# Tropical Cyclone Surface Wind Structure and Wind-Pressure Relationships


| | |
|---|---|
| **John A. Knaff**<br>**NOAA/NESDIS,RAMM Branch**<br>**CIRA/ Colorado State University**<br>**Campus Delivery 1375**<br>**Fort Collins, CO 80523-1375**<br>**USA** | **Bruce A. Harper**<br>**Systems Engineering Australia Pty Ltd.**<br>**U106 71 Beeston St**<br>**Brisbane 4006**<br>**Australia** |

# Acknowledgements

- Dan Brown (NOAA/NHC, Miami),
- Joe Courtney (BoM, Perth)
- Derrick Herndon (CIMSS, U. Wisc)
- Masashi Kunitsugu (JMA)
- Sébastien Langlade (Météo-France, La Reunion)
- Eric Uhlhorn (NOAA/HRD, Miami)

# Outline

- Review previous IWTC recommendations
- Justification/Importance of this topic
- Current practices at TC warning centers
- Estimation of surface winds and TC wind structure
  - Standardization of wind speed estimates
  - Improved measurements and their representativeness
  - New satellite methods
- Pressure-Wind Relationships (WPRs)
  - Select Research
  - Evaluation of new methods
  - Operational transition/changes in last four years
- Planned operational changes and observational capabilities
- Recommendations

# Previous IWTC Recommendations

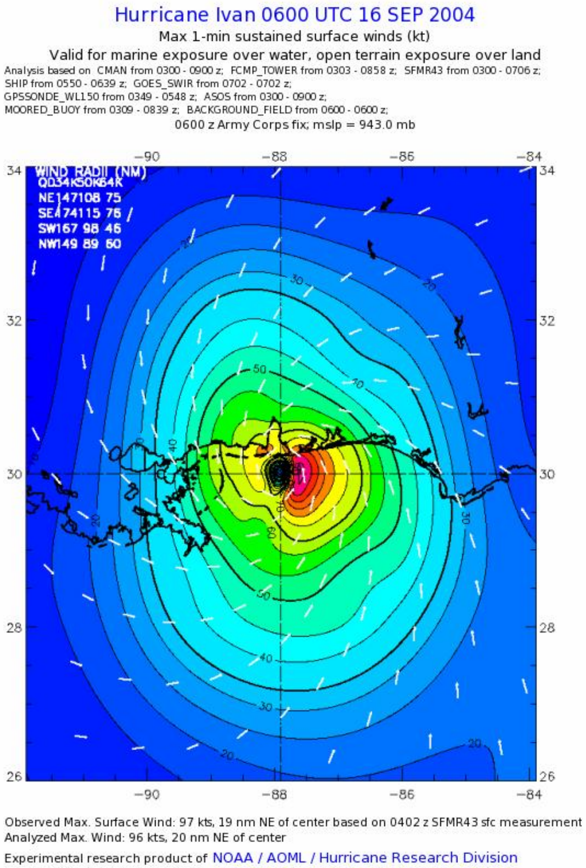
- The need to develop a unified enhanced Dvorak-like technique that will incorporate storm structure changes (including wind-pressure profile variations) and which also makes use of multiple satellite data sources.
- Development, testing and documentation of a public domain parametric wind field model that includes asymmetries to aid in the diagnosis of TC wind structure
- Improved understanding of the effects of variability of surface land roughness and topography on forecast wind speed.
- The need for a standard chart that enables users to convert between different wind-averaging periods and gust factors; facilitating the standardization of the wind reference amongst global TC warning centers.

# Importance/Justification

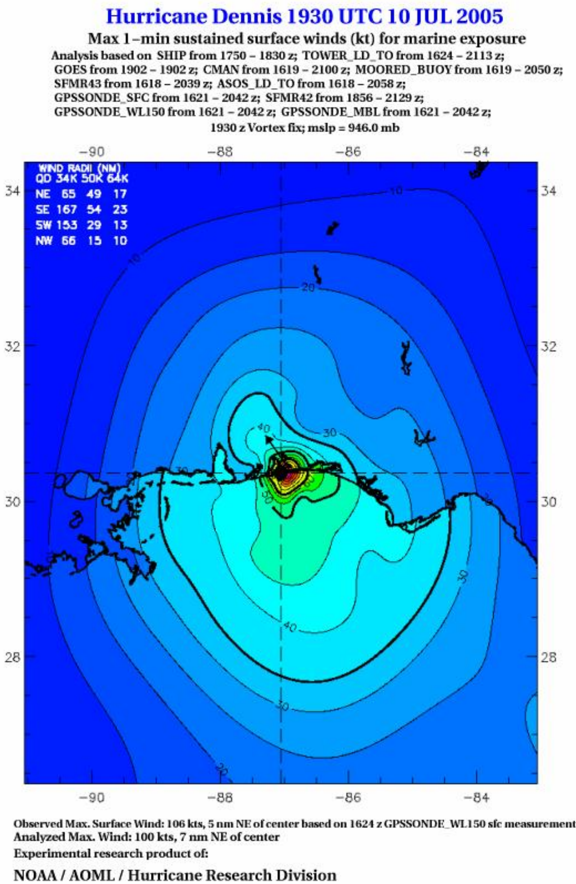
- The wind and pressure fields in tropical cyclones (TCs) are generally well approximated using gradient wind balance.
- As the government, industry and private sectors information needs become more sophisticated and the observational data improve, there is an increasing need for reliable TC surface wind and MSLP analyses.
- The traditional single-valued metric of TC intensity, the maximum surface wind (MSW), is increasingly insufficient to convey the information necessary for decision makers.
- There is also now clear evidence that TC impacts (wind and storm surge damage) are related to measures of the kinetic energy derived from the surface wind structures.
- TC central pressure, when assimilated into NWP models, has been shown to improve track forecasts.

# A Visual Example

**Ivan (2004) - 18 billion (2004 USD, $20.7 billion 2010 USD)**




**Dennis (2005) - $2.23 billion (2005 US dollars)**



# Agency Differences: Maximum Winds

Table 1 Defined surface wind averaging period in current WMO operational plans (from Harper et al. 2010).

| Association | Region | Average Wind Speed | Gust Wind Speed | Maximum Sustained wind speed |
|---|---|---|---|---|
| **RA I** | SW Indian Ocean | 10-min | Not defined | 1-min |
| **ESCAP Tropical Cyclone Panel** | North Indian Ocean | 10-min (recording) 3-min (non-recording) | Not defined | Maximum value of the average; either 10-min, 3-min, or 1-min at the surface |
| **RA IV** | Americas and the Caribbean | 1-min (recording and non-recording) | Not defined | Not defined but average is implied |
| **RA V** | S. Pacific Ocean and SE Indian Ocean | 10-min (1-min for USA Territories) | Not defined | Maximum value of the average |
| **ESCAP Typhoon Committee** | NW Pacific, South China Sea | 10-min (recording) 3-min (non-recording | Not defined | Maximum value of the average; 10-min, 3-min or 1min. |

Issue:

These are all different

# Agency Differences: Wind Field

Table 2 Wind field analysis and forecast practices.

| Association | Region | Wind radii | Forecasts | Observations used |
|---|---|---|---|---|
| **RA I** | SW Indian Ocean | 30-, 50-kt, 10-min, quadrants | No | Scatterometry, obs. of opportunity extent of clouds |
| **ESCAP Tropical Cyclone Panel** | North Indian Ocean | Not known | Yes | No Known |
| **RA IV** | Americas and the Caribbean | 34-, 50-, 64-kt, 1-minute max in quadrants | Yes, 34-kt through 72h , 64-kt through 36h | Scatterometry, obs. of opportunity, aircraft, climatology |
| **RA V** | S. Pacific Ocean and SE Indian Ocean | 34-, 50-, 64-kt, 10-min, quadrants | Yes through 48h | Scatterometry, obs. of opportunity |
| **ESCAP Typhoon Committee** | NW Pacific, South China Sea | 30-kt, 50-kt, 10-min circles/semicircle s | No | Scatterometry, obs. of opportunity |

Issue:

These are all different

# Agency Differences: Central Pressure

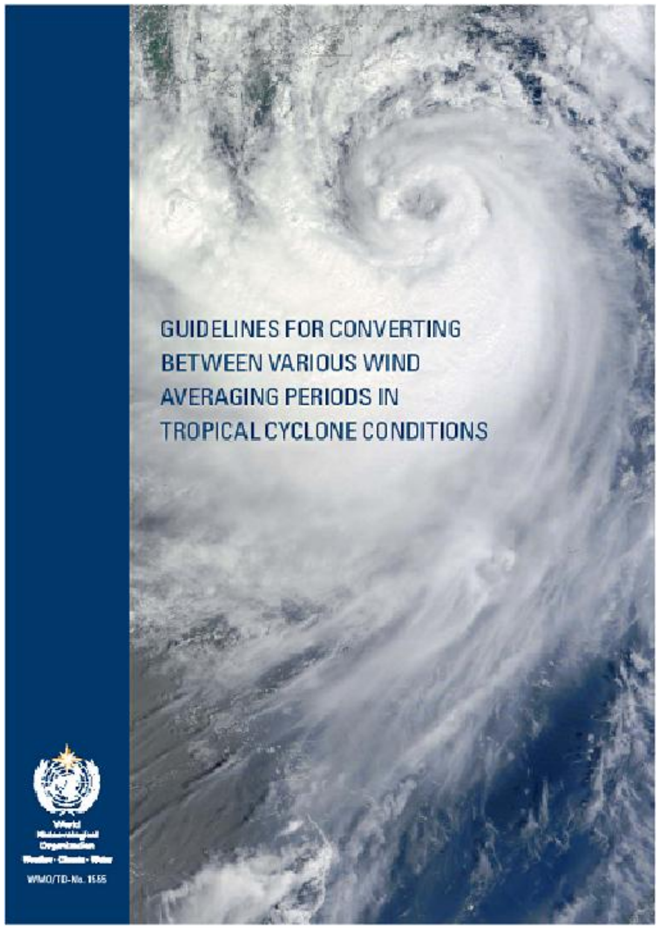
Table 2 Central Pressure (CP) analysis and forecast practices.

| Association | Region | Method | Forecasts | MSW estimate |
|---|---|---|---|---|
| **RA I** | SW Indian Ocean | Atkinson and Holliday (1979) | No | Dvorak, SatCon, Scatterometry |
| **ESCAP Tropical Cyclone Panel** | North Indian Ocean | Not known | No | Dvorak |
| **RA IV** | Americas and the Caribbean | Dvorak (1975), experiments with Courtney & Knaff (2009) | No | Dvorak, AMSU, Scatterometry, aircraft |
| **RA V** | S. Pacific Ocean and SE Indian Ocean | Various (prior to 2009), Courtney and Knaff(2009) | Yes | Dvorak, Scatterometery |
| **ESCAP Typhoon Committee** | NW Pacific, South China Sea | Koba (1991) | Yes through 48h | Dvorak, TRMM |

Issue:

These are all different

# Surface Winds: Standardization

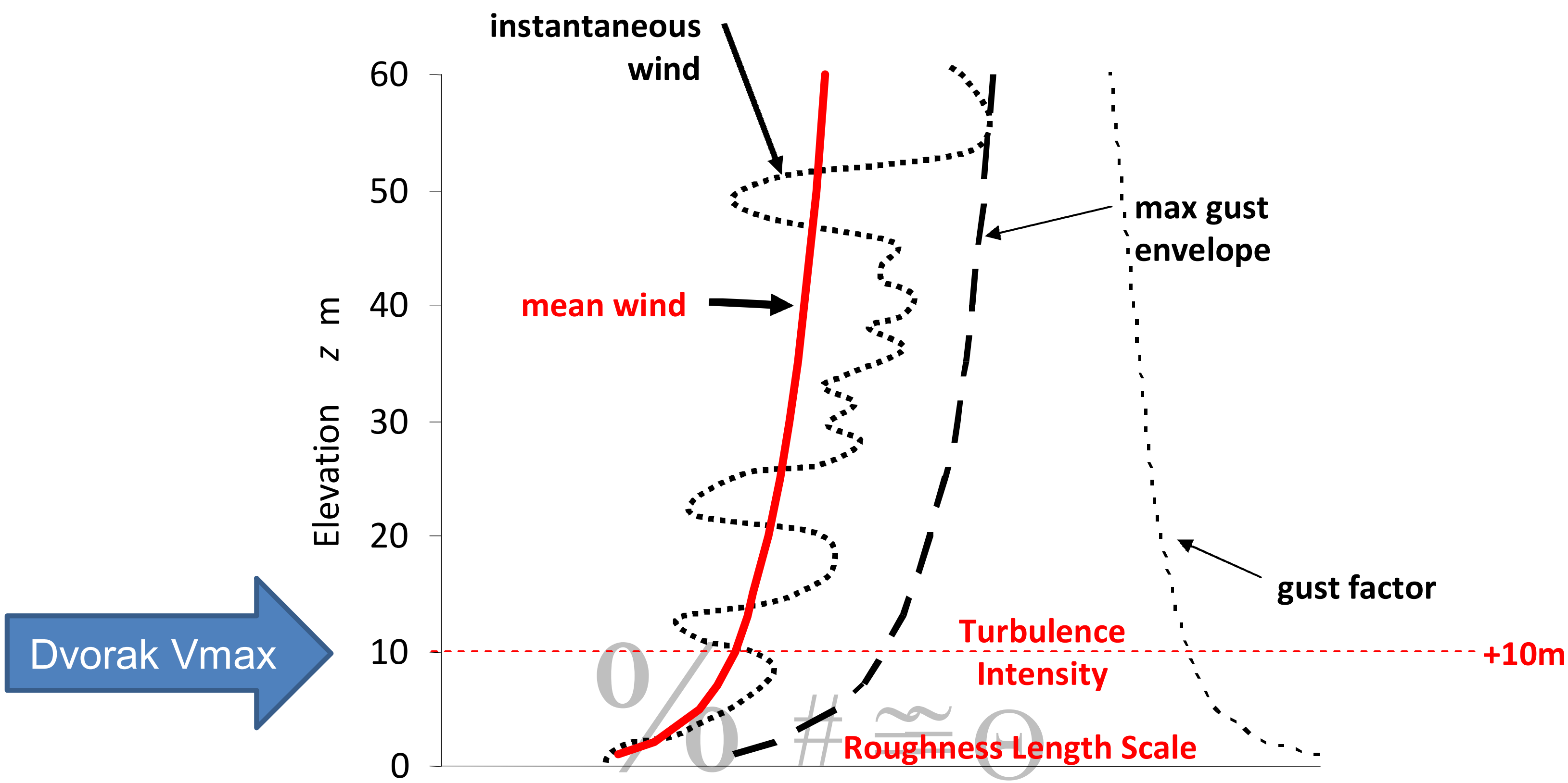



- Harper, Kepert and Ginger
- Initiated by the RSMC Tech Coordination Meeting in Nadi in 2002
- Review was substantially completed by 2004 – is now published.
- Aim was to provide clarity on wind conversion between the stated Regional Association "standard" averaging periods (1min, 2min, 3min, 10min)
- NB: we were not tasked with questioning the adopted "standards"

# Surface Winds: Standardization

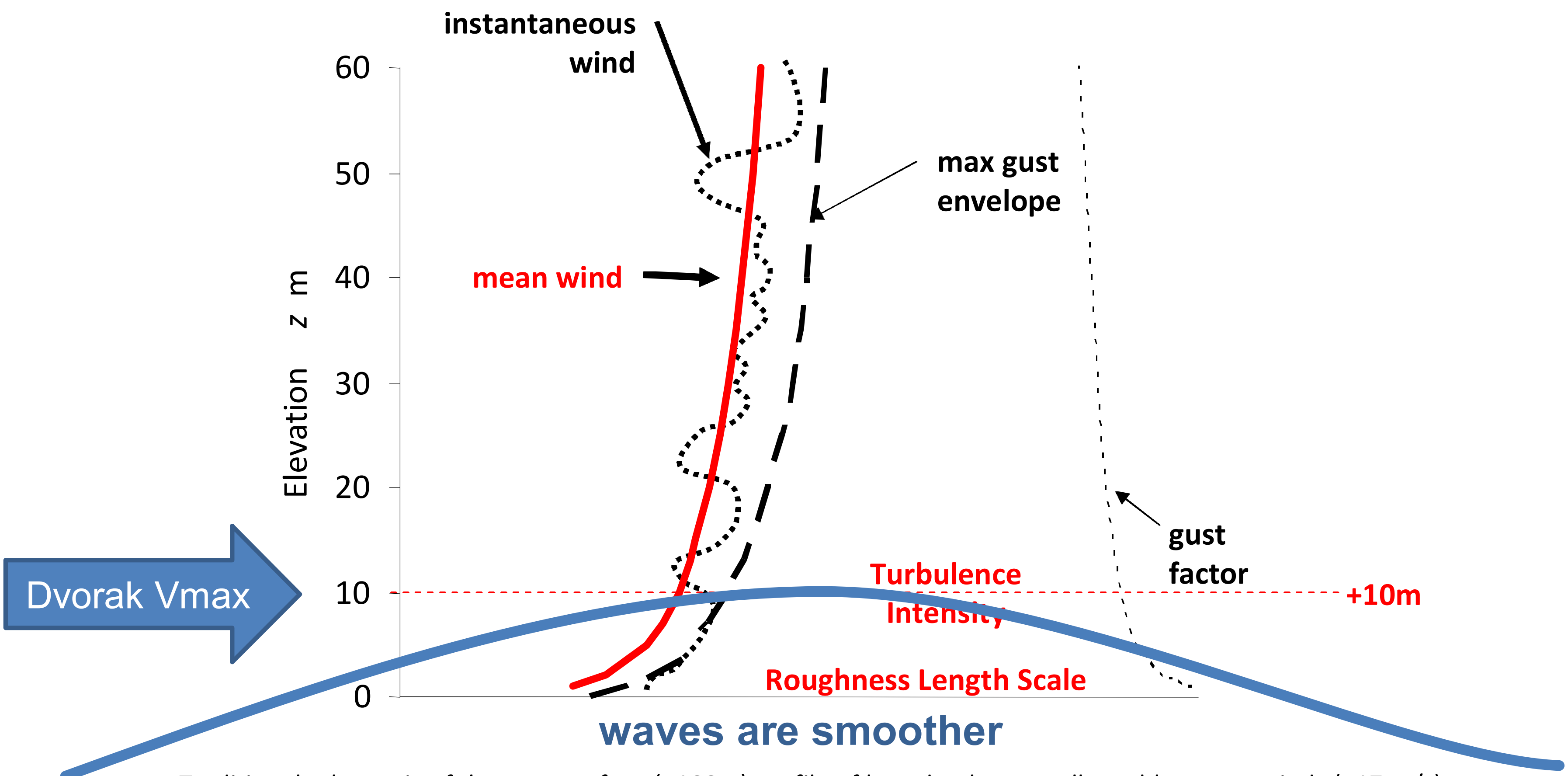
- The review uncovered a lack of rigour generally in the definition and use of TC wind metrics that leads to unnecessary variance in estimates and measures - but which is readily avoidable
- Importantly:
  - The “mean” wind cannot be converted to another “mean” wind but estimates of “gusts” above the mean can be made based on gust factor theory;
  - Short term averages of the wind are not necessarily “gusts” – just noisy “means”
  - “Gustiness” is a function of “exposure”
  - Must ensure that NWP models do not assimilate gusts (incl max 1-min sustained winds) or that gusts are used for TKE
  - Must ensure that wind measurements being made are representative (e.g. WMO 2008 standards)
  - A recommended nomenclature has been developed
  - TC near-surface wind turbulence characteristics in general are not distinguishable from extra-tropical winds

# Surface Winds: Near-Surface Equil Boundary Layer - Land




Traditional schematic of the near-surface (<100m) profile of broadscale neutrally-stable strong winds (>17 m/s).
(after Harper et al. 2010)

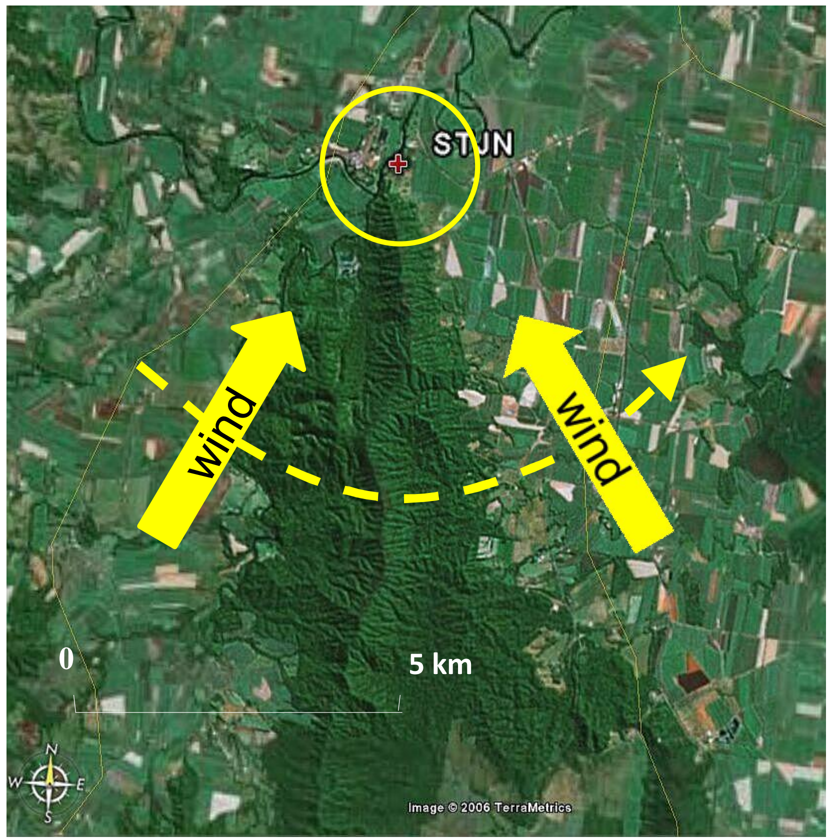
# Surface Winds: Near-Surface Equil Boundary Layer - Ocean



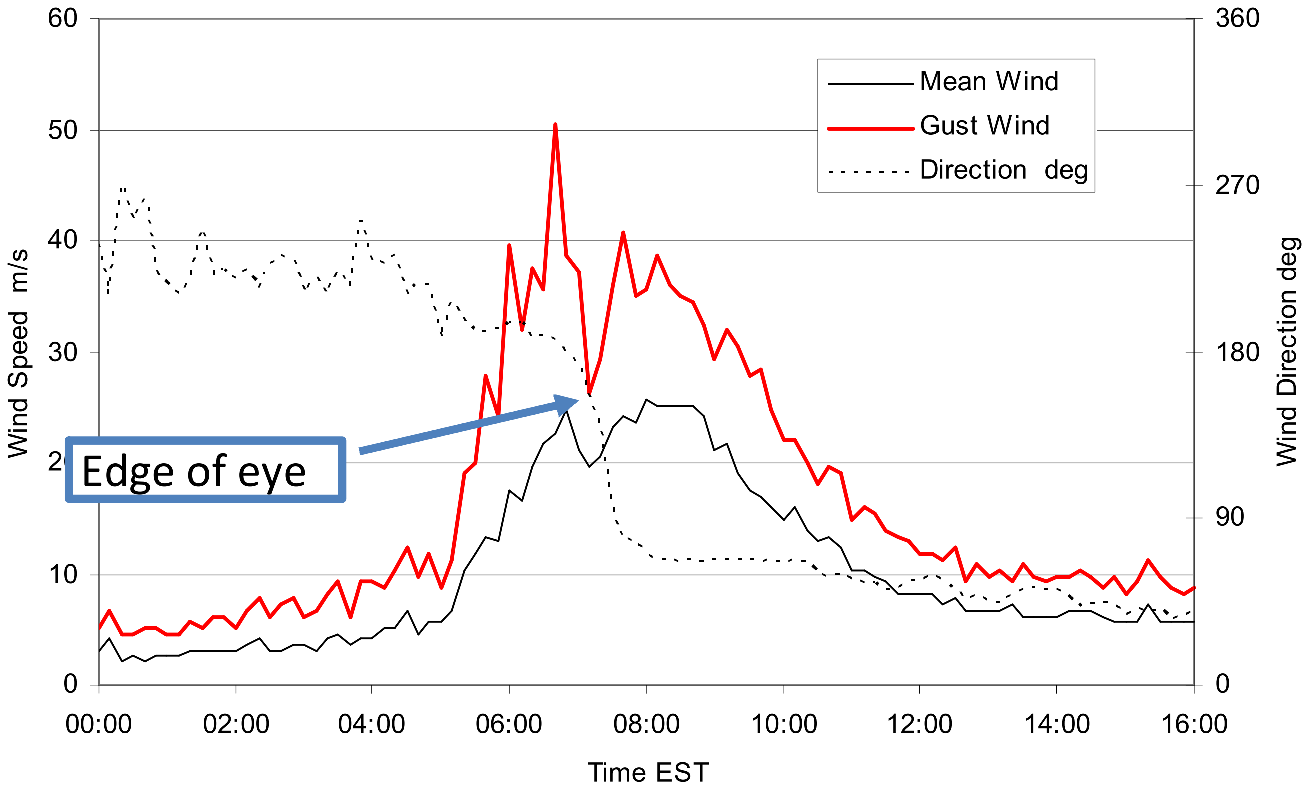

Traditional schematic of the near-surface (<100m) profile of broadscale neutrally-stable strong winds (>17 m/s).
(after Harper et al. 2010)

# Surface Winds: TC Larry Example - Exposure

Storm path north of the site

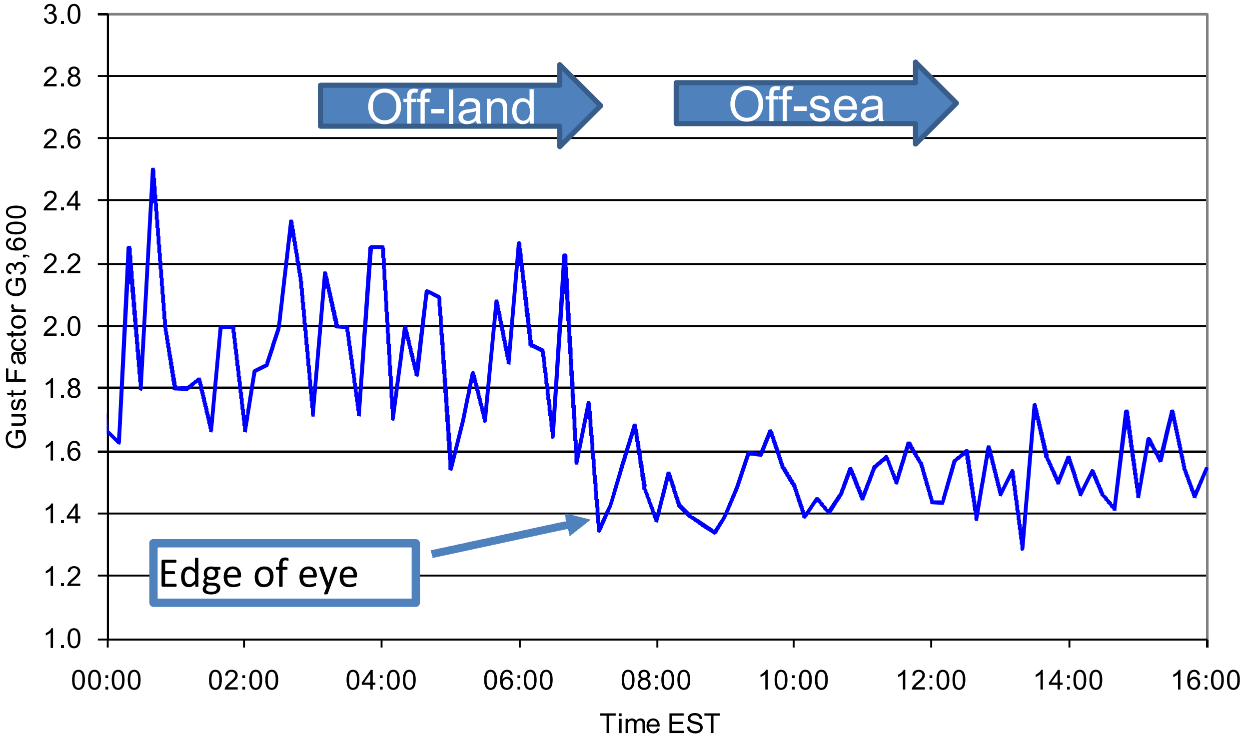


# Surface Winds: TC Larry Example – Gust Factor



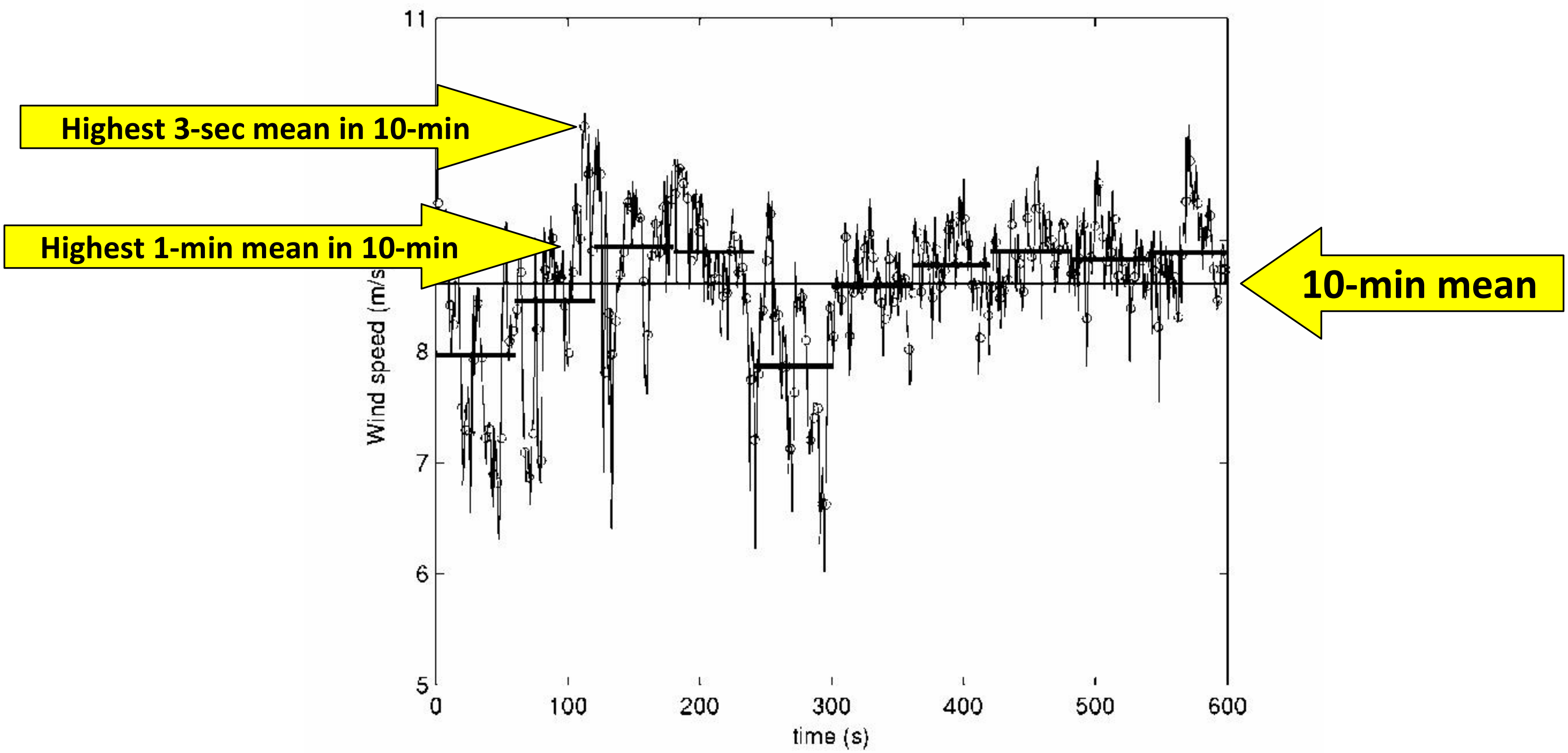

Based on Bureau of Meteorology Data

# Surface Winds: TC Larry Example – Gust Factor




Based on Bureau of Meteorology Data

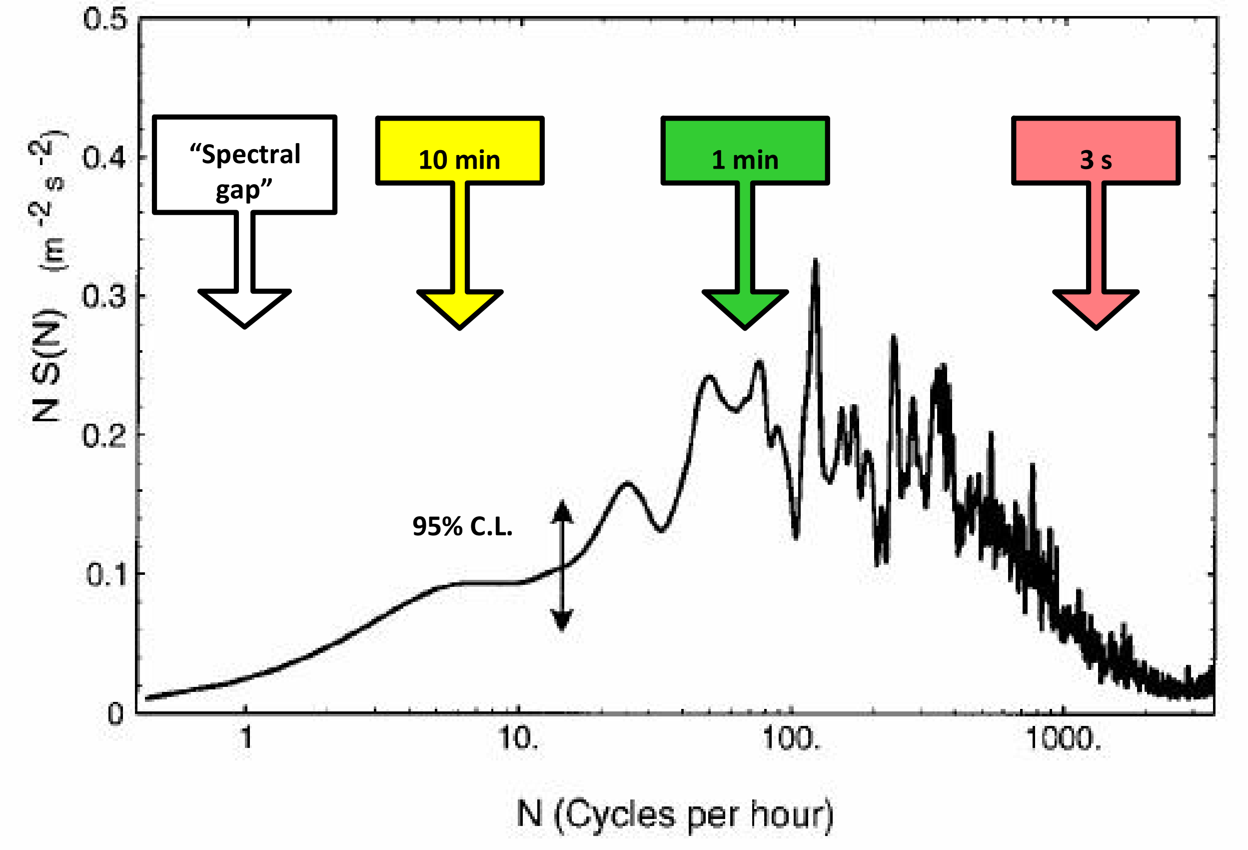
# 811 Estimates of the Mean (aka “sustained”) Wind




Thin line is the 1-sec averaged wind from a 10Hz sampling of 10 minutes of wind.
Circles are the 3-sec averages.
Thick horizontal bars are the 1-min averages.
Thin horizontal line is the 10-min average.

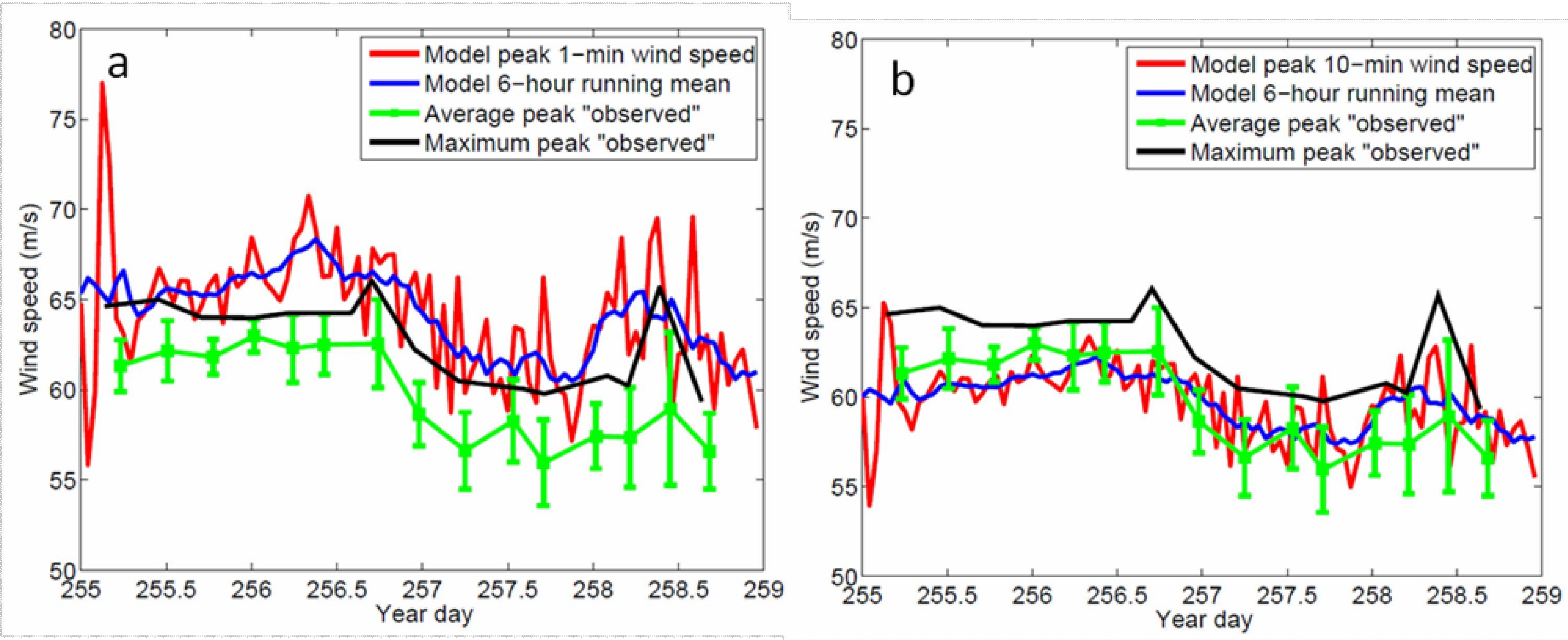
# Surface Winds: Sampling and Averaging Issues

Does it matter? ocean lakes long bridges ships tall buildings houses/ people




Example tropical cyclone wind energy spectrum after Powell et al. (1996) during Hurricane Bob.

# Surface Winds: Representativeness of Observations



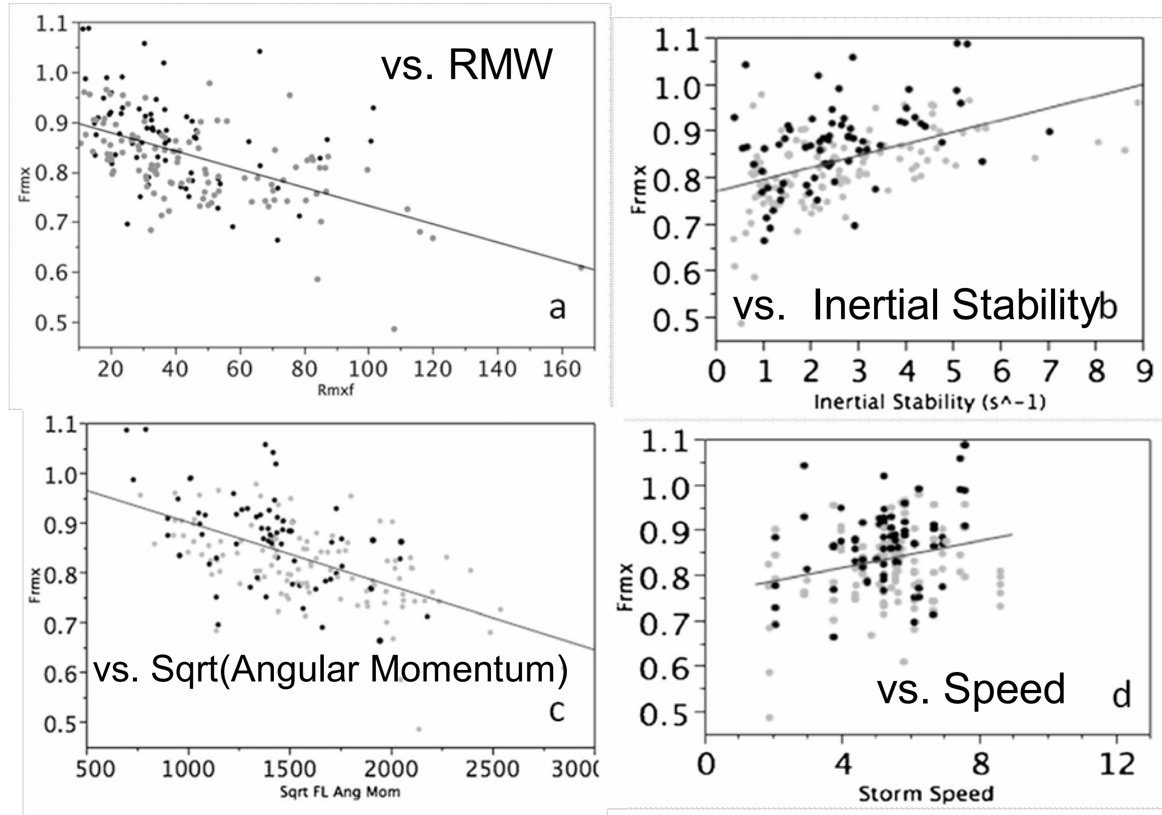

Courtesy of E. Uhlhorn

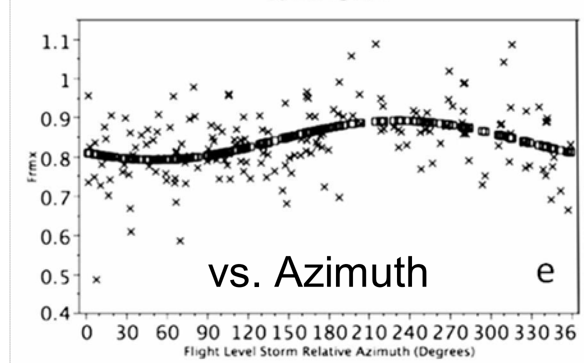
# Surface Wind: Flight-level to Surface Structure Variation

- Flight-level to surface wind reduction is a function of
  - RMW (negative)
  - Inertial Stability (positive)
  - Angular Momentum (negative)
  - Storm Speed (positive)
  - Storm relative direction
    - Higher rear left
    - Lower front right

- Flight-level to surface wind reduction varies from 0.84 ± 0.09

From Powell et al. (2009)




Slant reduction
Ratio of surface maximum wind to the flight-level maximum wind (along the same leg).

# Surface Winds: Size of the wind field

- Lee et al. (2010), Dean et al. (2009), Chavas and Emanuel (2010) all suggest the initial circulation size is important as storms often don’t grow much from that initial condition.
- Modeling studies have suggested that environmental moisture is important for determining TC size (Hill and Lackmann (2009); Xue and Wang (2010)).
- Maclay et al. (2008) found vertical wind shear, and eyewall replacement cycles to be related to the growth of the wind field in non-weakening TCs.

# Surface Winds: Asymmetries

**Inner Core wavenumber 1 asymmetries**

- Weakening cyclones in weak baroclinic environments
- Early stages of extra tropical transition

**Outer Core wavenumber 1 asymmetries**

- Late stages of extra tropical transition
- Stronger cyclones in increasingly baroclinic environments

- Symmetric inner core winds are associated with the more intense tropical cyclones in weakly baroclinic environments
- Strong and moderate vertical wind shear can modulate the location of the maximum winds that are normally located to the right (left) portion of the circulation in the Northern (Southern) Hemisphere

Fujibe and Kitabatake (2007), Ueno and Kunii (2009)

# Surface Winds: Parametric Model Developments

- Development since the 1950s
- Simple yet powerful and practical tools
  - Extensively used in engineering and risk assessment
  - implicitly linked with the WPR “issue”
- Proliferation of approaches
  - Schloemer (1954)
  - Holland (1980)
  - Harper and Holland (1999)
  - Willoughby et al (2006)
  - Vickery et al. (…) plus FPHLM
  - Holland (2010)
- Tremendous up-side still
  - to be test beds for new theoretical approaches
  - for probabilistic forecasting
  - to capture climatology information

**Holland (1980)**

**3 Parameter Model:**

**MSLP**

**RMW**

**B**

**Implicit WPR:**

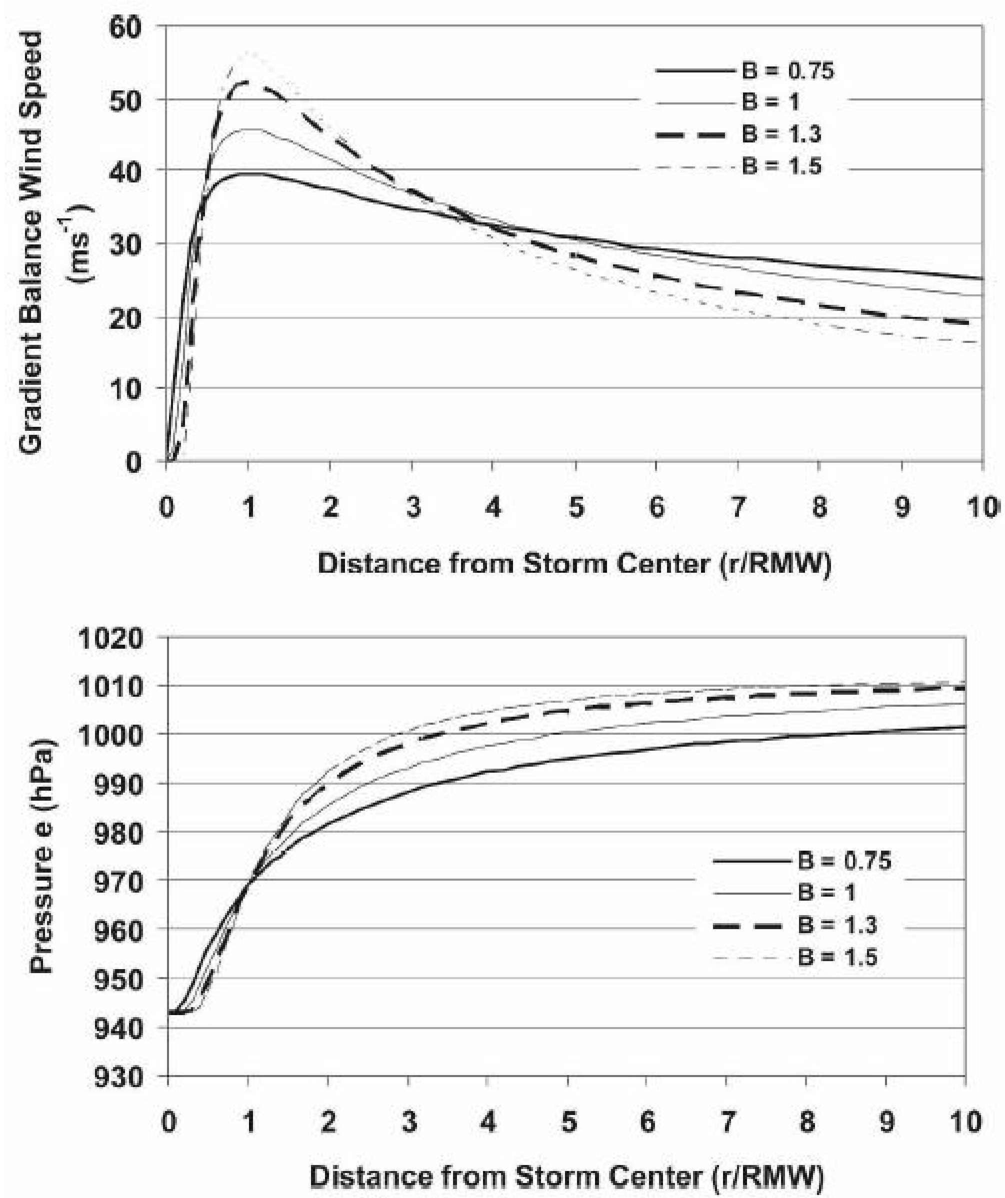
**MSW = *f* { $B^{0.5}$ ,$Deltap^{0.5}$ }**

**Plus:**

**B/L**

**Asymmetry**

**Inflow**




(Fig 1 from Vickery and Wadhera 2008).

**Holland (2010)**

**4 Parameter Model:**

**MSLP**

**RMW**

**B**

**X**

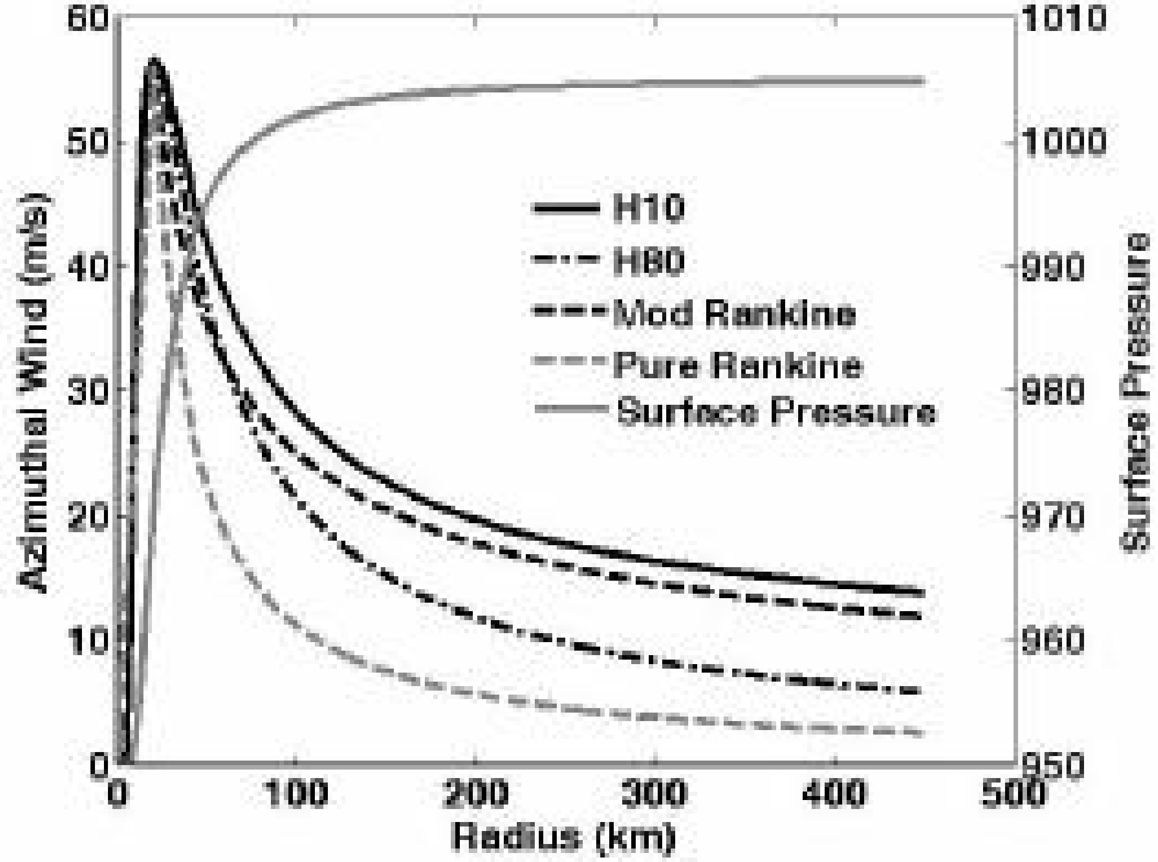



Fig 1 from Holland et al. (2010)

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

# Hurricane hazard modeling: The past, present, and future

Peter J. Vickery[a,*], Forrest J. Masters[b], Mark D. Powell[c], Dhiraj Wadhera[a]

[a] Applied Research Associates, Inc., Raleigh, NC, USA
[b] University of Florida, Gainesville, FL, USA
[c] NOAA Hurricane Research Division, Miami, FL, USA

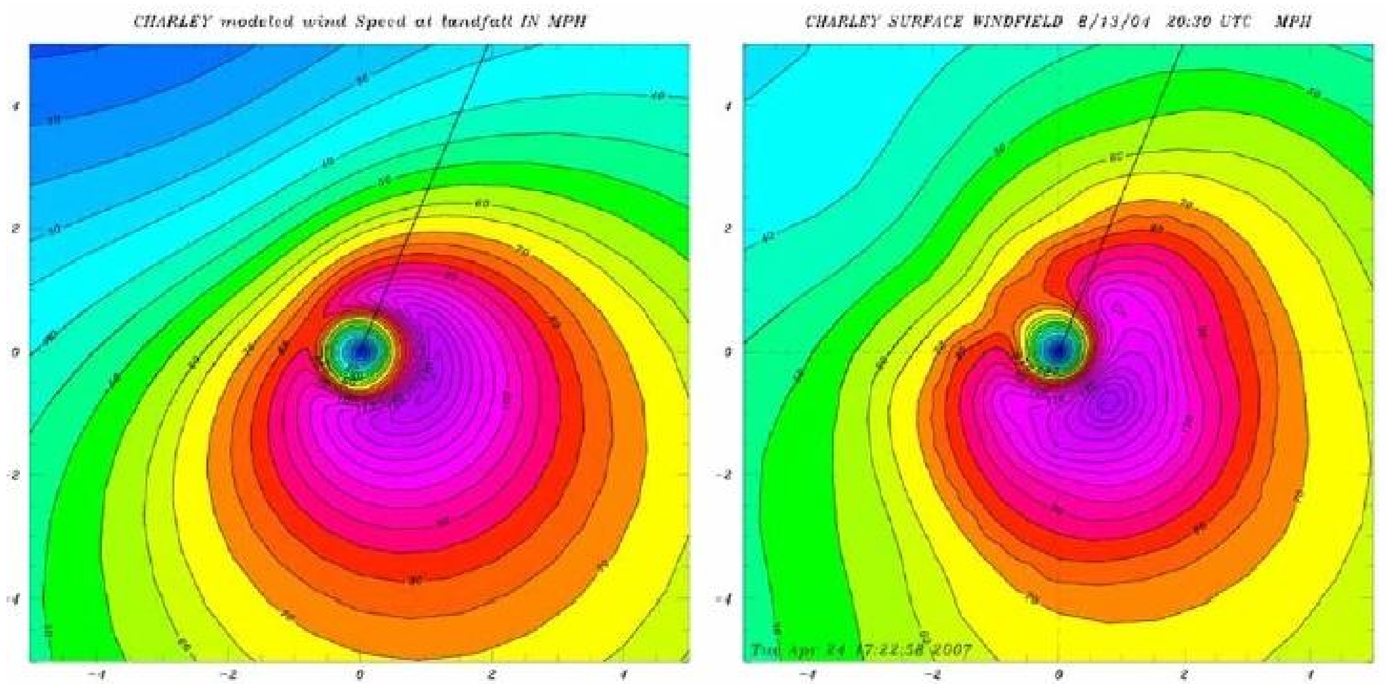
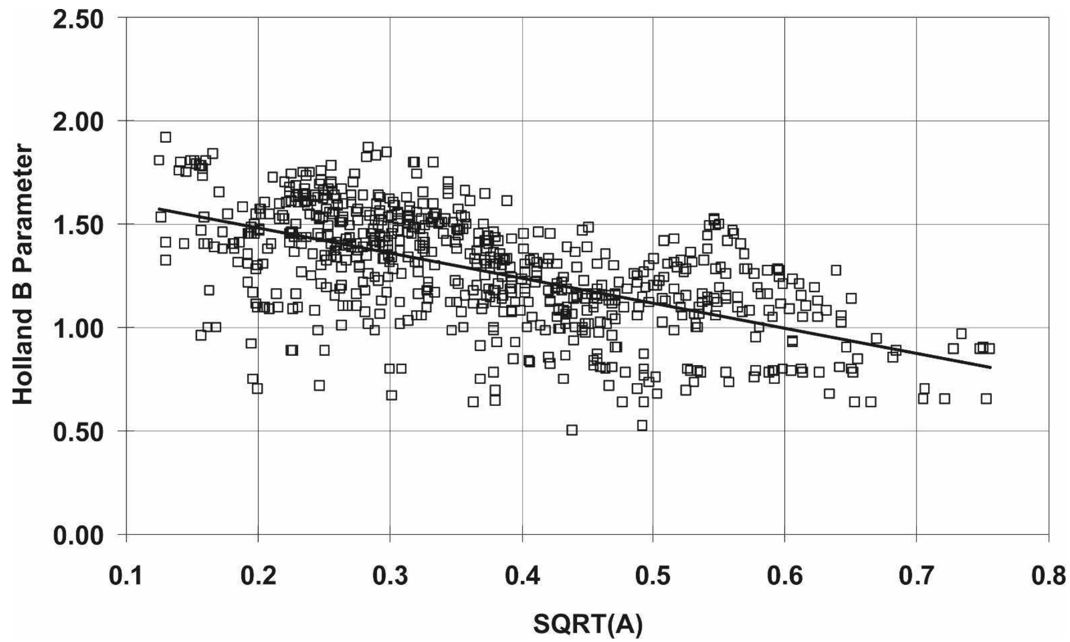



Fig. 9. Comparison of observed (right) and FPHLM modeled (left) landfall wind fields of Hurricanes Charley (2004, top) Line segment indicates storm heading. Horizontal coordinates are in units of r/RMW. Winds are for marine exposure. Vickery et al. 2009.

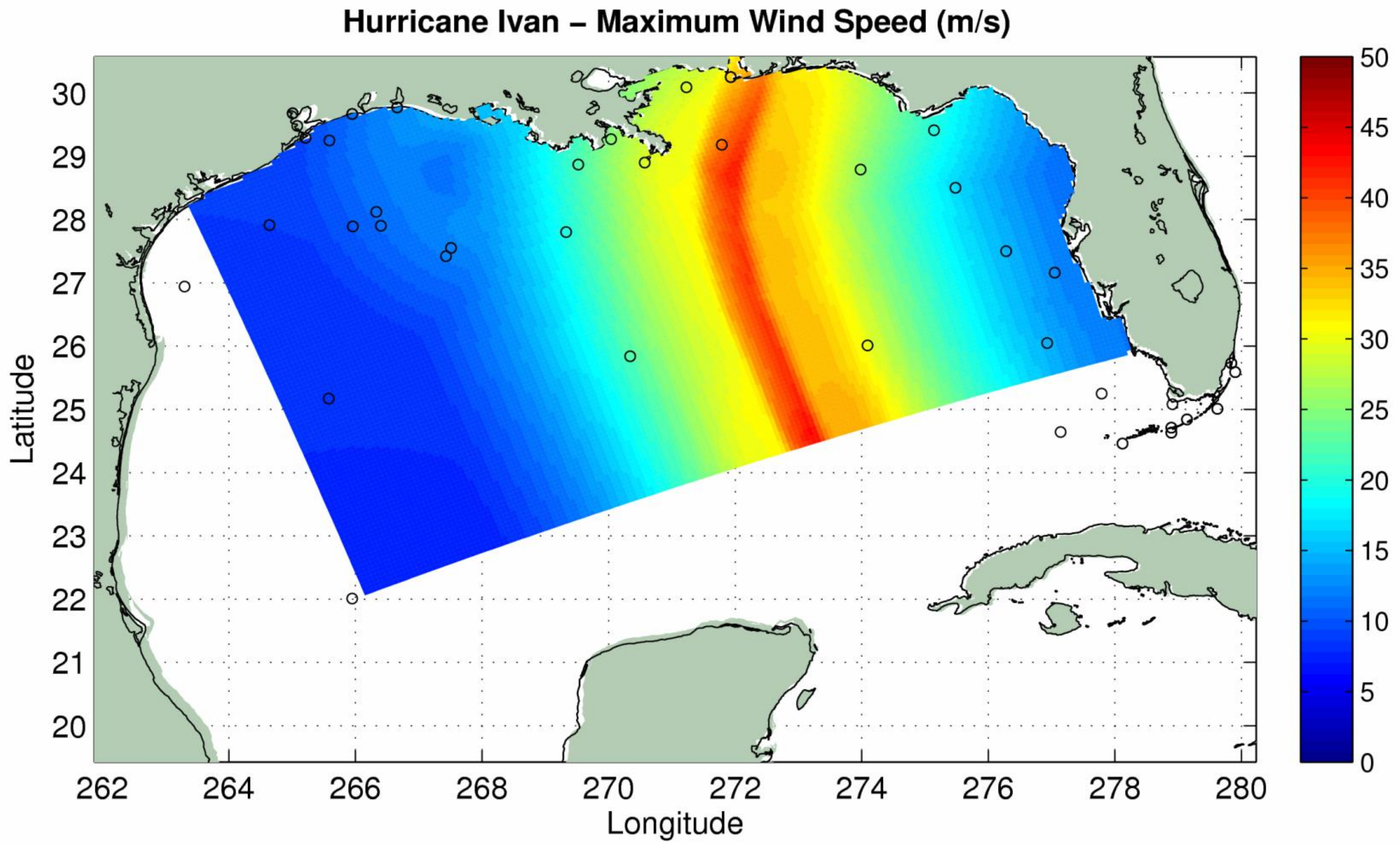
# Building a Parametric Climatology




Relationship between the Holland B parameter and the dimensionless parameter A for Atlantic tropical cyclones
(Fig 16 from Vickery and Wadhera 2008).

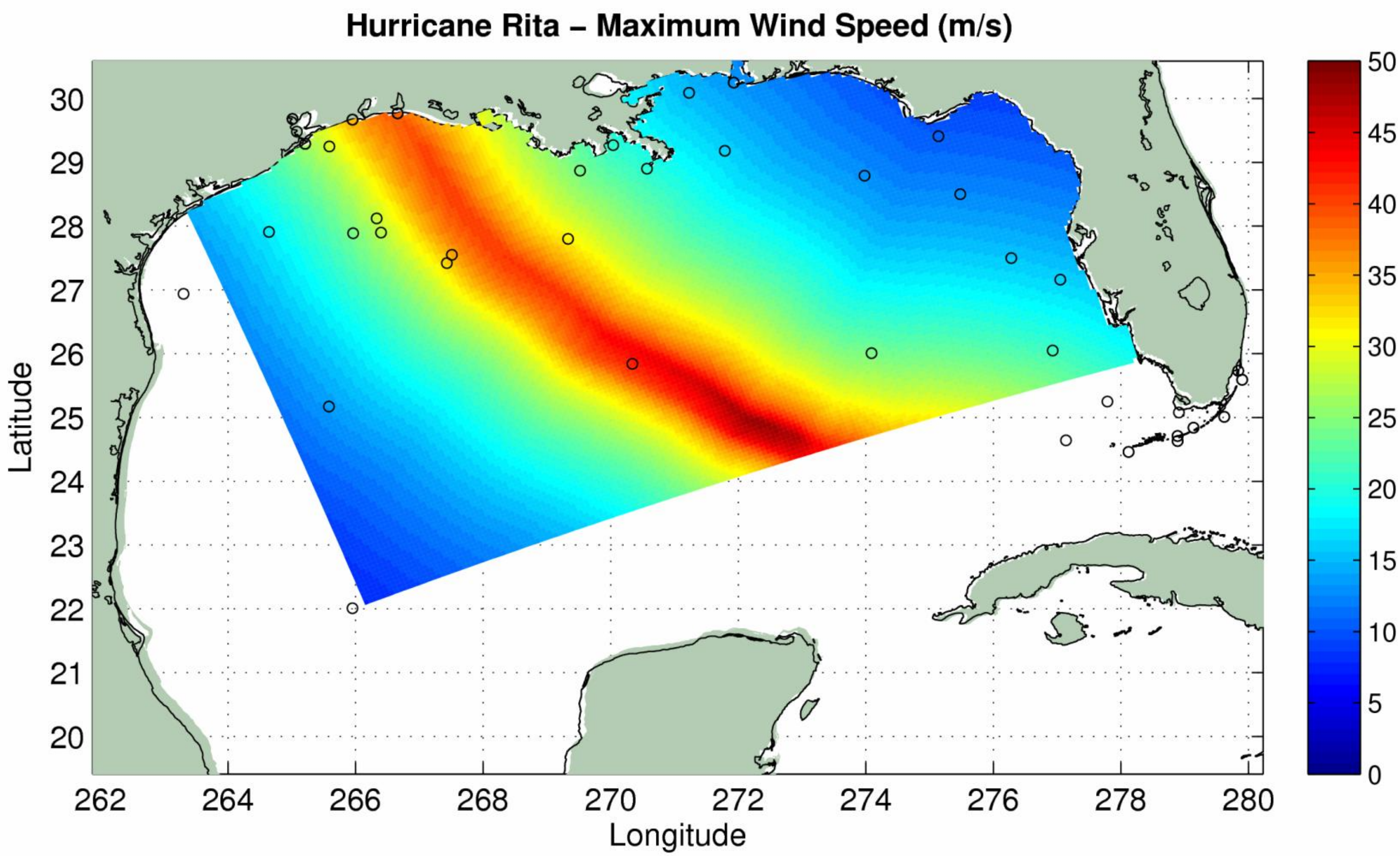
$$A = \frac{\mathrm{RMW} f_c}{\sqrt{2R_d(T_s - 273)\ln\left(1 + \frac{\Delta p}{p_c e}\right)}}. \qquad (19)$$

# “Double Holland”
# Met Inputs: x,y,t,MSLP,SurfObs



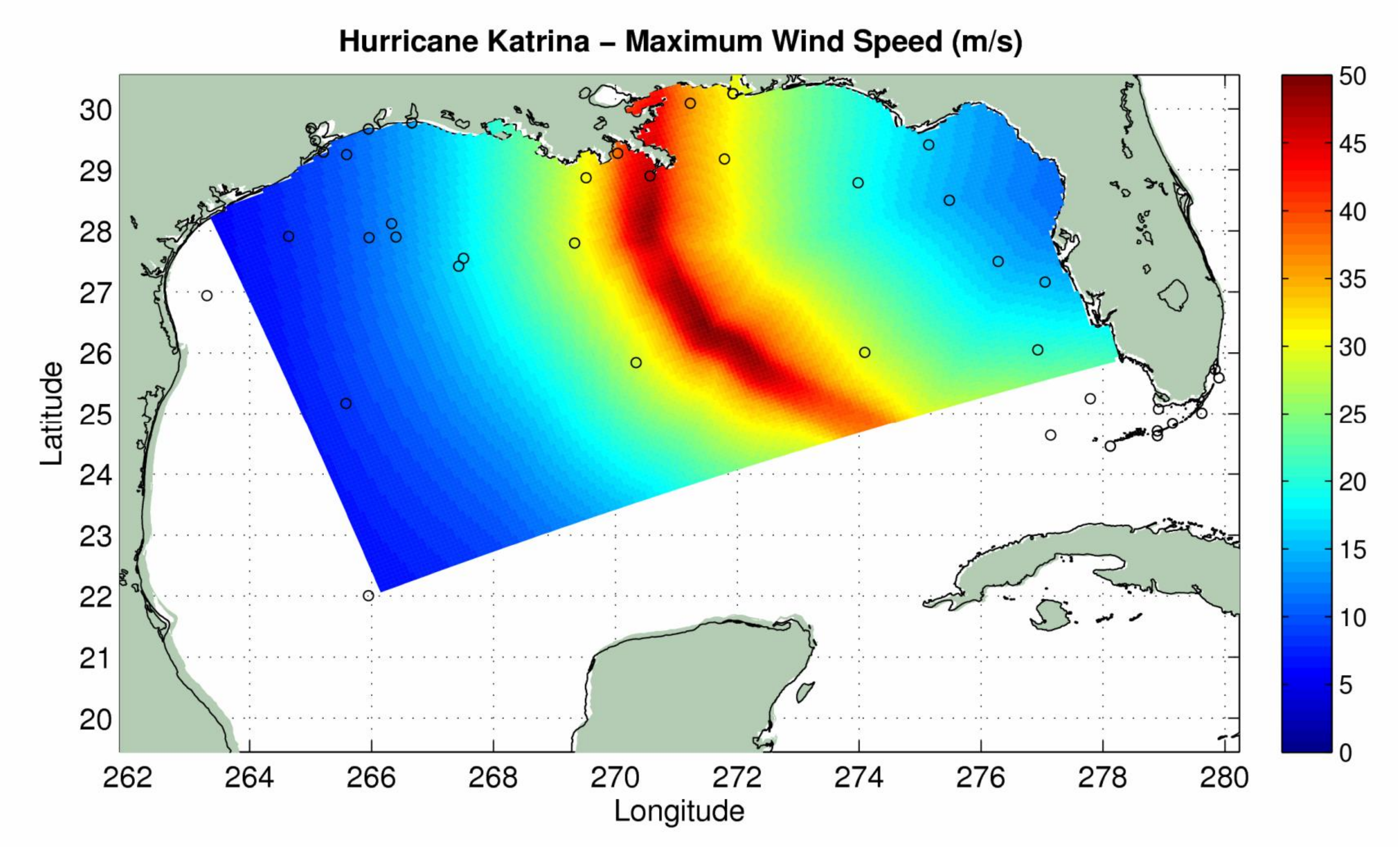

*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*

# “Double Holland”
# Met Inputs: x,y,t,MSLP,SurfObs




*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*

# “Double Holland”
# Met Inputs: x,y,t,MSLP,SurfObs




*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*

**6 Parameter Model:**

**Inner Vortex:**

**MSLP**

**RMW**

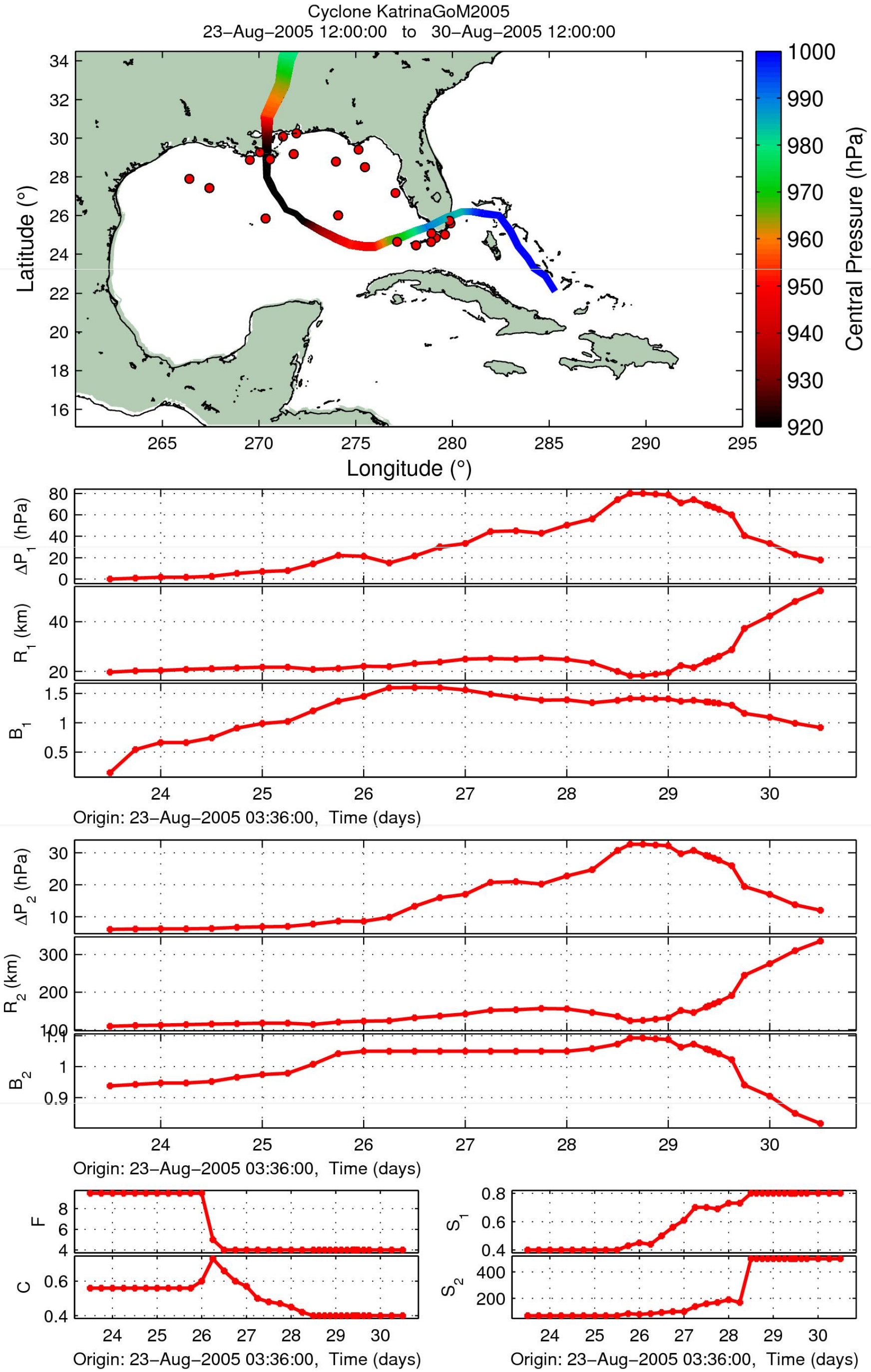
**B**

**Outer Vortex:**

**MSLP**

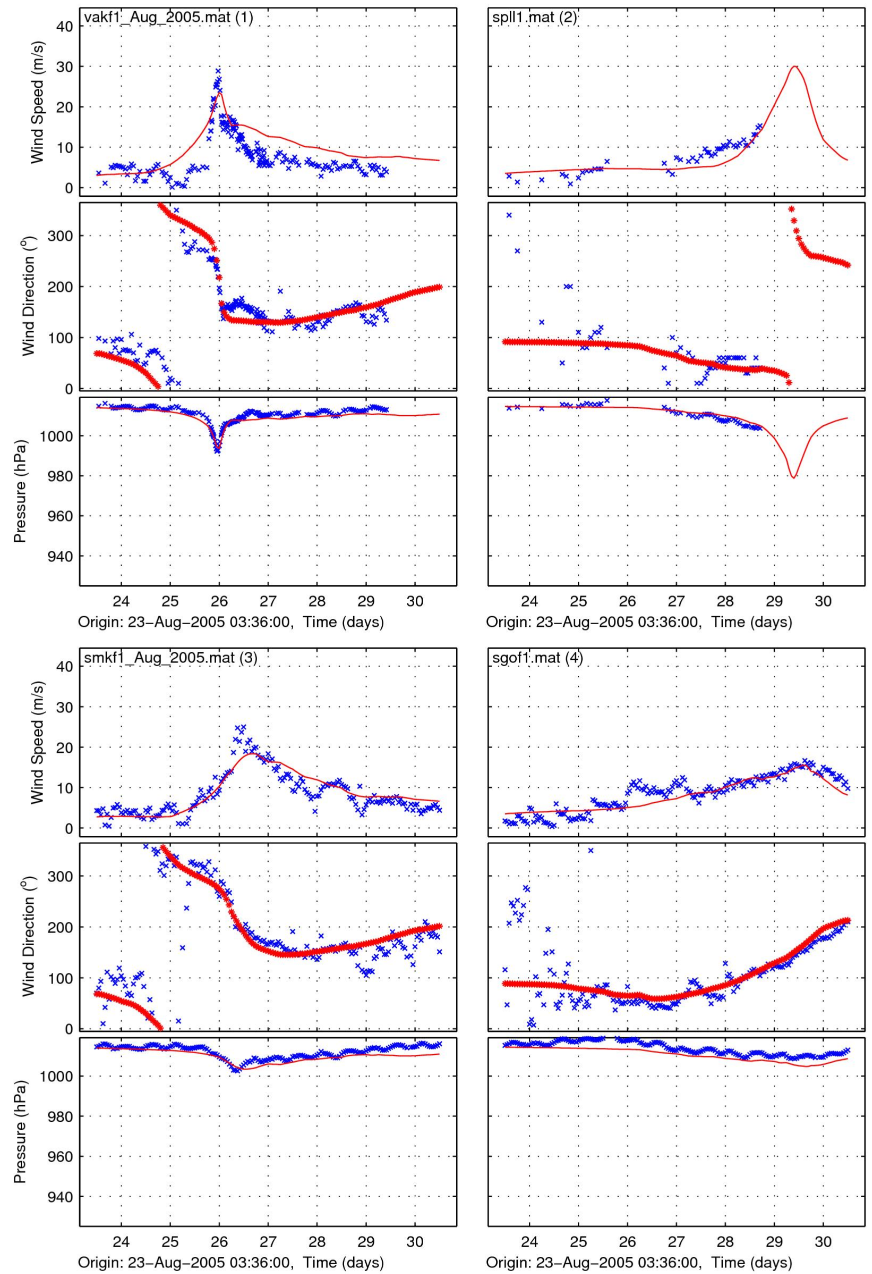
**RMW**

**B**

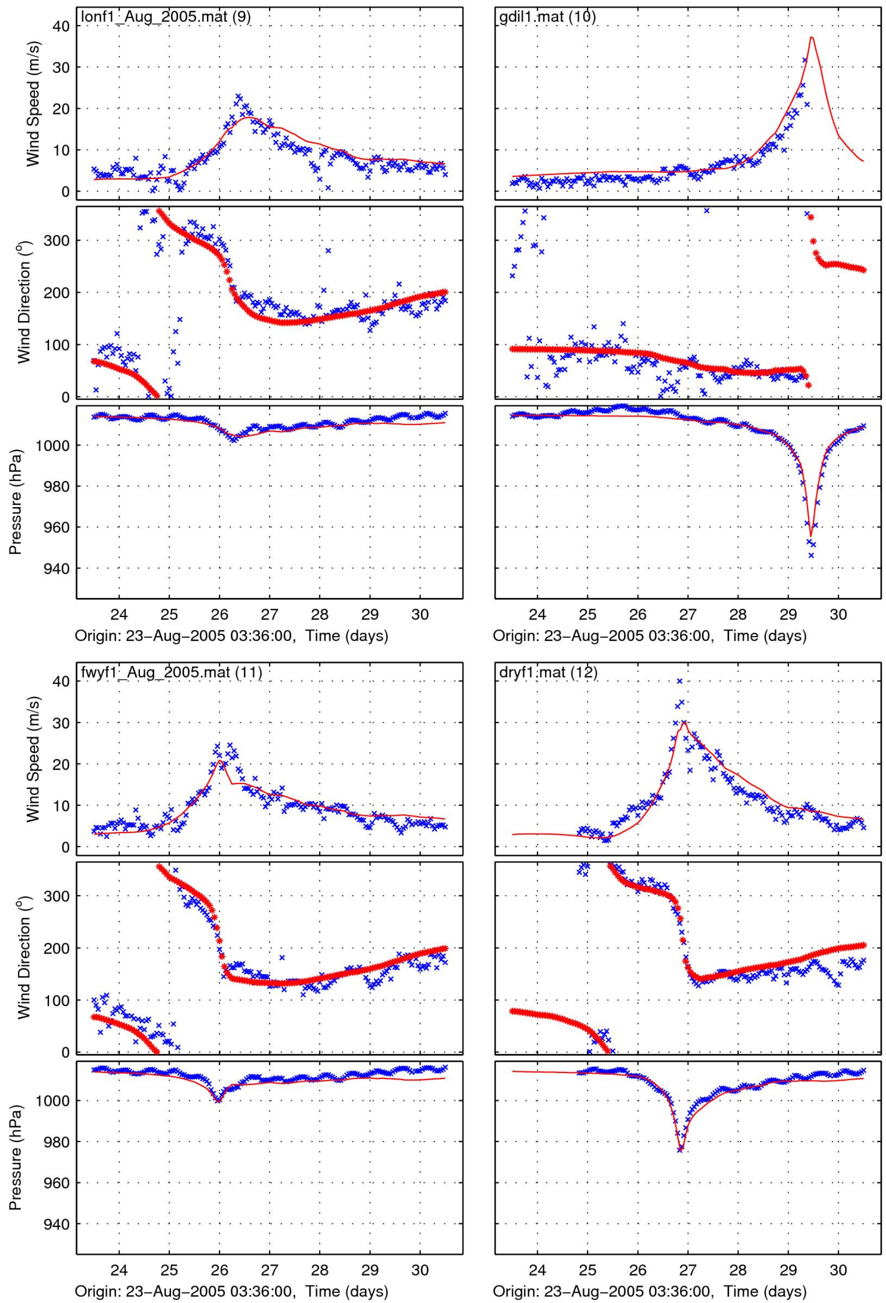



**"Super Parameters"**

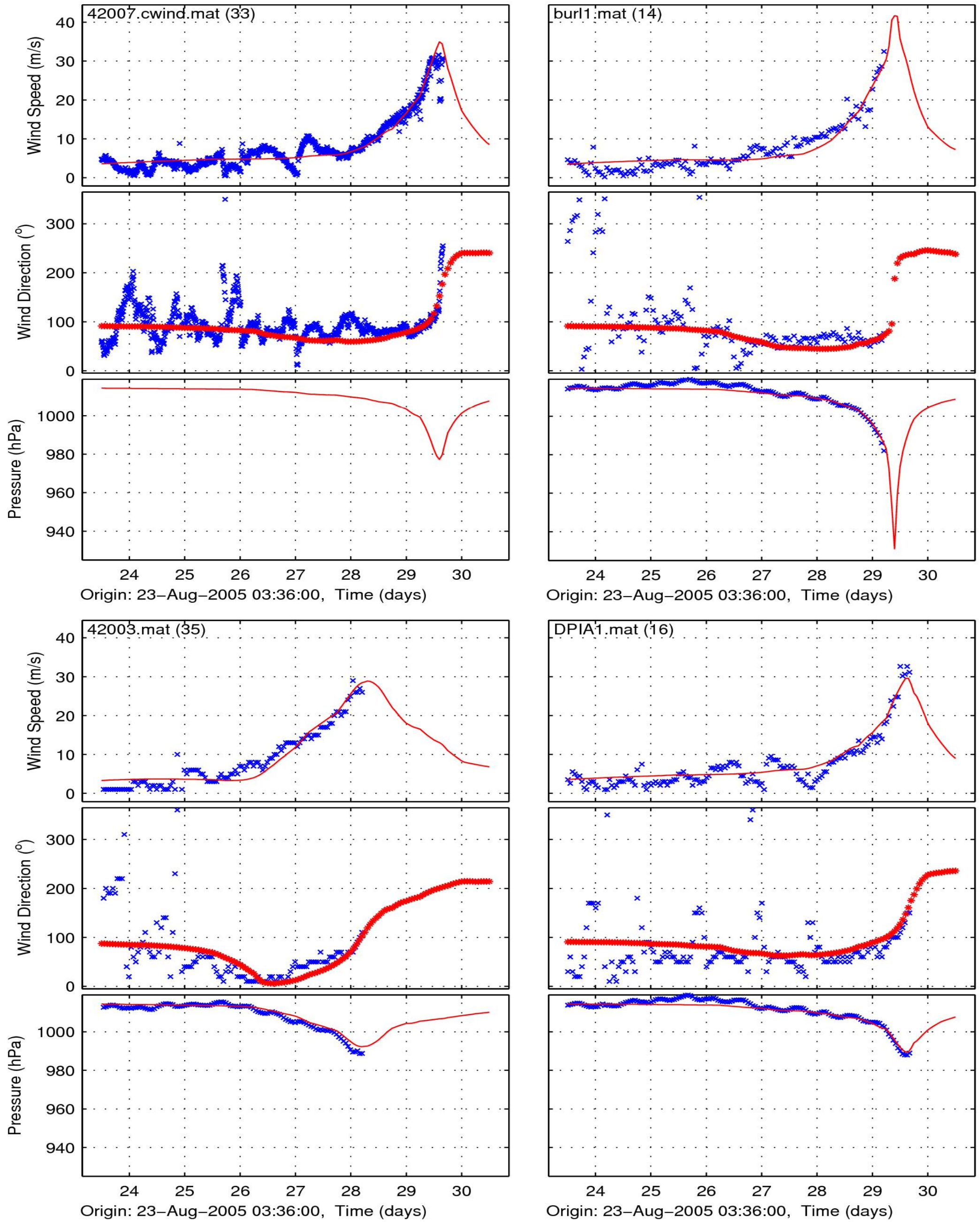
*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*




*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*

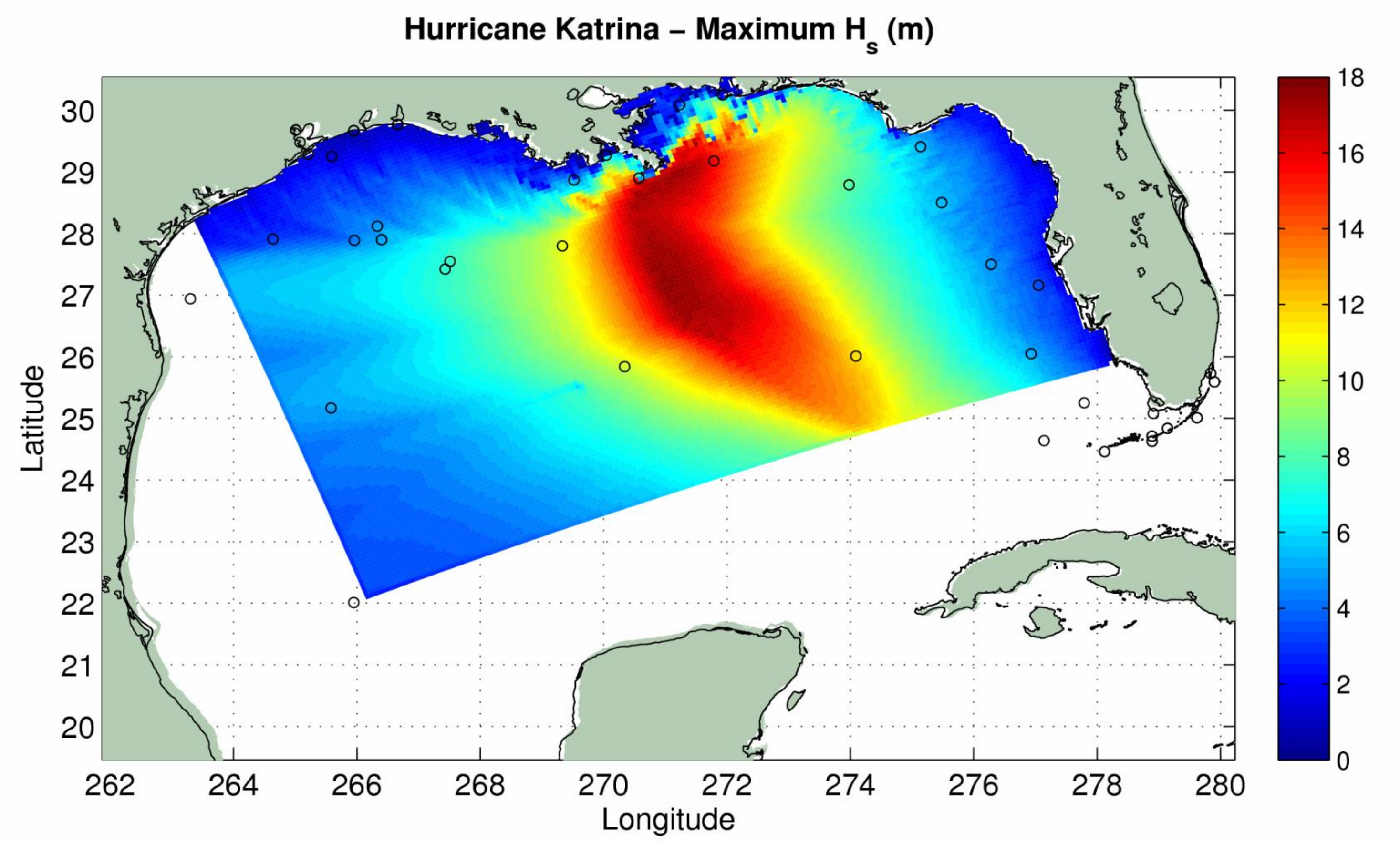



*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*

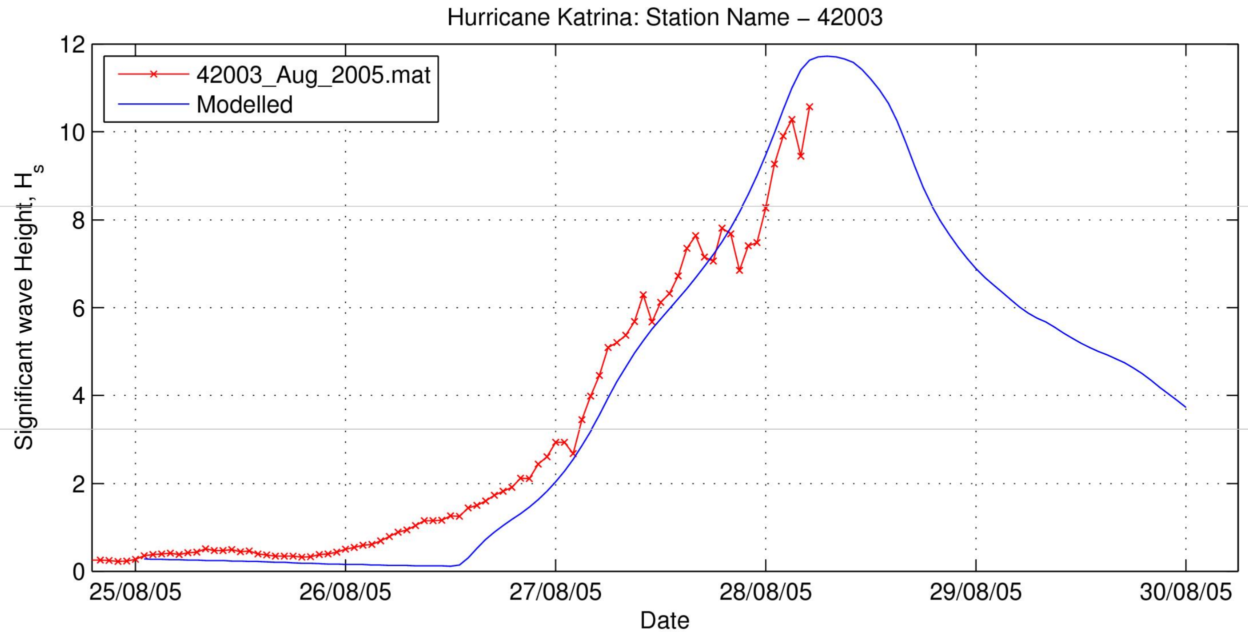


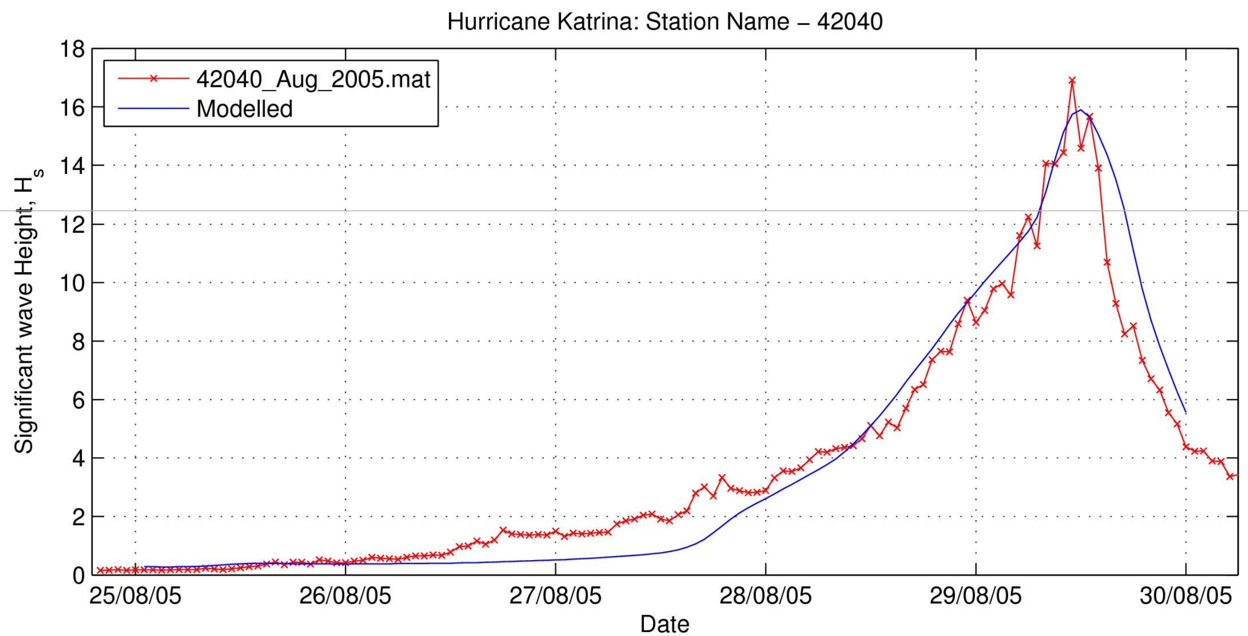

*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*

# "Double Holland" + WAM Spectral Model Significant Wave Heights




*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*




*Credits: Lou Mason, Australian Maritime College; Jason McConochie, Woodside Energy.*

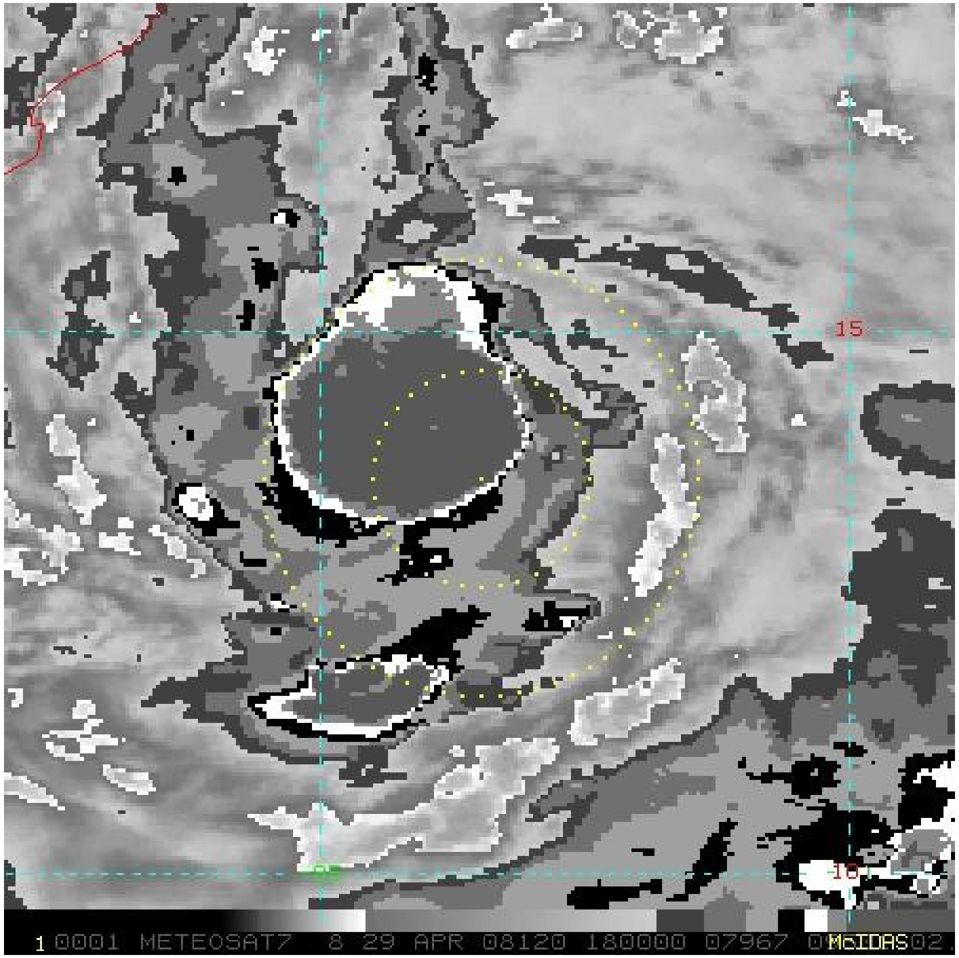
# Surface Winds: Satellite Techniques - Intensity

- Advanced Dvorak Technique (Olander and Velden (2009); latest 8.1.2)
  - Predicts MSLP from which MSW is then estimated
  - Use microwave during CDO periods
  - Center location via ARCHER (Wimmers & Velden 2010)
  - Working to implement variable wind-pressure relationships
- TRMM Microwave Imager (TMI) data (Hoshino and Nakazawa 2007)
  - Intensity from TMI brightness temperatures using multiple linear regression.
- SATCON (Herndon et al. 2010)
  - ADT + AMSU (two methods); weighted based on past performance
- Validation and conditional bias/error analysis of subjective Dvorak (Knaff et al. 2010)

# Surface Winds: Satellite Techniques – Surface Winds

- Flight-level/surface wind fields inferred from IR satellite data (Kossin et al. 2007; Mueller et al. 2006).
- All-weather winds from AMSR-E / WindSAT (Saitoh and Shibata, 2010) based on the Shibata (2006) algorithm.
- AMSU-based non-linear balance winds (Bessho et al. 2006)
- Multi-platform tropical cyclone surface wind analysis (Knaff et al. 2011)

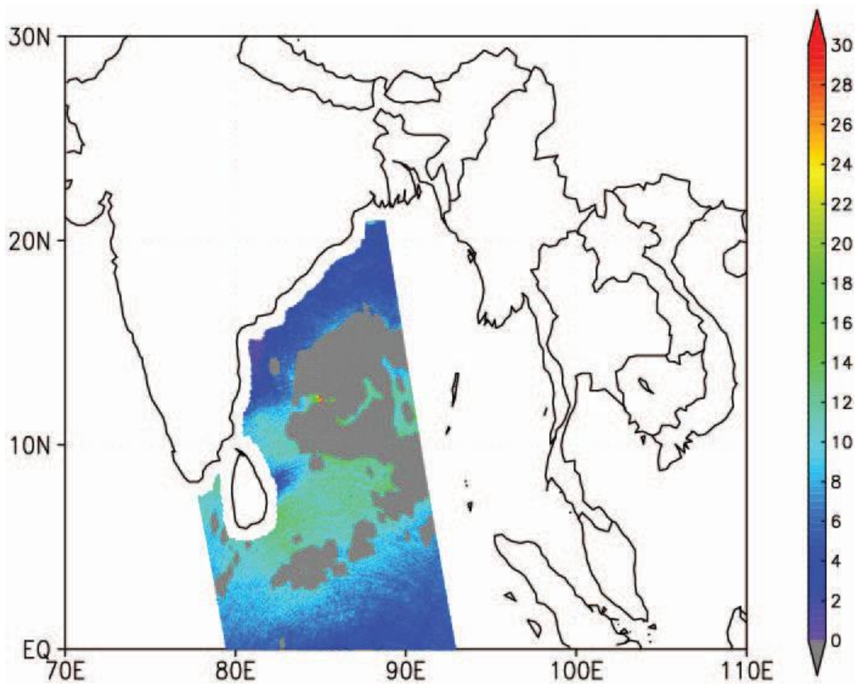
# Nargis 29 April 2008 18 UTC

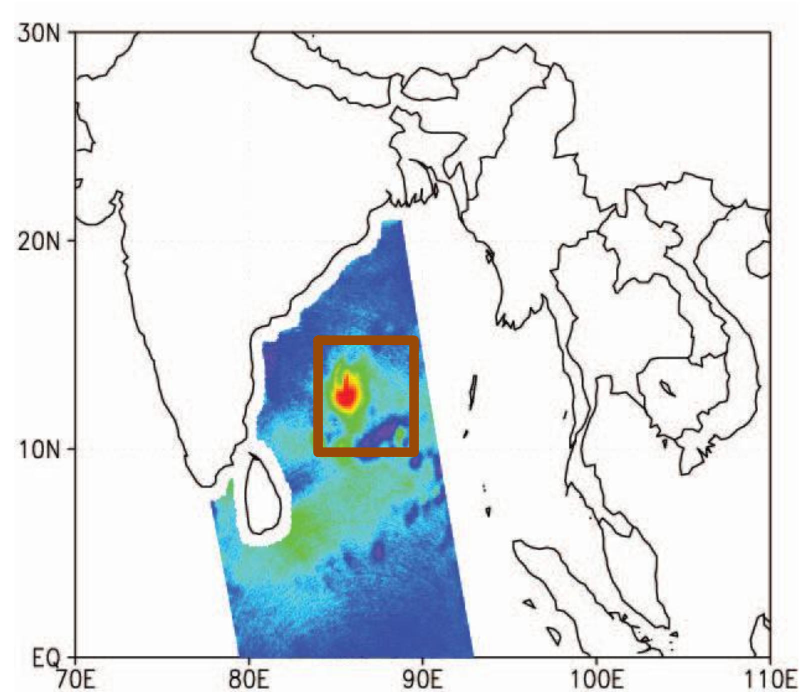


# AMSR-E/ WINDSAT All-Weather Surface Winds

**JAXA standard level 2** **All-weather sea surface wind**

TC Nargis 29 April 2008



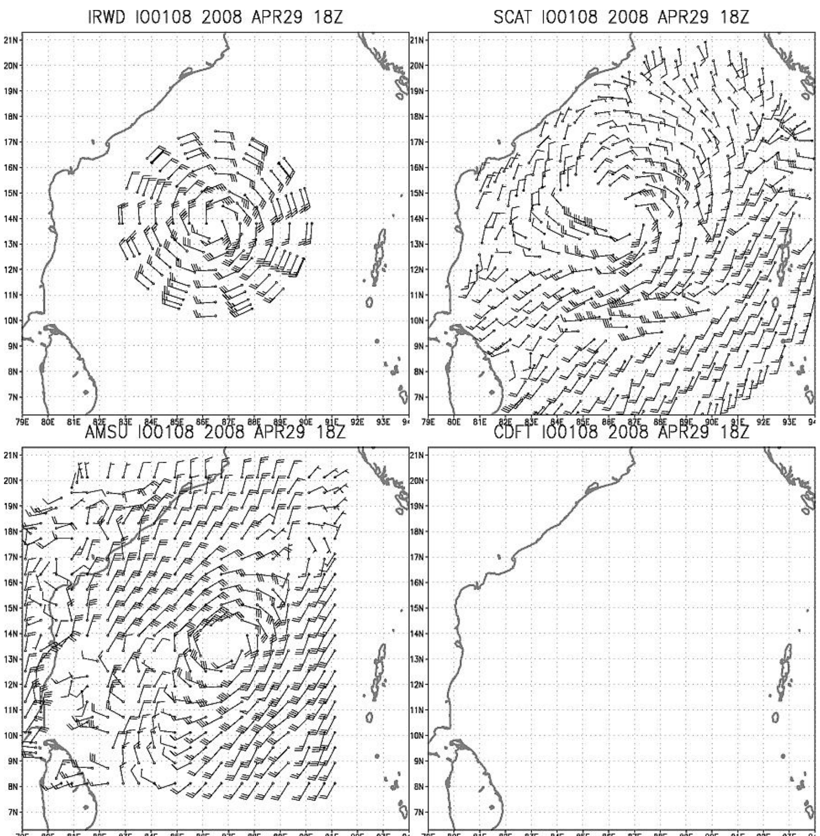




From Kazumori (2009)

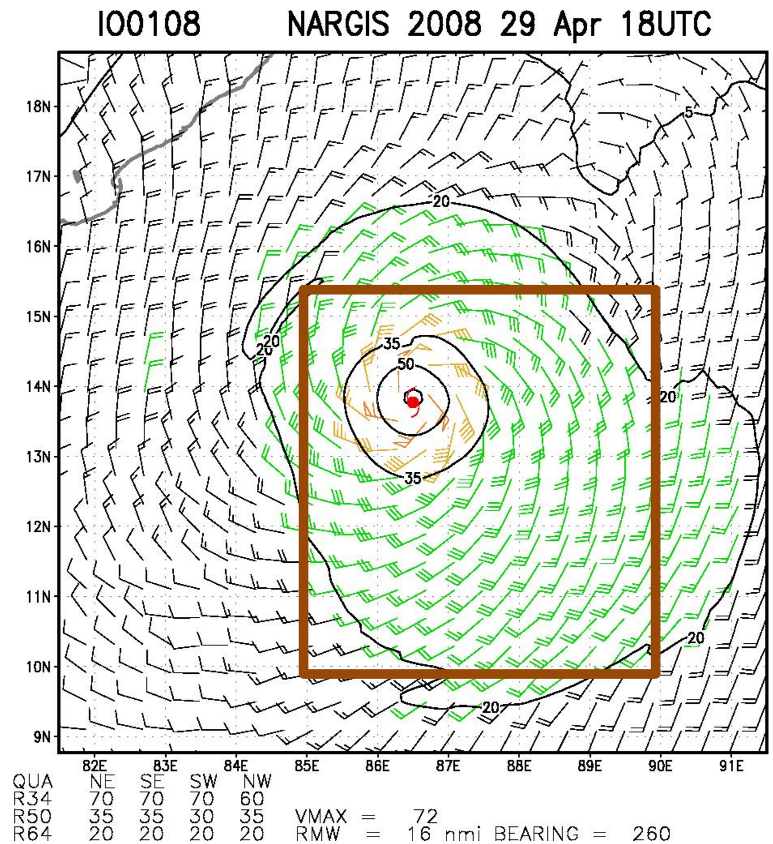
Shibata (2006) algorithm

# Multi-platform tropical cyclone surface wind analysis

**Inputs**




**Analysis**




http://www.ssd.noaa.gov/PS/TROP/mtcswa.html

# Pressure-Wind: Research

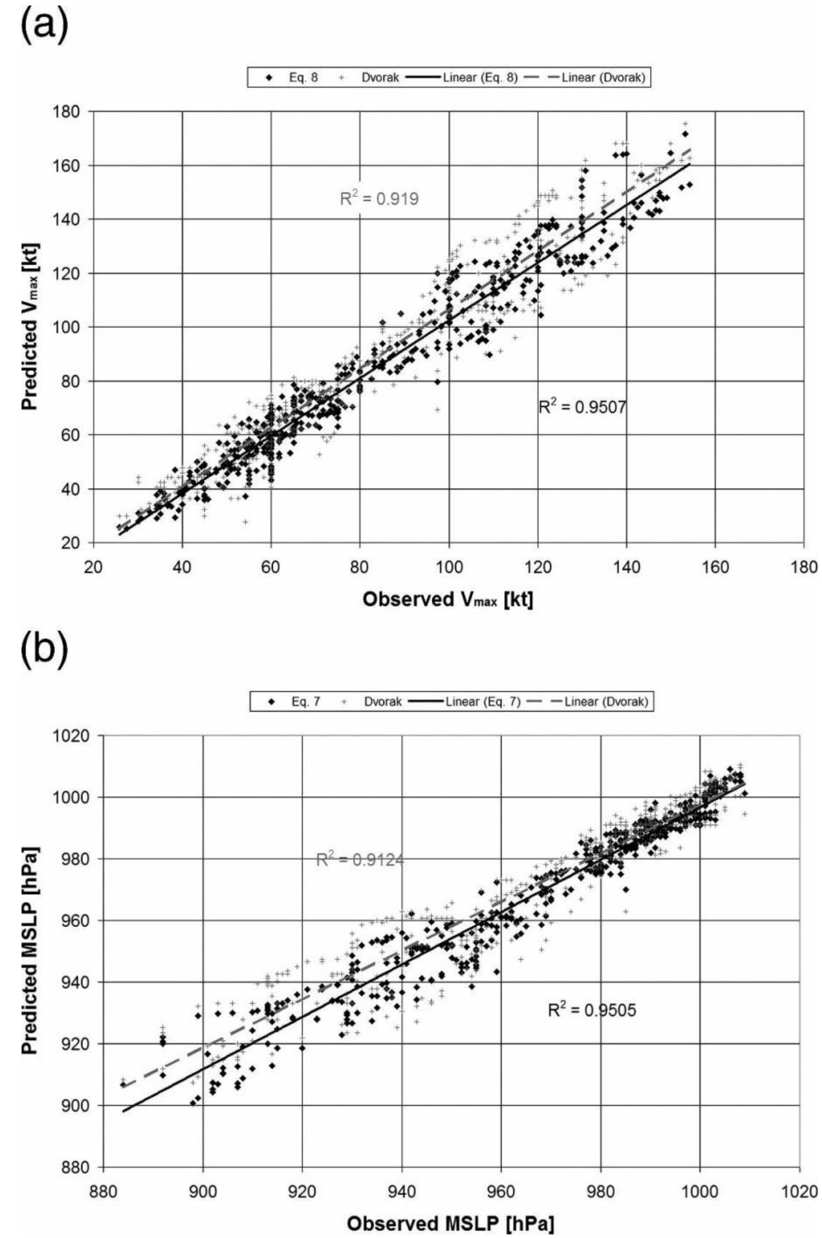
- Universal Wind-Pressure Relationships based on operationally available information
  - Knaff and Zehr (2007;KZ07)
  - Courtney and Knaff (2009; CK09)
  - Kieu et al. (2010) examined the WPRs of intense TCs and found that the frictional forcing in the planetary boundary layer and intensity trends were likely contributing to pressure drops for very intense TCs.
- CI-to-pressure-to-wind
  - Holland (2008) pressure is argued to be a more ‘robust’ parameter having less scatter than the wind. This is a parametric model approach and could be implemented in operations alone or in combination with other approaches. (notably several satellite techniques estimate $\Delta p$ directly)

## Knaff & Zehr (2007; KZ07)

- 15 years of aircraft MSLP, best-track MSW, ΔMSW, latitude, NCEP reanalyzes.
- Size is estimated from the tangential wind at r=500 km
- Environmental pressure is MSLP at r=900km
- Translation speed asymmetry estimated by Schwerdt (1979)
- Two equations wind-to-pressure and pressure-to-wind assumes a gradient type wind.

Issues and shortcomings:

- No cases < 12$^{o}$ latitude
- Size estimates affected by the fraction of land (Knaff and Zehr 2008), require NWP analyses
- Environmental pressure requires NWP analyses
- Does not account for variations of the radius of maximum winds



# Courtney & Knaff (2009; CK09)

- Uses the KZ07 equations
- Estimates size from R34 (non-zero average)
- Estimates environmental pressure from pressure of outer closed isobar
- Introduces a low-latitude set of equations
- Tested in NW Australia

Intended to unify methods used in Australian operations.

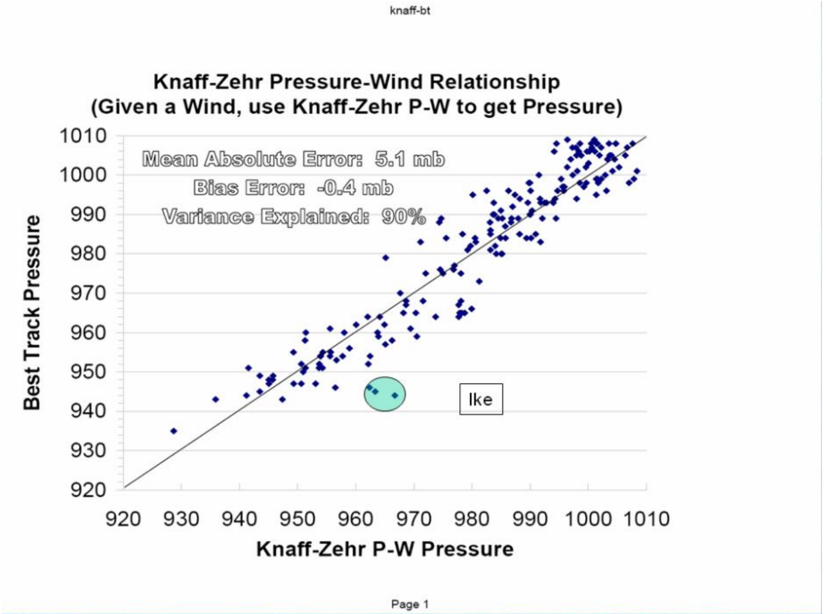
Mean Absolute Error in TPARC (n=14) of (thanks to Joe Courtney)

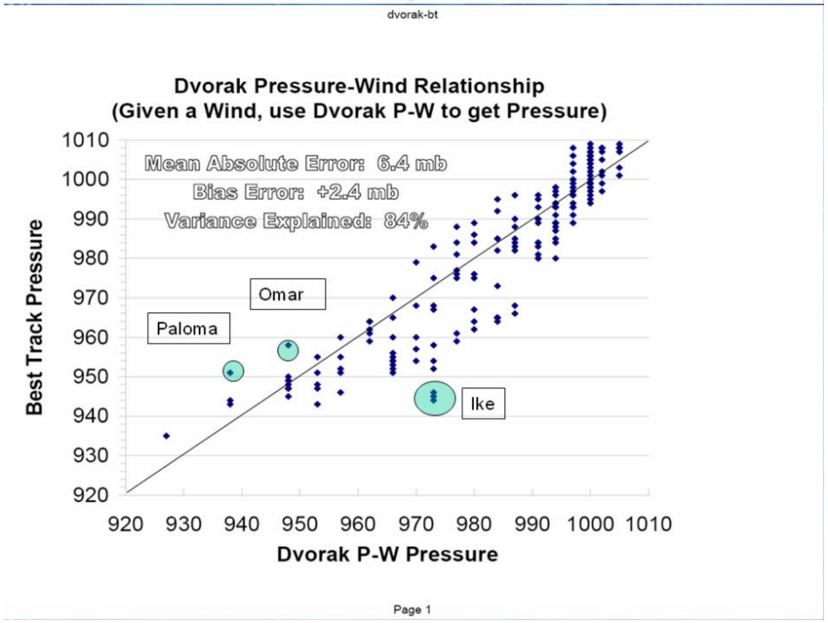
7.9 knots vs. JTWC best track

8.9 knots vs. SFMR maximums

Issues and shortcomings:

- Reliance on operational intensity estimates (i.e., Dvorak influenced)
- Does not account for RMW




Courtesy of Chris Landsea

# WPR: Review of CK09 at RSMC-La Reunion

| Système | Date/heure | Localisation obs | Vmax (kt) | MSLP (hPa) | MSLP_A&H (hPa) | ΔP1 | MSLP_C&K (hPa) | ΔP3 |
|---|---|---|---|---|---|---|---|---|
| **Enok** | 10/02/2007 0130 TU | St Brandon | 62 | 978 | **971** | **-7** | **980** | **2** |
| **Ivan** | 15/02/2008 15 TU | Tromelin | 63* | 969 | **970** | **1** | **980** | **11** |
| **Ernest** | 20/01/2005 06 TU | Mayotte | 43 | 994* | **989** | **-5** | **998** | **4** |
| **Dera** | 09/03/2001 19:55 TU | Europa | 63* | 972* | **970** | **-2** | **980** | **8** |
| **Hansella** | 06/04/1996 02 TU | Rodrigues | 68† | 965 | **966** | **1** | **965** | **0** |
| **Itelle** | 15/04/1996 05 TU | St Brandon | 70* | 970* | **964** | **-6** | **980** | **10** |
| **Colina** | 19/01/1993 14:40 TU | La Reunion | 70 | 975 | **964** | **-11** | **971** | **-4** |
| **Firinga** | 29/01/1989 0800 TU | La Reunion | 78 | 962 | **955** | **-7** | **963** | **1** |
| **Clotilda** | 13/02/1987 1020 TU | La Reunion | 64 | 976 | **969** | **-7** | **971** | **-5** |
| | | | | | **MEA** | ***5,2*** | | ***5,1*** |
| | | | | | **EQM** | ***7,3*** | | ***6,0*** |

Courtesy of Sébastien Langlade

# WPR: Operational Changes

- Australian TC Warning Centers, Fiji, PNG now using CK09 in operations (started 2009-2010 season)
- JTWC is using $V_{max} = 4.4(1010\text{-MSLP})^{0.76}$ based on binned Atkinson and Holliday (1977, 1979) data (started 2008)
- NHC started testing CK09 in 2010 in operations, may influence central pressures in the best track when aircraft recon is not available.

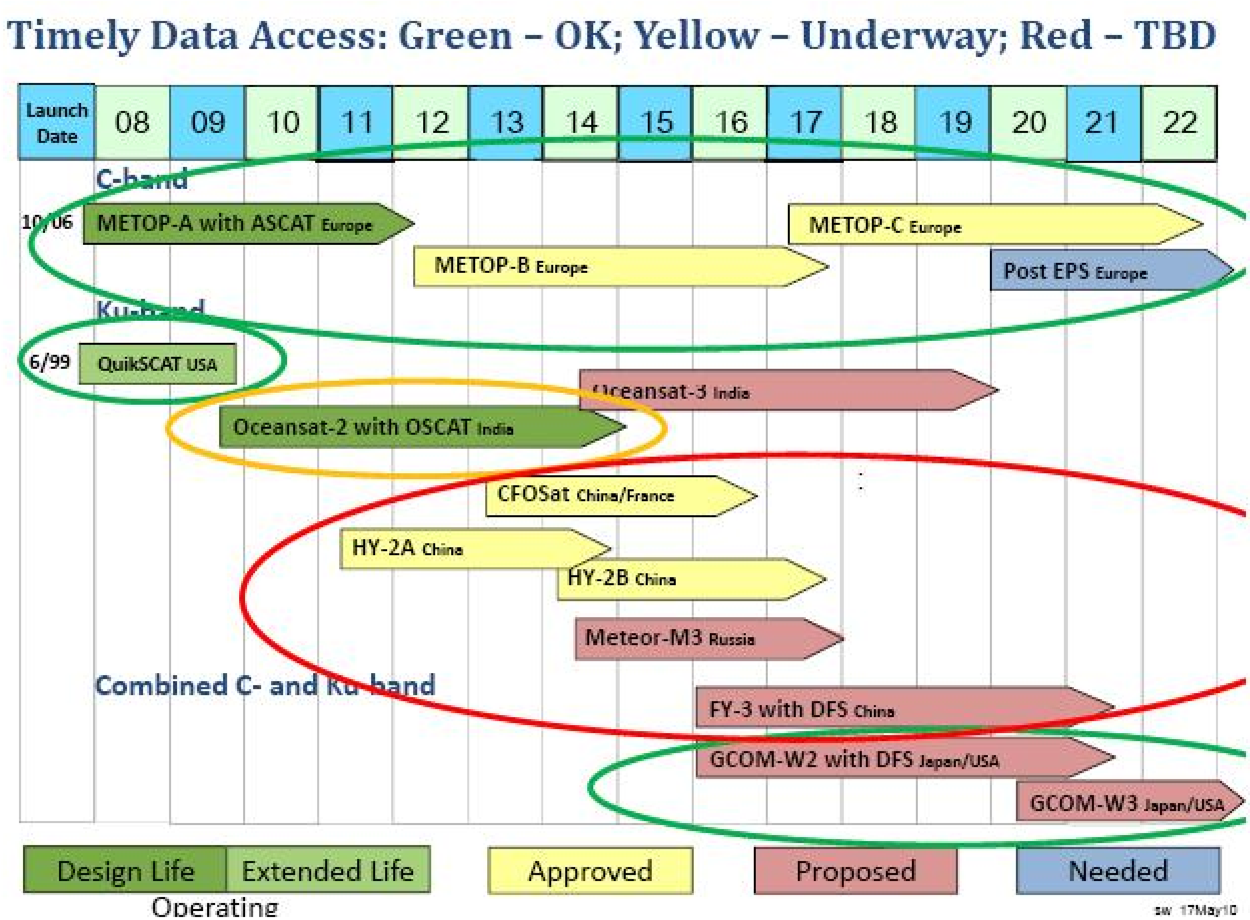
# Known Future Plans at RSMCs

- Tokyo
  - MSW estimations by multi-channel microwave imager data based on the study of Hoshino and Nakazawa (2007) are planned.
  - Warm core structures are planned to be detected based on the study of Bessho et al. (2010) and the CIMSS AMSU intensity algorithm is to be used to estimate MSLP based on the observed warming.
  - Use of all-weather surface wind speeds are planned using 7- and 10-GHz-band imagery of AMSRE and possibly WindSat data.

# Known Future Plans at RSMCs

- La Reunion
  - There are plans to use a Holland wind model (Holland 1980) profile in the operational setting to make adjustments and interpolations to ultimately improve the consistency of wind radii estimates.
  - plans to test the CK09 WPR for operational use in the future

# Recommendations: Remote Sensing Needs



# Recommendations: Remote Sensing Needs

- The WMO should support efforts to insure that the data from the current and continuing satellite OVW missions is both timely and freely available to operational users in formats that are easily used in operations by non-experts and forecasters.
- The WMO should support the continued development of techniques and new technology (e.g. Duel Frequency Scatterometer and All-weather surface winds) that would provide surface wind information in TC environments.

# Recommendations: Towards Universal WPRs

- The WMO should support the development of historical datasets, technologies and methods to improve the estimates of radii of maximum winds associated with TCs.

- The WMO should encourage research that improves the quantification of the relationship between the variations of RMW and MSLP.

- The CK09 method should be tested against any new reliable data sets. The difficulty of obtaining concurrent MSW and MSLP will limit this data set to aircraft reconnaissance and special in situ datasets. Should concerns about apparent weaknesses in the method be validated then potentially the algorithm could be updated. In this regard**, the WMO should encourage the collection of aircraft reconnaissance at lower latitude regions of the world (Australia, Western Pacific, and Indian Ocean).**

- Other TCWCs should consider adopting the CK09 WPR method to focus effort towards a universal methodology.

# Recommendations: Towards Universal Wind Averaging

- TCWCs that routinely provide wind speed estimates using shorter averaging periods than the WMO standard provide those 10-min winds in addition to the peak 1-min/3-min average.
- Routine use of the conversions between various wind averaging periods and the WMO standard (Harper et al. 2010) be adopted by all RSMCs and TCWCs.
- Further research be undertaken into the issue of MSW metrics.
- WMO should promote the adoption of standard operational measures of TC wind structure estimates among RSMCs (thresholds, averaging time periods, maximum vs. average, surface vs. 10-m).

# Data/Science Stewardship Activities

- Best tracks are being reanalyzed by some of the RSMCs
- NOAA/NESDIS IBTrACS program
  - Contains the most complete global set of historical TCs available
  - Combines information from numerous agency TC datasets
  - Simplifies inter-agency comparisons by providing storm data from multiple sources in one place
  - Provides data in popular electronic formats to facilitate analysis
  - Checks the quality of storm inventories, positions, pressures, and wind speeds, passing that information on to the user
- Combining historical data and modern/newer techniques can
  - Develop consistent wind structure/ MSLP for historical cases

# Surface Winds: Momentum Flux

**2006**

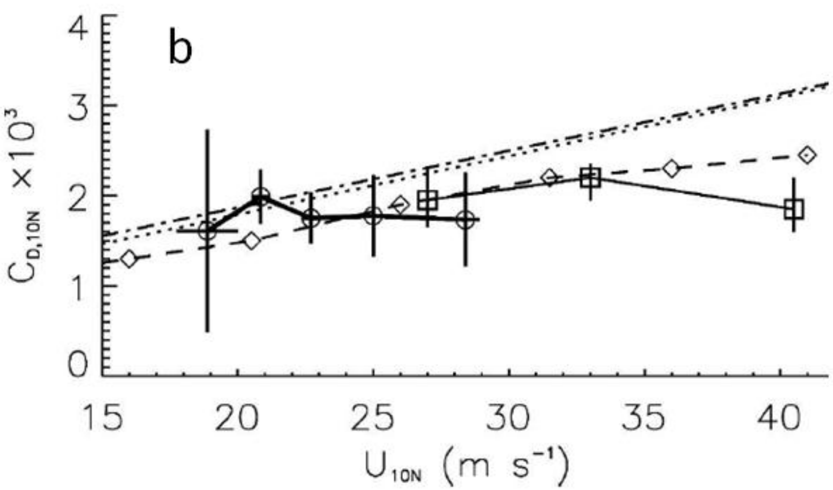
- Before the CBLAST experiment, it was commonly assumed that $C_d$ behaviour at weaker winds less than 20-25 $ms^{-1}$, *viz.* a linear increase with wind speed (e.g. Large and Pond 1981, Smith 1980), continued at greater wind speeds.

**Now**

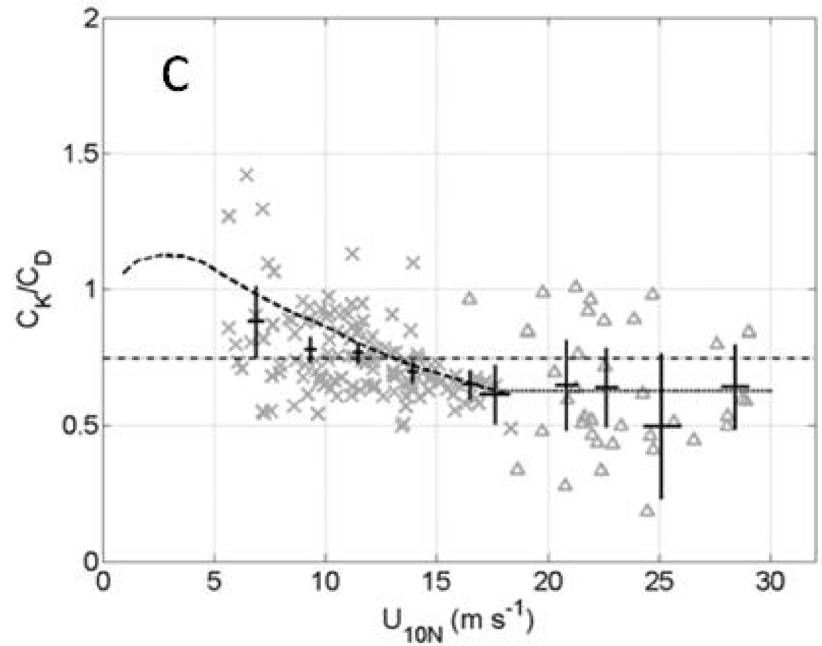
- $C_d$ does not continue to increase with wind speed at TC speeds, but rather levels off or even slightly decreases - momentum flux, and thus drag, at these speeds is relatively weaker than previously assumed.
- Enthalpy exchange coefficient $C_k$ do not appear to be a function of wind speed.

# Surface Winds: Momentum Flux

**Drag Coefficient**




**Enthalpy exchange to drag ratio**




These results impact our understanding and modeling of intensity change and maximum intensity theories.

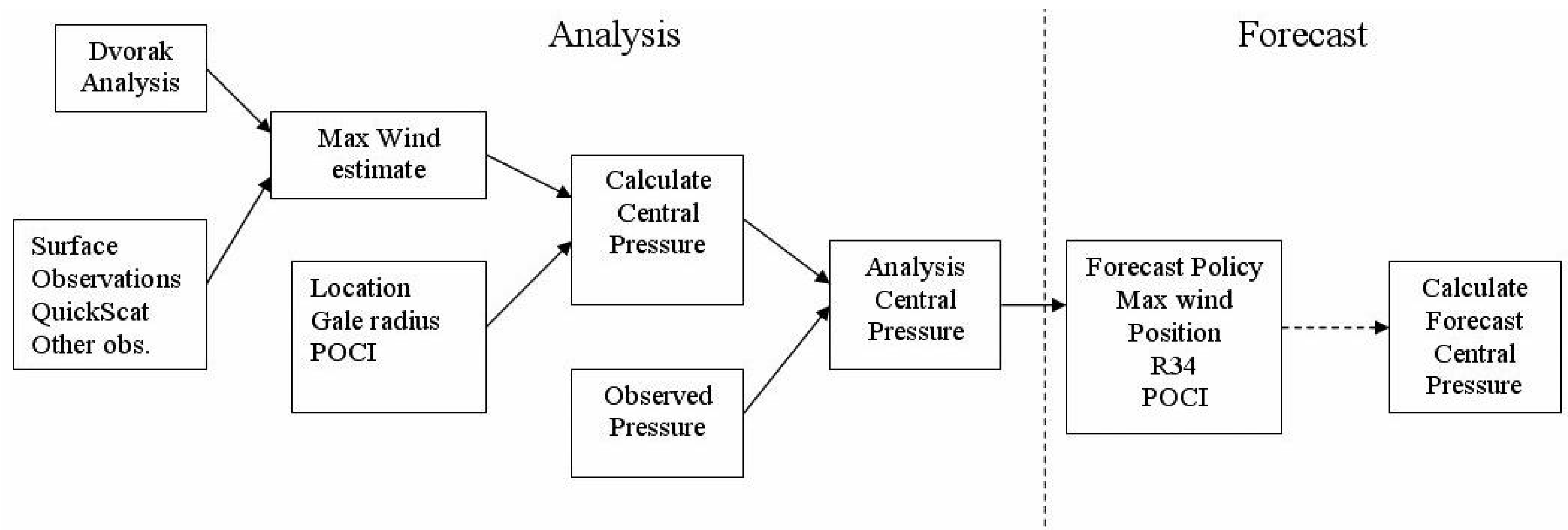
# Surface Winds: Asymmetries

- Wavenumber-one asymmetries in the inner region of the cyclone were related to 1) mature TCs just beginning extra tropical transition (ET) and 2) weakening thermally symmetric TCs. (Fujibe and Kitabatake 2007)

- Wavenumber-one asymmetries in the outer regions of the TC were related to 1) strong TCs in a thermally asymmetric environment and 2) weak TCs at late stages of ET. Symmetric inner core winds were associated with strong mature and symmetric TC. (Fujibe and Kitabatake 2007)

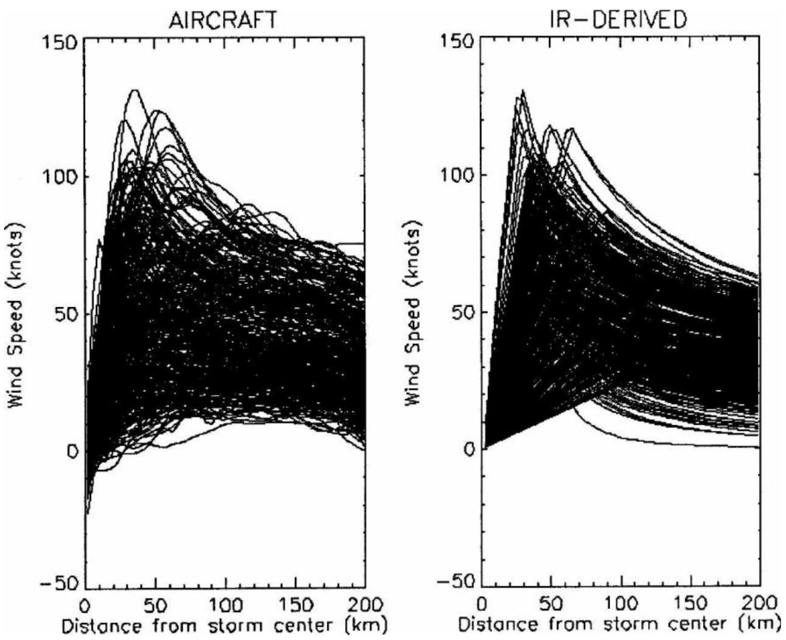
- Using mesoscale analysis data revealed that the azimuthal location of tangential wind maximum relative to storm direction depends strongly on the directional difference between shear and storm motion. (Ueno and Kunii 2009)
  - When the **shear amplitude is smaller** than the TC motion vector, storm asymmetries tended to be on the **right (NH**) with respect to motion.
  - However, under relatively **strong shear** conditions, that are in the same direction as motion, **maximum winds could be shifted to the left with respect to motion**.

# CK09 in Operations

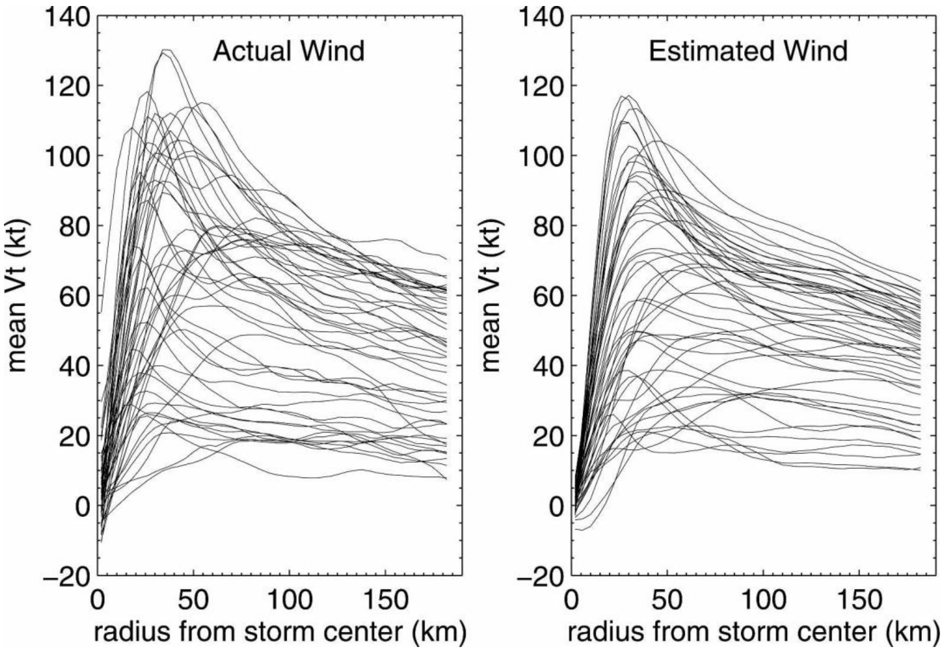


# IR-based winds

**Mueller et al. 2006**




**Kossin et al. 2007**




Given: IR radial profiles and intensity

Rankine Vortex (RMW, Vr=182) Canonical Correlation