Tropical Cyclone Intensity Analysis and Forecasting

Dr. Mark DeMaria
Cooperative Institute for Research in the Atmosphere
Colorado State University, Fort Collins, CO

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NHC, Miami, FL
6 March 2023
Outline

• Estimating the Current Intensity (with poll question)

• Factors that Influence Intensity Change (with poll question)

• Intensity Forecasting Models

• Official Intensity Forecasts

• Intensity Forecast Example (with poll question)
Definition of Intensity

• 1-min maximum sustained surface winds (10 m) in open exposure

• Other intensity measures
  • Minimum sea-level pressure
  • Maximum 2-min winds, 10-min winds, etc
  • Integrated wind measures (IKE, etc)
How Do We Estimate Intensity?

- Satellites (primary)
  - Geostationary infrared & visible images (Dvorak Technique)
  - Microwave soundings (AMSU, ATMS)
  - Scatterometer derived surface winds (ASCAT)

- Surface observations
  - Ships, buoys, land stations (limited)
How Do We Estimate Intensity?

- Aircraft reconnaissance
  - Flight-level winds
  - GPS dropsondes
  - Stepped-Frequency Microwave Radiometer (SFMR)
- Doppler radar
  - Land-based (WSR-88D)
  - Airborne
Example: Estimating the Current Intensity of Hurricane Bill

19 August 1800 UTC

Dvorak classification:

TAFB: **T6.5** = 127 kt
SAB: **T6.0** = 115 kt

3-hr average ADT: **T6.4** = 125 kt
<table>
<thead>
<tr>
<th>Cl Number</th>
<th>MWS (kt)</th>
<th>MSLP (Atlantic)</th>
<th>MSLP (NW Pacific)</th>
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<tbody>
<tr>
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<td>6.5</td>
<td>127</td>
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<td>858 mb</td>
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### Vortex Message

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>A)</td>
<td>Date/Time of center fix</td>
</tr>
<tr>
<td>B)</td>
<td>Center position</td>
</tr>
<tr>
<td>C)</td>
<td>Std surface/min height</td>
</tr>
<tr>
<td>D)</td>
<td>Max sfc wind (visually observed or SFMR)</td>
</tr>
<tr>
<td>E)</td>
<td>Bearing/range of (D) from center</td>
</tr>
<tr>
<td>F)</td>
<td>Max flt-lvl wind on inbound leg</td>
</tr>
<tr>
<td>G)</td>
<td>Bearing/range of (F)</td>
</tr>
<tr>
<td>H)</td>
<td>Minimum pressure</td>
</tr>
<tr>
<td>I)</td>
<td>Max flt-lvl temp outside eyewall/PA</td>
</tr>
<tr>
<td>J)</td>
<td>Max flt-lvl temp inside eye/PA</td>
</tr>
<tr>
<td>K)</td>
<td>DPT/SST at (J)</td>
</tr>
<tr>
<td>L)</td>
<td>Eyewall character (e.g., CLOSED)</td>
</tr>
<tr>
<td>M)</td>
<td>Eye diameter (nm)</td>
</tr>
<tr>
<td>N)</td>
<td>Method of fix</td>
</tr>
<tr>
<td>O)</td>
<td>Fix accuracy (NAV/MET)</td>
</tr>
<tr>
<td>P)</td>
<td>Remarks (includes outbound max)</td>
</tr>
</tbody>
</table>

**SFMR surface wind**

90% from 700 mb

Surface estimate = 0.9 \times 135 \text{ kt} = 122 \text{ kt}
Dropsonde

MBL Wind
(average of lowest 500 m)

WL150 Wind
(average of lowest 150 m)

Surface Wind

Hurricane Georges
19 September 1998
1959 UTC

Wind Speed (mph)
**Northeast eyewall:**

**Surface = 122 kt (gust?)**

- **MBL (lowest 500 m) =** $139 \times 0.8 = 111 \text{ kt}$
- **WL150 (lowest 150 m) =** $134 \times 0.83 = 111 \text{ kt}$
Determine the Official Intensity

- Subjective Dvorak: 127 / 115 kt
- Objective ADT: 125 kt
- SFMR surface wind: 102 kt
- Recon sfc-adjusted flight-level wind: 122 kt
- Dropsonde surface value: 122 kt
- Drop sfc-adjusted WL150: 111 kt
- Drop sfc-adjusted MBL: 111 kt

- OFCL at 1800 UTC: 115 kt

We can only sample a part of the TC. Each observation has strengths and weaknesses. We want a value that is representative of the TC’s circulation.
Poll Question 1
Intensity Estimation
What is the initial intensity?

15/0600 UTC

Dvorak Classifications:

TAFB: T4.5
SAB: T4.5

3-hr average ADT: T4.4
# Dvorak Scale

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</table>
What is the initial intensity given the following estimates?

<table>
<thead>
<tr>
<th>Method</th>
<th>Intensity</th>
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</thead>
<tbody>
<tr>
<td>Subjective Dvorak</td>
<td>77 kt</td>
</tr>
<tr>
<td>Objective Dvorak (ADT)</td>
<td>75 kt</td>
</tr>
<tr>
<td>SFMR Surface Wind</td>
<td>65 kt</td>
</tr>
<tr>
<td>Recon-adjusted Flight-level Wind</td>
<td>60 kt</td>
</tr>
<tr>
<td>Dropsonde Surface Wind</td>
<td>63 kt</td>
</tr>
<tr>
<td>Dropsonde Surface-adjusted MBL</td>
<td>50 kt</td>
</tr>
<tr>
<td>Dropsonde Surface-adjusted WL150</td>
<td>55 kt</td>
</tr>
<tr>
<td>Official Intensity at 0600 UTC</td>
<td>65 kt</td>
</tr>
</tbody>
</table>
Factors Affecting Tropical Cyclone Intensity Changes

• Sea surface temperature (SST) / upper ocean heat content (OHC)

• Environmental winds, esp. vertical wind shear

• Trough interactions

• Temperature and moisture patterns in the storm environment

• Internal effects (e.g. eyewall replacement cycles)

• Interaction with land
Ocean Heat Content estimates the amount of heat available over a depth of warm water. The greater the depth, the more available heat that can be potentially converted to energy.

Sea Surface Temperatures only provide a view of the very top layer of the ocean.
Vertical Wind Shear

DEEP CONVECTION

EXPOSED CENTER

45000 ft
30000 ft
20000 ft
10000 ft
5000 ft
1000 ft
Hurricane Jose 12 UTC 10 Sept 2017

Vertical cross-section of vorticity and potential temperature anomaly from the GFS model for the initialization of the 1200 UTC forecast on September 10
Vertical cross-section of vorticity and potential temperature anomaly from the GFS model for the initialization of the 1200 UTC forecast on September 10
Saharan Air Layer

~500 hPa
~20,000 ft

~700 hPa
~10,000 ft

~850 hPa
~5,000 ft

Marine Layer

~1500 ft

North Africa
Getting Dry Air into the TC Circulation

Saharan Air Layer

Pressure (hPa)

Wind Speed (kt)

GPS Sonde
How Moisture Affects Stability

LCL and LFC

How Moisture Affects Stability

LCL and LFC
Satellite TPW Products Useful for Tracking Dry Air Intrusions

TC-centered TPW Loop for Hurricane Isaac Sept 2018
In addition to large-scale environmental influences, tropical cyclone intensity change can be caused by inner-core processes, such as eyewall replacement cycles:

In stronger hurricanes, we often see a concentric eyewall develop at a larger distance from the center than the radius of the original eyewall.

When this outer eyewall becomes dominant, some weakening usually occurs.

However, this outer eyewall could contract, in which case the hurricane would re-intensify.
Hurricane Matthew Radar Loop
Hurricane Matthew Maximum Wind

Wind Speed (kt)

Date (Month/Day)

Best Track
Sat (TAFB)
Sat (SAB)
ADT
AC (sfc)
AC (fit->sfc)
AC (DVK P->W)
Scatterometer
Surface
Drop (sfc)
Drop (LLM xtrp)
AMSU

Hurricane Matthew
28 September - 9 October 2016
In general, winds weaken over land due to lack of latent heating and increased friction.

Strong winds move inland farther if the TC is moving faster.

Terrain can cause significant local “speed-ups” (sometimes by more than 10 – 30%) over hills, valleys, etc.

Higher elevations in mountainous areas can have stronger winds than at sea level – common on Caribbean islands.
Poll Question 2
Physical Processes
Oceanic Heat Content (kJ/cm\(^2\)) for Hurricane Ian (2022)

What can you infer about possible intensity changes in the next 1 to 2 days from the OHC analysis for Ian?
What can you infer about possible intensity changes in the next 1 to 2 days from the OHC analysis for Ian?

A. The large OHC values along the forecast track suggest high salinity, which will cause Ian to intensify.
B. The large OHC values along the forecast track will limit SST cooling due to mixing, which favors intensification.
C. OHC does not provide information about intensity change because it is only the sea surface temperature that matters.
D. The OHC will have little effect because Ian will move across western Cuba.
E. The OHC will decrease along Ian’s track, making it less likely to intensify.
Weather Forecast Methods

• Classical Statistical Models
  – Use observable parameters to statistical predict future evolution

• Numerical Weather Prediction (NWP)
  – Physically based forecast models

• Statistical-Dynamical Models
  – Use NWP forecasts and other input for statistical prediction of desired variables
    • Station surface temperature, precipitation, hurricane intensity changes

Tropical Cyclone Intensity Forecast Models

• Statistical Models:
  – Decay SHIFOR (Statistical Hurricane Intensity Forecast with inland decay).
    • Based on historical information - climatology and persistence (uses CLIPER track).
    • Baseline for skill of intensity forecasts
  – Trajectory CLIPER
    • Statistically estimate track and intensity tendency instead of change over fixed time
      – e.g., $\frac{dV}{dt}$ instead of $V(t) - V(0)$

• Statistical-Dynamical Models:
  – SHIPS and DSHIPS (Statistical Hurricane Intensity Prediction Scheme):
    • Based on climatology, persistence, and statistical relationships to current and forecast environmental conditions (with inland decay applied in DSHIPS)
  – LGEM (Logistic Growth Equation Model):
    • Uses same inputs as SHIPS, but environmental conditions are variable over the length of the forecast (SHIPS averages over the entire forecast)
    • More sensitive to environmental changes

• Dynamical Models:
  – HWRF, HMON, COAMPS-TC, GFS, UKMET, NOGAPS, ECMWF
Overview of the SHIPS Model

• Multiple linear regression
  \[ y = a_0 + a_1 x_1 + \ldots + a_N x_N \]
  • \( y \) = intensity change at given forecast time
    \( (V_6-V_0), (V_{12}-V_0), \ldots, (V_{120}-V_0) \)
  • \( x_i \) = predictors of intensity change
  • \( a_i \) = regression coefficients

• Different coefficients for each forecast time
• Predictors \( x_i \) averaged over forecast period
• \( x, y \) normalized by subtracting sample mean, dividing by standard deviation
SHIPS Predictors

1. Climatology (days from peak)
2. $V_0$ ($V_{\text{max}}$ at $t=0$ hr)
3. Persistence ($V_0 - V_{-12}$)
4. $V_0 \times \text{Per}$
5. Zonal storm motion
6. Steering layer pressure
7. %IR pixels < -20°C
8. IR pixel standard deviation
9. Max Potential Intensity – $V_0$
10. Square of No. 9
11. Ocean heat content
12. $T$ at 200 hPa
13. $T$ at 250 hPa
14. RH (700-500 hPa)
15. $\theta_e$ of sfc parcel - $\theta_e$ of env
16. 850-200 hPa env shear
17. Shear * $V_0$
18. Shear direction
19. Shear*sin(lat)
20. Shear from other levels
21. 0-1000 km 850 hPa vorticity
22. 0-1000 km 200 hPa divergence
23. GFS vortex tendency
24. Low-level T advection
25. GFS vortex warm core
SHIPS Regression Coefficients at 24 and 96 hr

\[ \text{POT} = \text{Potential Intensity} - \text{Vmax}(0) \]

\[ \text{SHDC} = 200-850 \text{ hPa Shear} \]

\[ \text{VSHR} = \text{Vmax} \times \text{SHDC} \]

\[ \text{LHRD} = \text{SHDC} \times \sin(\text{lat}) \]

\[ \text{TWA} = \text{GFS Vortex} \]

\[ \text{PER} = \text{Persistence} \]
Impact of Land

• Detect when forecast track crosses land
• Replace multiple regression prediction with

\[ \frac{dV}{dt} = - \mu(V-V_b) \]

\[ \mu = \text{climatological decay rate } \sim 1/10 \text{ hr}^{-1} \]
\[ V_b = \text{background intensity over land} \]

• Decay rate reduced if area within 1 deg lat is partially over water
Example of Land Effect
Limitations of SHIPS

• V predictions can be negative
• Most predictors averaged over entire forecast period
  – Slow response to changing synoptic environment
• Strong cyclones that move over land and back over water can have low bias
• Logistic Growth Equation Model (LGEM) relaxes these assumptions
Operational LGEM Intensity Model

\[ \frac{dV}{dt} = \kappa V - \beta \left( \frac{V}{V_{mpi}} \right)^n V \]

(A) \hspace{1cm} (B)

\( V_{mpi} \) = Maximum Potential Intensity estimate

\( \kappa \) = Max wind growth rate (from SHIPS predictors)

\( \beta, n \) = empirical constants \( = \frac{1}{24} \text{ hr}, 2.5 \)

Steady State Solution: \( V_s = V_{mpi} \left( \frac{\beta}{\kappa} \right)^{1/n} \)
LGEM versus SHIPS

• Advantages
  – Prediction equation bounds the solution between 0 and $V_{mpi}$
  – Time evolution of predictors (Shear, etc) better accounted for
  – Movement between water and land handled better because of time stepping

• Disadvantages
  – Model fitting more involved
  – Inclusion of persistence more difficult
  – SHIPS forecasts easier to interpret
LGEM Improvement over SHIPS
Retrospective runs with 2021 Models
2013-2020 Sample

Intensity Error Reduction (%)

Forecast Time (hr)

Atlantic
East Pacific
SHIPS/LGEM extended from 5 to 7 days starting in 2020
SHIPS Diagnostic File

Available in real time from ftp://ftp.nhc.noaa.gov/atcf/stext
### SHIPS Diagnostic File

**Available in real time from** ftp://ftp.nhc.noaa.gov/atcf/stext

**Mean=15 kt**

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<th>18</th>
<th>24</th>
<th>30</th>
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<th>48</th>
<th>60</th>
<th>72</th>
<th>84</th>
<th>108</th>
<th>120</th>
<th>132</th>
<th>144</th>
<th>156</th>
<th>168</th>
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<tbody>
<tr>
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<td>83</td>
<td>87</td>
<td>90</td>
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<td>103</td>
<td>103</td>
<td>97</td>
<td>95</td>
<td>91</td>
</tr>
<tr>
<td>V (KT) LAND</td>
<td>80</td>
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<td>87</td>
<td>90</td>
<td>94</td>
<td>97</td>
<td>102</td>
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<td>103</td>
<td>103</td>
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<tr>
<td>V (KT) LGEM</td>
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<td>86</td>
<td>89</td>
<td>92</td>
<td>99</td>
<td>105</td>
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<td>103</td>
<td>103</td>
<td>92</td>
<td>89</td>
<td>86</td>
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</table>

**Mean=55%**

| SHAR (KT)   | -1 | -2 | -1 | -1 | -4 | -1 | -5 | -2 | -4 | 0  | 0  | 0  | -2 | -2 | -1 | 1  | 2  | 3  | 2  |
|-------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| SHEAR ADJ (KT) | -1 | -2 | -1 | -1 | -4 | -1 | -5 | -2 | -4 | 0  | 0  | 0  | -2 | -2 | -1 | 1  | 2  | 3  | 2  |
| SST (C)     | 29.4| 29.4| 29.3| 29.4| 29.4| 29.3| 29.3| 29.5| 29.8| 29.9| 29.8| 29.7| 29.8| 29.6| 29.4| 29.6| 29.6| 29.6|
| POT. INT. (KT) | 159 | 159 | 157 | 158 | 158 | 156 | 156 | 159 | 162 | 160 | 163 | 163 | 165 | 161 | 164 | 159 | 156 | 159 |
| ADCP INT. (KT) | 147 | 144 | 141 | 142 | 142 | 136 | 138 | 141 | 140 | 133 | 137 | 138 | 135 | 137 | 131 | 129 | 129 | 129 |
| ZOO MB (C) | -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3| -53.3|
| 200 MB VXT (C) | -0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.6 | 0.6 | 0.6 | 1.0 | 0.9 | 1.0 | 1.3 | 0.9 | 0.8 | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 |
| THE DEV (C) | 11 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| 700-500 MB RH | 56 | 56 | 57 | 57 | 59 | 59 | 58 | 63 | 61 | 61 | 64 | 64 | 65 | 60 | 62 | 56 | 55 | 50 | 50 |
| MODEL VTX (KT) | 12 | 13 | 14 | 14 | 16 | 17 | 20 | 21 | 23 | 22 | 22 | 27 | 26 | 28 | 26 | 26 | 29 | 27 | 28 |
| 200 MB DIV | 36 | 30 | 14 | 49 | 30 | 13 | 14 | -3 | 25 | -3 | 25 | 10 | 60 | 23 | 63 | 49 | 89 | 89 | 89 |
| 700-500 TADV | 0 | 1 | 0 | 2 | 1 | 6 | -1 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 | -4 |

**Mean=30kJ/cm²**

| LAND (KM) | 397 | 444 | 513 | 565 | 622 | 617 | 503 | 332 | 184 | 84 | 44 | 46 | 78 | 77 | 61 | -61 | -146 | -77 |
|-----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| LAT (DEG N) | 22.8 | 23.6 | 24.3 | 24.9 | 25.4 | 26.1 | 26.5 | 26.8 | 27.0 | 27.2 | 27.5 | 27.9 | 28.5 | xx.x | xx.x | xx.x | xx.x | xx.x |
| LONG (DEG W) | 68.0 | 68.8 | 69.5 | 70.4 | 71.3 | 73.2 | 75.0 | 76.7 | 78.2 | 79.3 | 80.3 | 81.0 | 81.5 | xx.x | xx.x | xx.x | xx.x | xx.x |
| STM SPEED (KT) | 11 | 10 | 10 | 10 | 9 | 9 | 8 | 7 | 6 | 6 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |

**Heat Content**

| 45 | 45 | 50 | 58 | 56 | 40 | 30 | 22 | 15 | 10 | 16 | 7 | 4 |

**Forecast Track from OFCI**

**Initial Heading/Speed (Deg/KT):** 330/11

**T-12 Max Wind:** 75

**Pressure of Steering Level (MB):** 623

**Goes IR BRIGHTNESS TEMP, STD DEV:** 14.5 (MEAN=14.5)

**% Goes IR Pixels with T < -20 C:** 50-200 KM RAD: 65.0 (MEAN=65.0)

**Prelim RI Prob (DV, GE, 35 KT IN 36 HR):** 18.7
SHIPS Forecasts For East Pacific Hurricane Georgette (2016)

SHIPS forecasts often miss peak intensity during rapid intensification periods.
24 hr Intensity Change PDF

Atlantic Over-Water Cases

Mean: 4.3 kt  Std Dev: 15 kt  Range -55 kt to +95 kt

4th percentile: -25 kt  96th percentile: +30 kt
The Rapid Intensification Index

• Define RI as 30 kt or greater intensity increase in 24 hr
• Find subset of SHIPS predictors that separate RI and non-RI cases
• Use training sample to convert discriminant function value to a probability of RI
• AL and EP/CP versions include more thresholds (25, 30, 35, 40 kt changes, etc)
Linear Discriminant Analysis

• 2 class example
  – Objectively determine which of two classes a data sample belongs to
    • Rapid intensifier or non-rapid intensifier
  – Predictors for each data sample provide input to the classification

• Discriminant function (DF) linearly weights the inputs

\[ DF = a_0 + a_1x_1 + \ldots + a_Nx_N \]

• Weights chosen to maximize separation of the classes
Graphical Interpretation of the Discriminant Function

DF chosen to best separate red and blue points
RII Discriminators

1. Previous 12 h max wind change (persistence)
2. Current intensity
3. Maximum Potential Intensity - Current intensity
4. Oceanic Heat Content
5. 200-850 hPa shear magnitude (0-500 km)
6. 200 hPa divergence (0-1000 km)
7. Mid-level dry air parameter
8. TPW < 45 mm in upshear direction
9. IR imagery cold pixel variable
10. Azimuthal standard deviation of IR brightness temperature
PATRICIA INTENSIFIED FROM 40 KT TO 185 KT IN 48 HOURS!

21 OCT 2015 12 UTC

23 OCT 2015 12 UTC
### RI Guidance

#### Hurricane Patricia (2015 - East Pacific)

![Table showing RI guidance for Hurricane Patricia](image)

**RI Guidance for Hurricane Patricia (2015 - East Pacific)**

**EAST PACIFIC 2021 SHIPS INTENSITY FORECAST**

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**2021 E. Pacific RI INDEX EP202015 PATRICIA 10/22/15 06 UTC**

**Predictor**

- **POT = MPI-VMAX (KT)**
- **12 HR PERSISTENCE (KT)**
- **D200 (10**°**7s-1)**
- **850-200 MB SHEAR (KT)**
- **MAXIMUM WIND (KT)**
- **STD DEV OF IR BR TEMP**
- **MAXIMUM WIND (KT)**
- **BL DRY-AIR FLUX (W/M^2)**
- **HEAT CONTENT (KJ/CM^2)**
- **%area of TPW <45 mm upshear**
- **2nd PC OF IR BR TEMP**

**Value**

- **RI Predictor**
- **Range**
- **Scaled Value (0-1)**
- **% Contribution**

**Example**

- **SHIPS Prob RI for 20kt/12hr RI threshold = 100%**
  - is 15.9 times climatological mean (6.3%)
GOES-16 Imagery and Lightning Locations
Using GLM to Improve the RII

• Experimental tests using lightning in RII show improved skill
• Plan to run real-time experimental version this season

RII PREDICTORS

POT: SST Potential
SHDC: Shear
D200: Divergence
PER: Persistence
PC30: % IR pixels < -30°C
TBSTDo: GOES IR brightness temp standard deviation
OHC: Ocean heat content
RHLO: Relative humidity
LM02: Inner-core lightning
LM24: Outer-rainband lightning

Stevenson et al. (2014, MWR)
Regional Models: HWRF, HMON, COAMPS-TC

Global Models: NCEP GFS, UKMET, ECMWF, Navy NAVGEM, Canadian

These models have forecast errors due to...

- sparse observations
- inadequate resolution (need to go down to a few km grid spacing; the HMON and HWRF, our highest-resolution operational hurricane models, are currently 1-2 km).
- incomplete understanding and simulation of basic physics of intensity change.
- problems with representation of shear.

Steady improvements over past few years due to...
### HAFSv1.0

<table>
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<tr>
<th>Domain*</th>
<th>Resolution*</th>
<th>DA/VI</th>
<th>Ocean/Wave Coupling</th>
<th>Physics</th>
<th>Basins</th>
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<td><strong>HFSA</strong></td>
<td>Storm-centric with one moving nest, parent: ~78x75 degree, nest: ~12x12 degree</td>
<td>Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top</td>
<td>Vmax &gt; 50 kt warm-cycling VI and 4DEnVar DA</td>
<td>Two-way HYCOM, one-way WW3 coupling for NHC AOR</td>
<td>Physics suite-1</td>
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<td><strong>HFSB</strong></td>
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<td>Two-way HYCOM No Wave</td>
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**CMEPS**

- **ATM (FV3)**
- **OCN (HYCOM/MOM6)**
- **WAVE (WWIII)**
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<tr>
<th></th>
<th>Suite 1</th>
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<td><strong>Land/ocean Surface</strong></td>
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<td>NOAH LSM VIIRS veg type HYCOM</td>
<td>Ek et al. (2003) …</td>
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<td><strong>Surface Layer</strong></td>
<td>GFS, HWRF TC-specific sea surface roughnesses</td>
<td>GFS, HWRF TC-specific sea surface roughnesses</td>
<td>Miyakoda and Sirutis (1986); Long (1984, 1986)</td>
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<td>Sa-TKE-EDMF, TC-related calibration, ( tc_{pbl}=1 ), mixing length tuning</td>
<td>Han et al. (2019) *Chen et al. (2022)</td>
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<td><strong>Radiation</strong></td>
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<td><strong>Cumulus convection (deep &amp; shallow)</strong></td>
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<td>Han et al. (2017)</td>
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<td>Unified GWD (orographic on/convective off)</td>
<td>Unified GWD (orographic on/convective off)</td>
<td>Alpert et al. (1988)</td>
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</table>
Final configurations: Track/intensity forecast skills (NATL)
Late Model Verification

Track

Intensity

~10% max improvement

~10% max improvement
Consensus Forecasts

- **ICON** – Consensus that is computed by averaging the forecast intensities from Decay-SHIPS, LGEM, HWRF, HMON, COAMPS-TC.

- **IVCN** – Consensus that requires at least 2 of Decay-SHIPS, LGEM, HWRF, HMON and COAMPS-TC.

- **FSSE (Florida State Superensemble)** – Consensus that uses dynamical models and the previous NHC forecast. The FSSE learns from past performances of its member models in a “training phase”, then accounts for the model biases.

- **HCCA (HFIP Corrected Consensus Approach)** – FSSE approach adapted to NHC operations
Fig. 5. NHC and intensity model skill for (a) 2004–06, (b) 2008–10, (c) 2013–15, and (d) 2017–19. NHC skill is shown in black, and the various models are depicted in the other colors. The number of verifying events at each forecast lead time is shown above the x axis. Models not previously defined: NHC forecasts (OFCL), HWRF interpolated forecasts (HWFI), GFDL interpolated forecasts (GFDI), GFDL run off the U.S. Navy Global Atmospheric Prediction System (GFNI), Florida State Super Ensemble (FSSE), GFS interpolated forecasts (GFSI), and ECMWF interpolated forecasts (EMXI).
NHC Official Intensity Forecast

• Based on statistical guidance from SHIPS and LGEM, qualitative guidance from dynamical models and consensus.
• HWRF and COAMPS TC more skillful last few years
• Persistence is used quite a bit!
• Obvious signs in the environment, i.e. cooler waters, increasing upper-level winds, are taken into account.
• Generally corresponds to what is normal for a storm in any particular situation (e.g. the standard Dvorak development rate).
• Tends to be conservative; extreme events are almost never forecast.
• For forecasts 48 hr and beyond, the average error is roughly 1 SSHWS Category (10-15 knots).
Atlantic Intensity Error Trends

Only small improvements between 1970-2009, but errors have decreased more sharply this decade.

Figure from J. Cangialosi (2022)
Poll Question 3

Intensity

Forecast
Part 2: 36-Hour Forecast Intensity

Model Track Guidance
Water Vapor Imagery and Mid- to Upper Level Winds

Infrared Imagery (Window Channel)

Total Precipitable Water

Oceanic Heat Content
### SHIPS/LGEM Model Guidance

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**FORECAST TRACK FROM OFCI**

INITIAL HEADING/SPEED (DEG/KT): 290/2

CK, CY: -1/1

T-12 MAX WIND: 60

PRESSURE OF STEERING LEVEL (MB): 591 (MEAN=618)

GOES IR BRIGHTNESS TEMP, STD DEV. 50-200 KM RAD: 10.1 (MEAN=14.5)

% GOES IR PIXELS WITH T < -20 C 50-200 KM RAD: 74.0 (MEAN=65.0)

PRELIM RI PROB (DV .GE. 30 KT IN 24 HR): 10.4
# Rapid Intensification Index

** ** ATLANTIC RI INDEX  
(SHIPS−RII PREDICTOR TABLE for 30 KT OR MORE MAXIMUM WIND INCREASE IN NEXT 24−h)  

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Value</th>
<th>RI Predictor</th>
<th>Range</th>
<th>Scaled Value(0−1)</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 HR PERSISTENCE (KT)</td>
<td>5.0</td>
<td>−49.5 to 33.0</td>
<td></td>
<td>0.66</td>
<td>6.3</td>
</tr>
<tr>
<td>850-200 MB SHEAR (KT)</td>
<td>12.5</td>
<td>28.8 to 2.9</td>
<td></td>
<td>0.63</td>
<td>2.7</td>
</tr>
<tr>
<td>HEAT CONTENT (KJ/cm²)</td>
<td>38.4</td>
<td>0.0 to 155.1</td>
<td></td>
<td>0.25</td>
<td>0.8</td>
</tr>
<tr>
<td>STD DEV OF IR BR TEMP</td>
<td>10.1</td>
<td>37.5 to 2.9</td>
<td></td>
<td>0.79</td>
<td>3.3</td>
</tr>
<tr>
<td>2nd PC OF IR BR TEMP</td>
<td>0.1</td>
<td>2.8 to −3.1</td>
<td></td>
<td>0.45</td>
<td>1.9</td>
</tr>
<tr>
<td>MAXIMUM WIND (kt)</td>
<td>65.0</td>
<td>22.5 to 121.0</td>
<td></td>
<td>0.89</td>
<td>1.3</td>
</tr>
<tr>
<td>D200 (10**7s−1)</td>
<td>85.6</td>
<td>−23.1 to 181.5</td>
<td></td>
<td>0.53</td>
<td>0.9</td>
</tr>
<tr>
<td>POT = MPI−VMAX (KT)</td>
<td>79.6</td>
<td>28.4 to 139.1</td>
<td></td>
<td>0.46</td>
<td>1.1</td>
</tr>
<tr>
<td>% AREA WITH TPW &lt;45 mm</td>
<td>0.0</td>
<td>100.0 to 0.0</td>
<td></td>
<td>1.00</td>
<td>1.0</td>
</tr>
<tr>
<td>BL DRY−AIR FLUX (w/m²)</td>
<td>156.8</td>
<td>960.3 to −67.1</td>
<td></td>
<td>0.78</td>
<td>0.0</td>
</tr>
</tbody>
</table>

SHIPS Prob RI for 20kt/ 12hr RI threshold= 11% is 2.0 times sample mean (5.5%)  
SHIPS Prob RI for 25kt/ 24hr RI threshold= 33% is 2.8 times sample mean (11.6%)  
SHIPS Prob RI for 30kt/ 24hr RI threshold= 19% is 2.7 times sample mean (7.2%)  
SHIPS Prob RI for 35kt/ 24hr RI threshold= 15% is 3.7 times sample mean (4.2%)  
SHIPS Prob RI for 40kt/ 24hr RI threshold= 11% is 3.8 times sample mean (2.8%)  
SHIPS Prob RI for 45kt/ 36hr RI threshold= 21% is 4.3 times sample mean (4.9%)  
SHIPS Prob RI for 55kt/ 48hr RI threshold= 20% is 3.8 times sample mean (5.1%)
Answer: 36 hr Max Wind = 100 kt
NHC Official Forecast was 75 kt

Bonus Question: What TC was this?
Concluding Remarks

• There is less skill for intensity forecasting than track forecasting but considerable improvements have been made in last decade.

• Current guidance is provided mainly by HWRF, DSHIPS, LGEM, IVCN and more recently, COAMPS-TC, HMON, GFS, FSSE and HCCA.
  – Dynamical models more skillful for basin-wide intensity forecasts.
  – Statistical methods more generally skillful for identifying RI cases.
  – HWRF/HMON to be replaced by two versions of HAFS in 2023.

• We still have significant difficulty in forecasting rapidly intensifying and rapidly weakening storms.

• The main hope for the future lies in improved dynamical models, coupled with enhanced observations and understanding of the hurricane’s inner core - Hurricane Forecast Improvement Project (HFIP).

• Consensus approaches should also lead to future improvements.

• GOES-16/-18 is providing new imagery and lightning data for dynamical and statistical-dynamical intensity models.