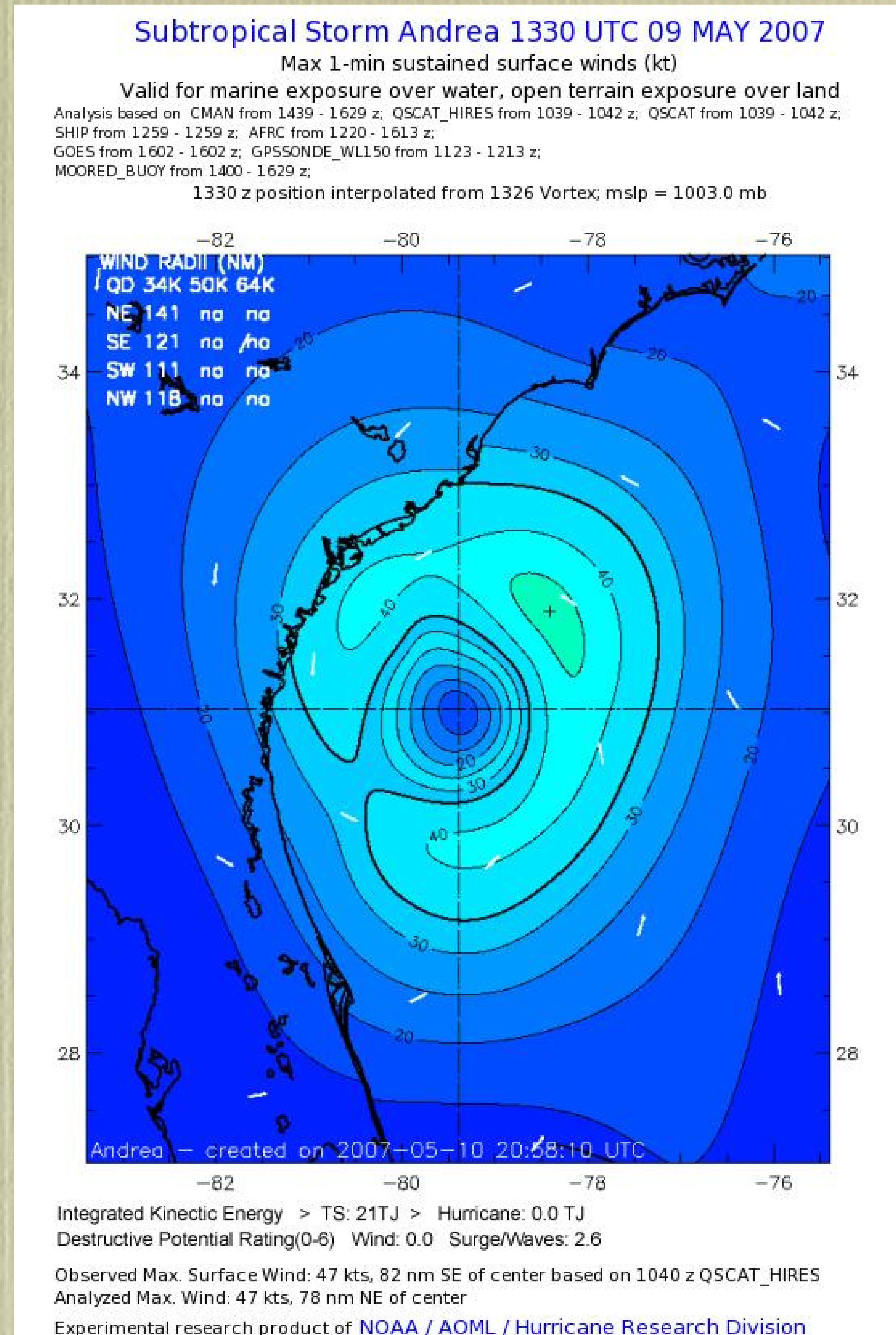
  - A set of equations have been developed to compute IKE based on operational Rmax, Vmax, R_{33}, R_{26}, and R_{18}

- **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

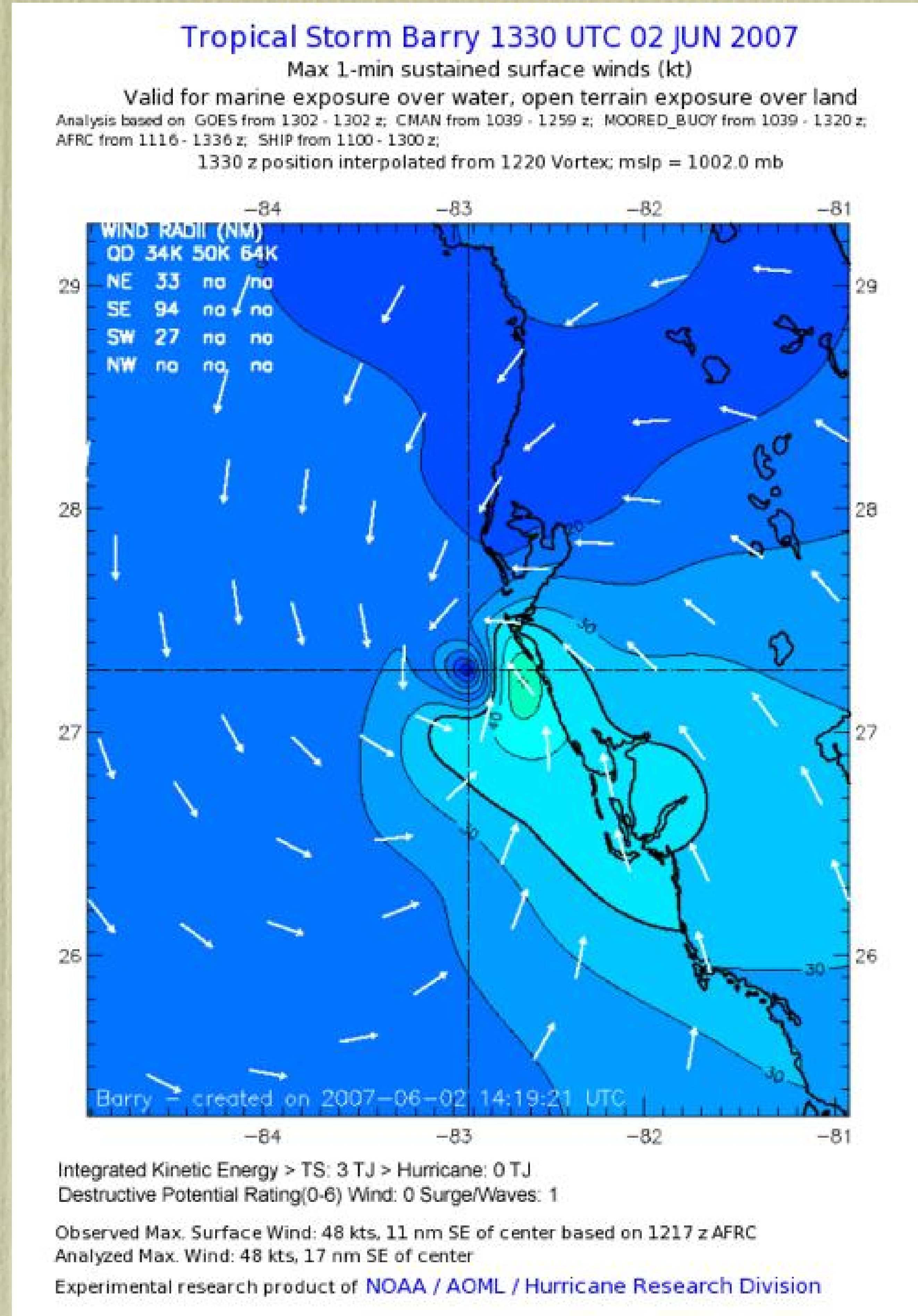
- **Wind and Surge Destructive Potential Rating**
  - Physically based on wind stress and wind loading
  - Continuous, 0-5 range is familiar
  - Apportions threat into surge and wind (Weather Channel)
  - Comparing historical storms may help improve risk perception among public

- **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

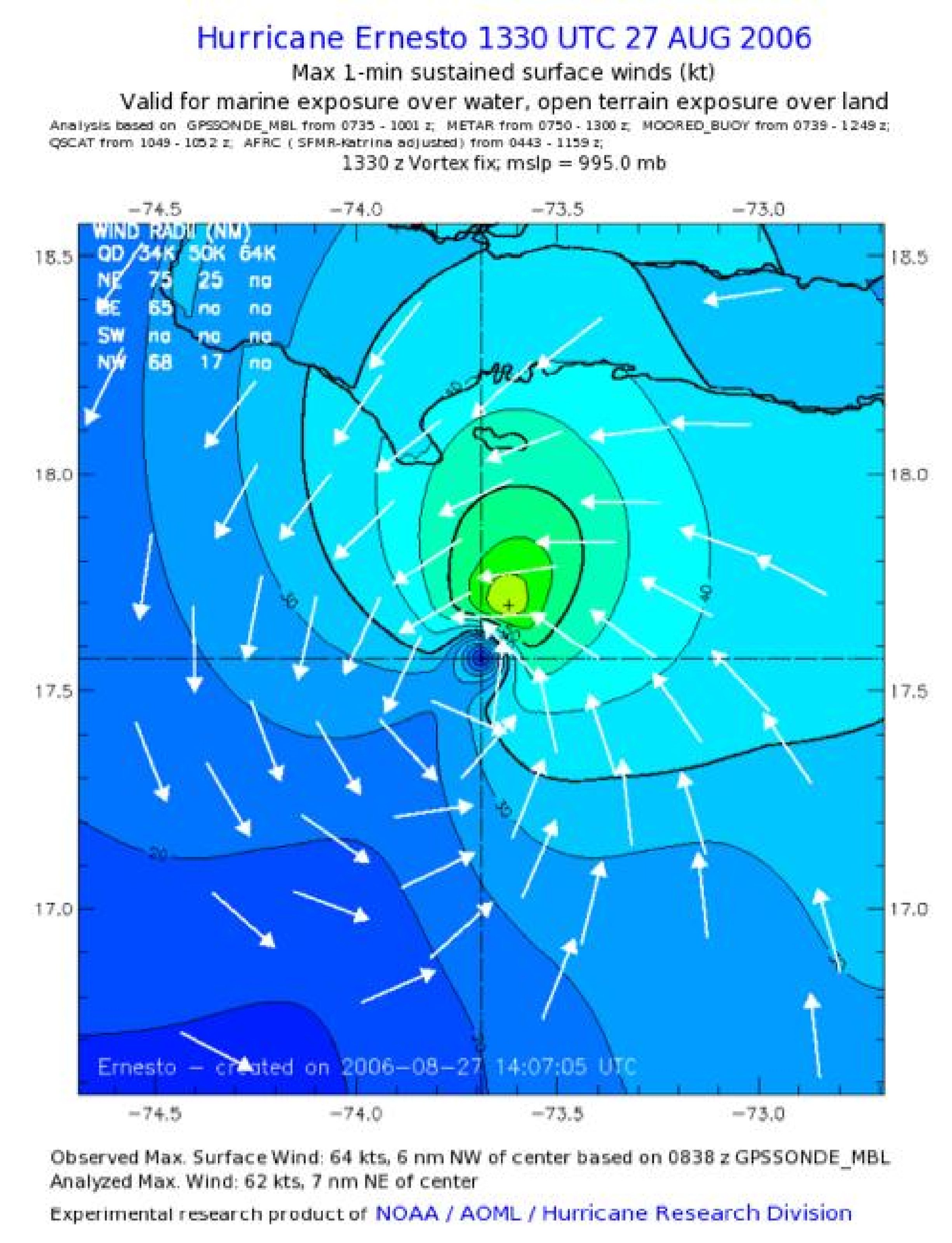
Subtropical Storm Andrea



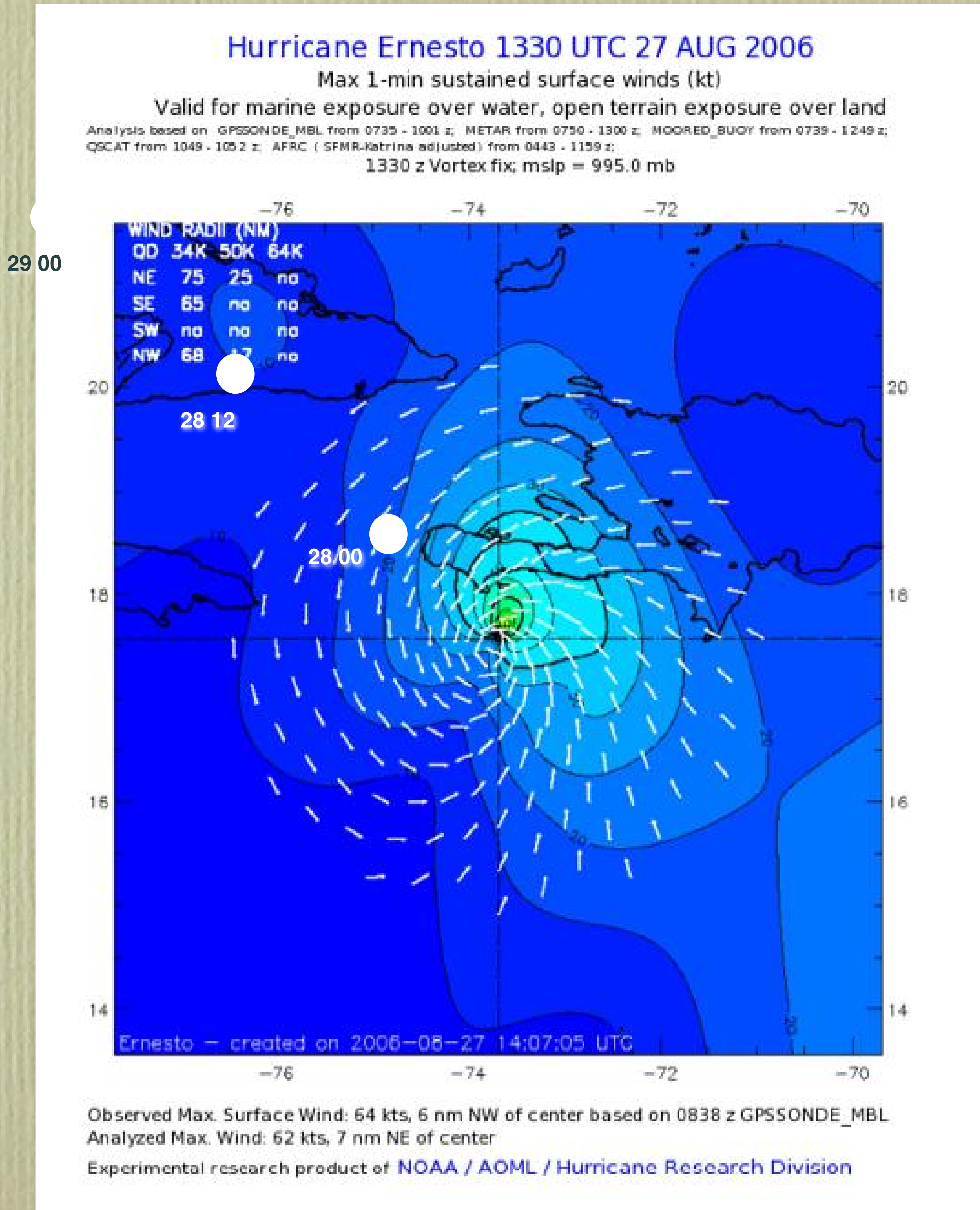
Tropical Storm Barry



- Hurricane Ernesto Example



SS 1
WDP 0
SDP 1.3



DDhhoo	WDP	SDP
27-1500	0.2	1.3
28-0000	0.1	1.2
28-1200	0.2	1.5
29-0000	0.2	1.9

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