Tropical Cyclone Intensity Analysis and Forecasting

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NHC, Miami, FL

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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)

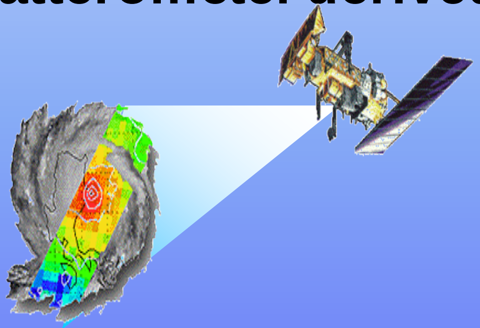
Definition of Intensity

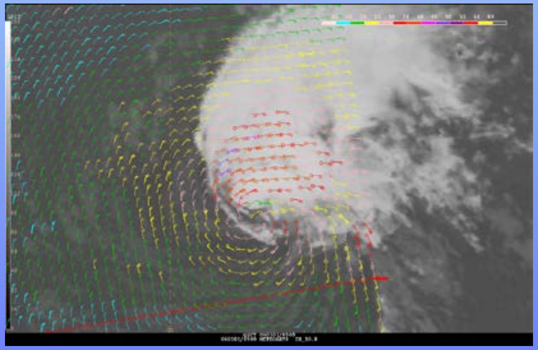
- 1-min maximum sustained surface winds (10 m) in open exposure
- Other intensity measures
  - Minimum sea-level pressure
  - Maximum 2-min winds, 10-min winds, etc
  - Integrated wind measures (IKE, etc)

How Do We Estimate Intensity?

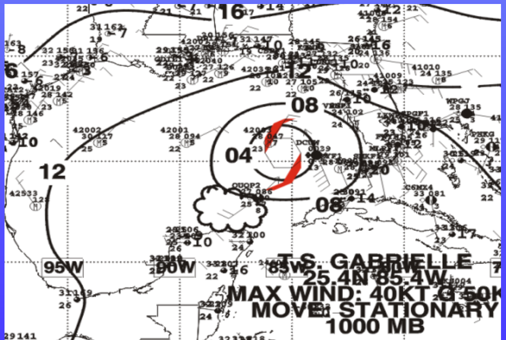
- **Satellites (primary)**
  - **Geostationary infrared & visible images (Dvorak Technique)**

  - **Microwave soundings (AMSU, ATMS)**
  - **Scatterometer derived surface winds (ASCAT)**



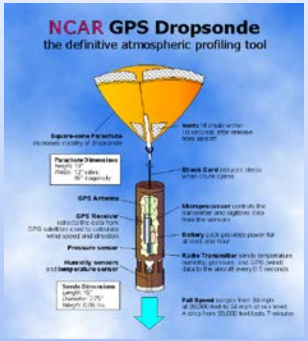


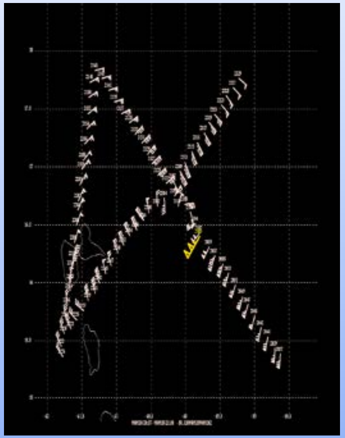
- **Surface observations**
  - **Ships, buoys, land stations (limited)**

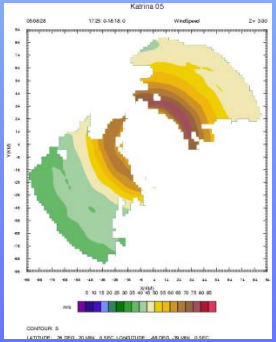


How Do We Estimate Intensity?

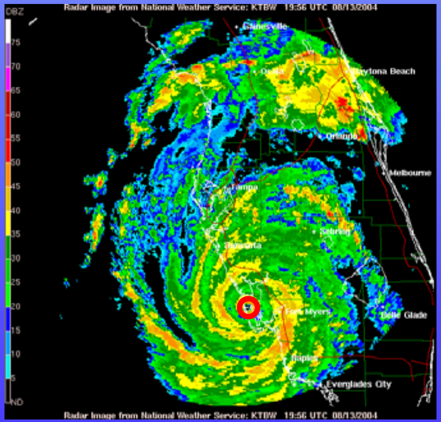
- **Aircraft reconnaissance**
  - **Flight-level winds**
  - **GPS dropsondes**
  - **Stepped-Frequency Microwave Radiometer (SFMR)**

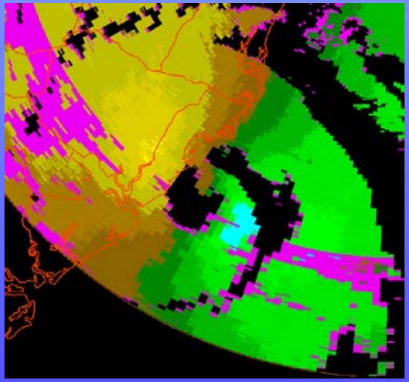




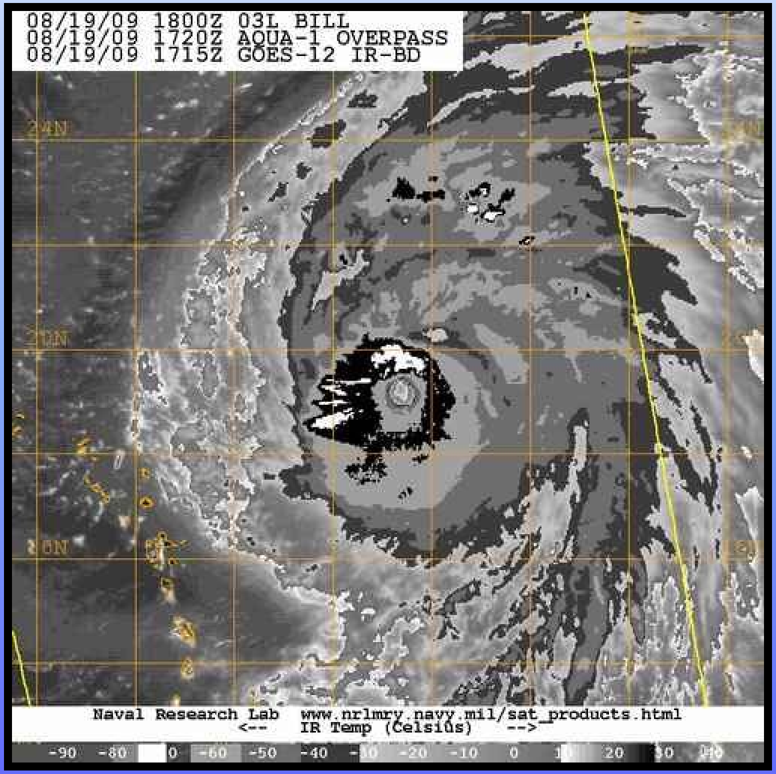


- **Doppler radar**
  - **Land-based (WSR-88D)**
  - **Airborne**





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

Dvorak Scale

CI Number	MWS (kt)	MSLP (Atlantic)	MSLP (NW Pacific)
1.0	25		
1.5	25		
2.0	30	1009 mb	1000 mb
2.5	35	1005 mb	997 mb
3.0	45	1000 mb	991 mb
3.5	55	994 mb	984 mb
4.0	65	987 mb	976 mb
4.5	77	979 mb	966 mb
5.0	90	970 mb	954 mb
5.5	102	960 mb	941 mb
6.0	115	948 mb	927 mb
6.5	127	935 mb	914 mb
7.0	140	921 mb	898 mb
7.5	155	906 mb	879 mb
8.0	170	890 mb	858 mb

Vortex Message

```
000
URNT12 KNHC 191819 CCA
VORTEX DATA MESSAGE   AL032009
A. 19/17:57:30Z
B. 19 deg 16 min N
  056 deg 55 min W
C. 700 mb 2665 m
D. 102 kt
E. 056 deg 24 nm
F. 134 deg 135 kt
G. 055 deg 27 nm
H. 947 mb
I. 11 C / 3045 m
J. 19 C / 3047 m
K. 6 C / NA
L. OPEN SW
M. C32
N. 12345 / 07
O. 0.02 / 0.5 nm
P. AF303 0203A BILL              OB 12 CC
MAX FL WIND 135 KT NE QUAD 17:48:30Z
;
```

SFMR surface wind

90% from 700 mb
Surface estimate =
0.9 × 135 kt = 122 kt

A) Date/Time of center fix

B) Center position

C) Std surface/min height

D) Max sfc wind (visually observed or SFMR)

E) Bearing/range of (D) from center

F) Max flt-lvl wind on inbound leg

G) Bearing/range of (F)

H) Minimum pressure

I) Max flt-lvl temp outside eyewall/PA

J) Max flt-lvl temp inside eye/PA

K) DPT/SST at (J)

L) Eyewall character (e.g., CLOSED)

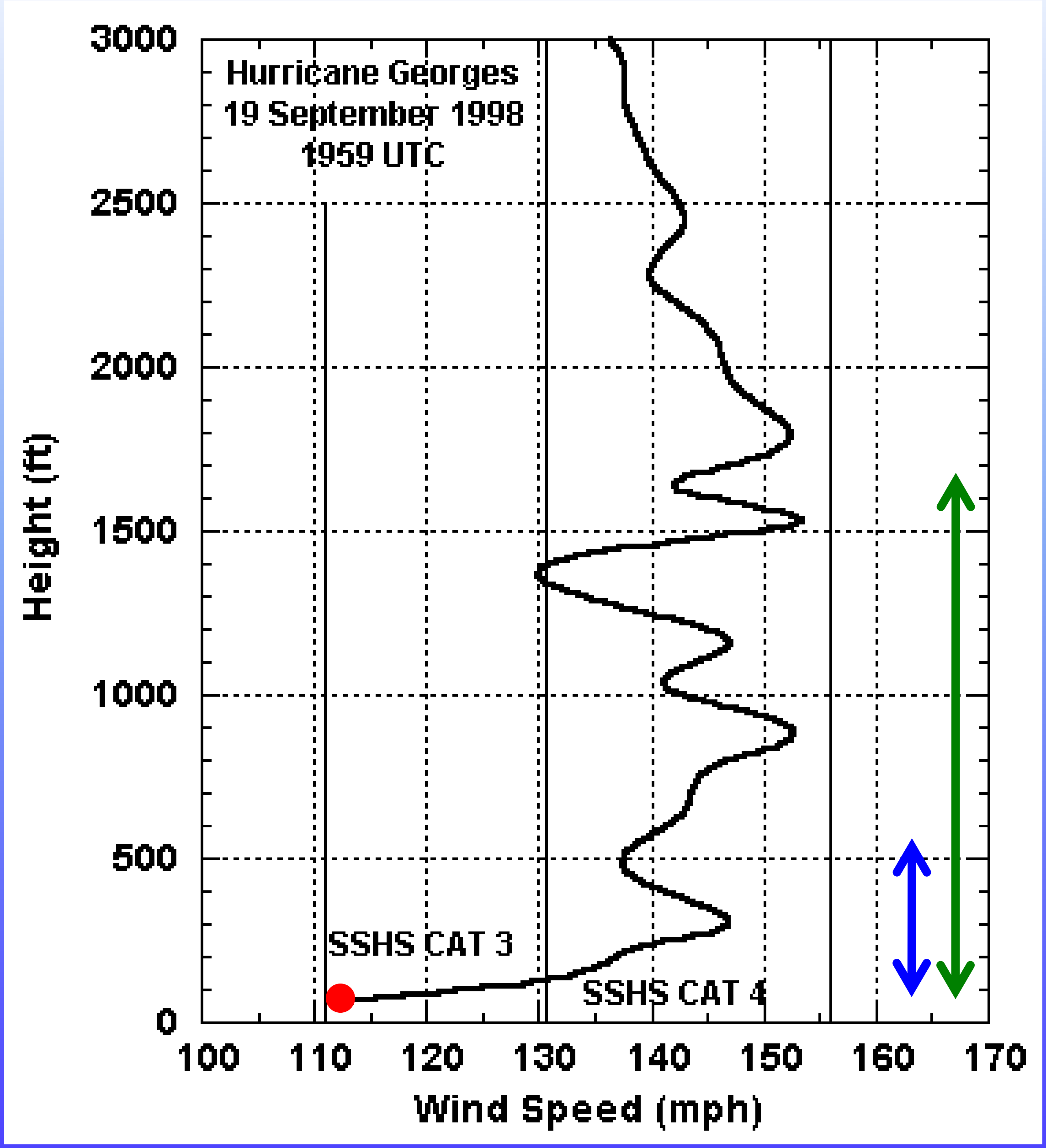
M) Eye diameter (nm)

N) Method of fix

O) Fix accuracy (NAV/MET)

P) Remarks (includes outbound max)

Dropsonde



MBL Wind
(average of lowest 500 m)

WL150 Wind
(average of lowest 150 m)

Surface Wind

Dropsonde

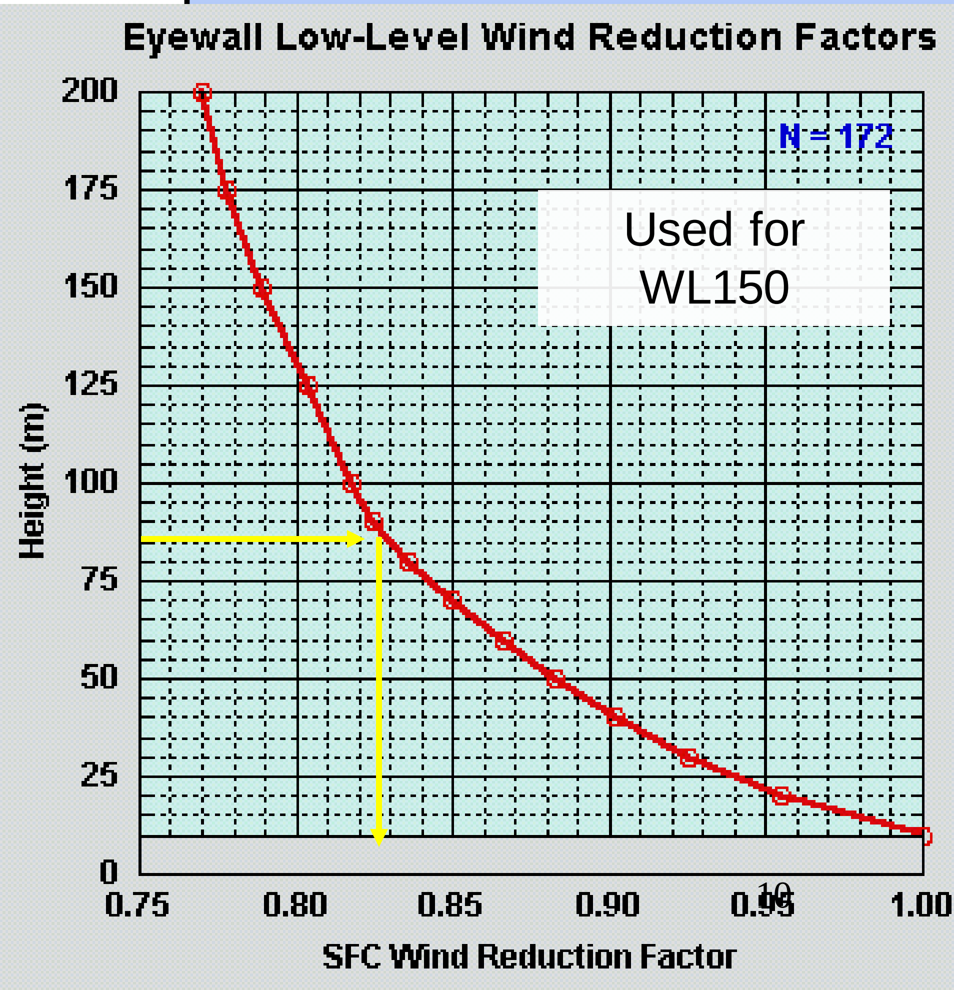
```
000
UZNT13 KNHC 192344
XXAA  69237 99203 70578 07807 99955 25600 09122 00912 ///// /////
92277 23801 10140 85016 20600 11641 70686 148// 14599 88999 77999
31313 09608 82322
61616 NOAA3 WX03A BILL4 OB 11
62626 REL 2033N05779W 232240 SPG 2042N05793W 232707 WL150 09134 0
86 DLM WND 12128 954696 MBL WND 10139 LST WND 011=
XXBB  69238 99203 70578 07807 00955 25600 11941 24400 22920 23802
33741 17000 44719 16001 55695 146//
21212 00955 09122 11952 08618 22943 09640 33938 09646 449
55916 10646 66896 11139 77749 13635 88740 14618 99695 150
31313 09608 82322
61616 NOAA3 WX03A BILL4 OB 11
62626 REL 2033N05779W 232240 SPG 2042N05793W 232707 WL150
86 DLM WND 12128 954696 MBL WND 10139 LST WND 011=
```

Northeast eyewall:

Surface = 122 kt (gust?)

MBL (lowest 500 m) =
$139 \times 0.8 = 111$ kt

WL150 (lowest 150 m) =
$134 \times 0.83 = 111$ 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

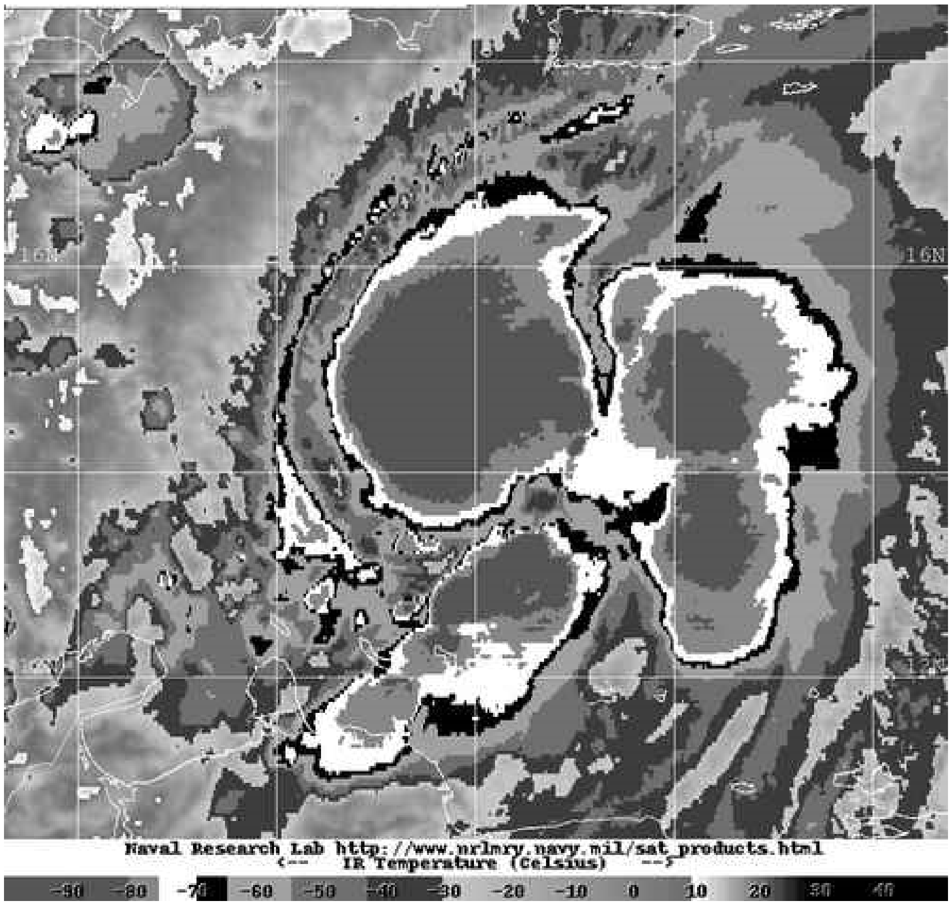
We want a value that is

***representative* of the TC's circulation**

Poll Question 1
Intensity Estimation

What is the initial intensity?

15/0600 UTC



Dvorak Classifications:

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7.5	155	906 mb	879 mb
8.0	170	890 mb	858 mb

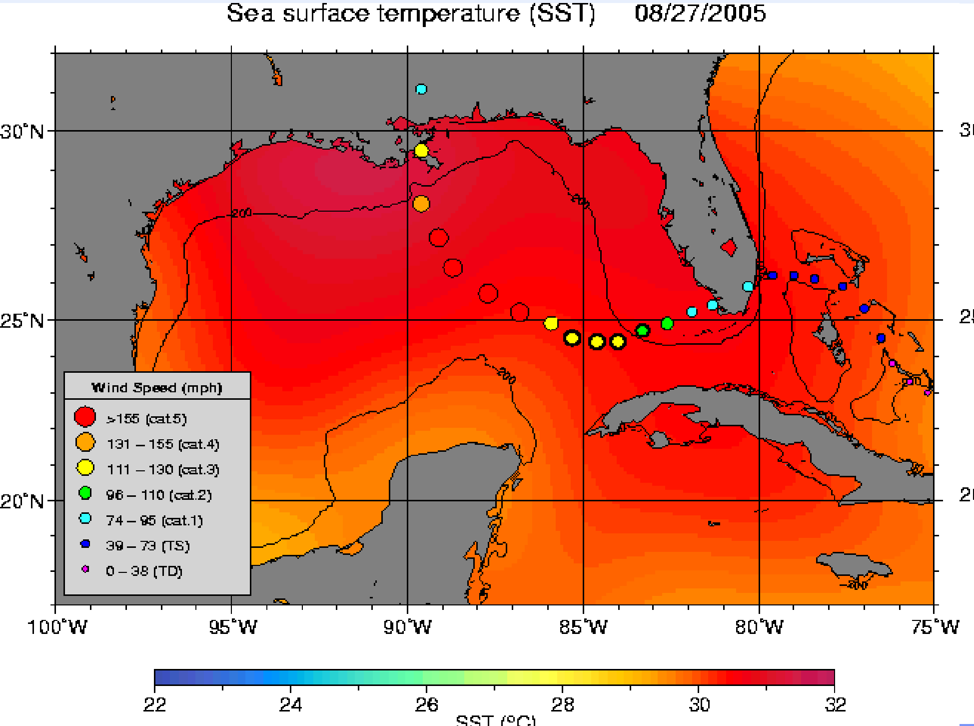
What is the initial intensity given the following estimates?

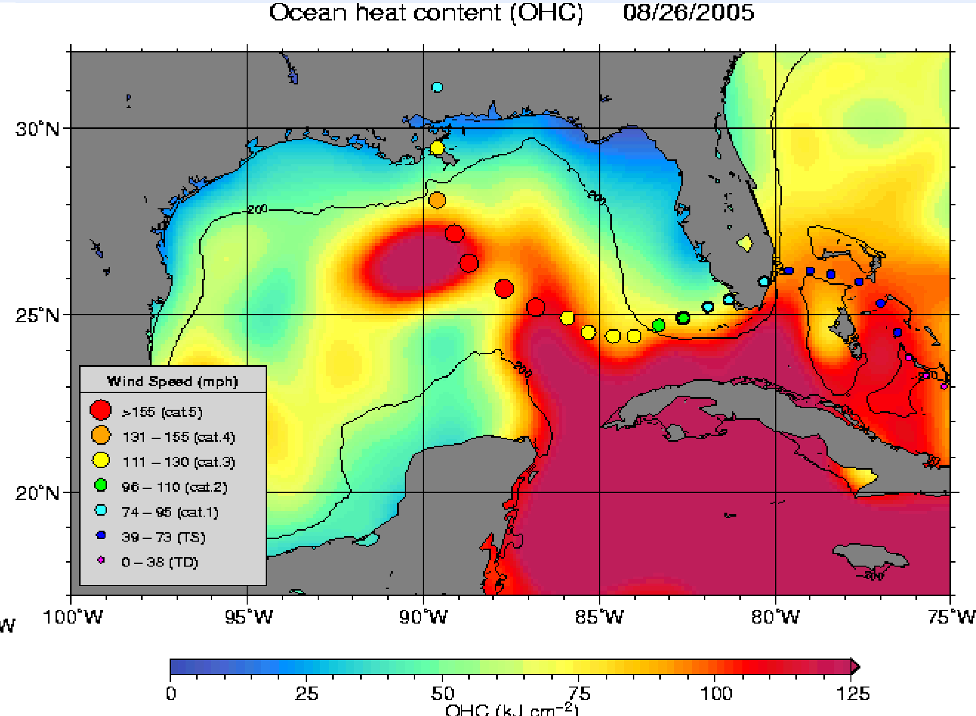
Subjective Dvorak	77 kt
Objective Dvorak (ADT)	75 kt
SFMR Surface Wind	65 kt
Recon-adjusted Flight-level Wind	60 kt
Dropsonde Surface Wind	63 kt
Dropsonde Surface-adjusted MBL	50 kt
Dropsonde Surface-adjusted WL150	55 kt
Official Intensity at 0600 UTC	65 kt

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**

SST vs. OHC





Sea Surface Temperatures

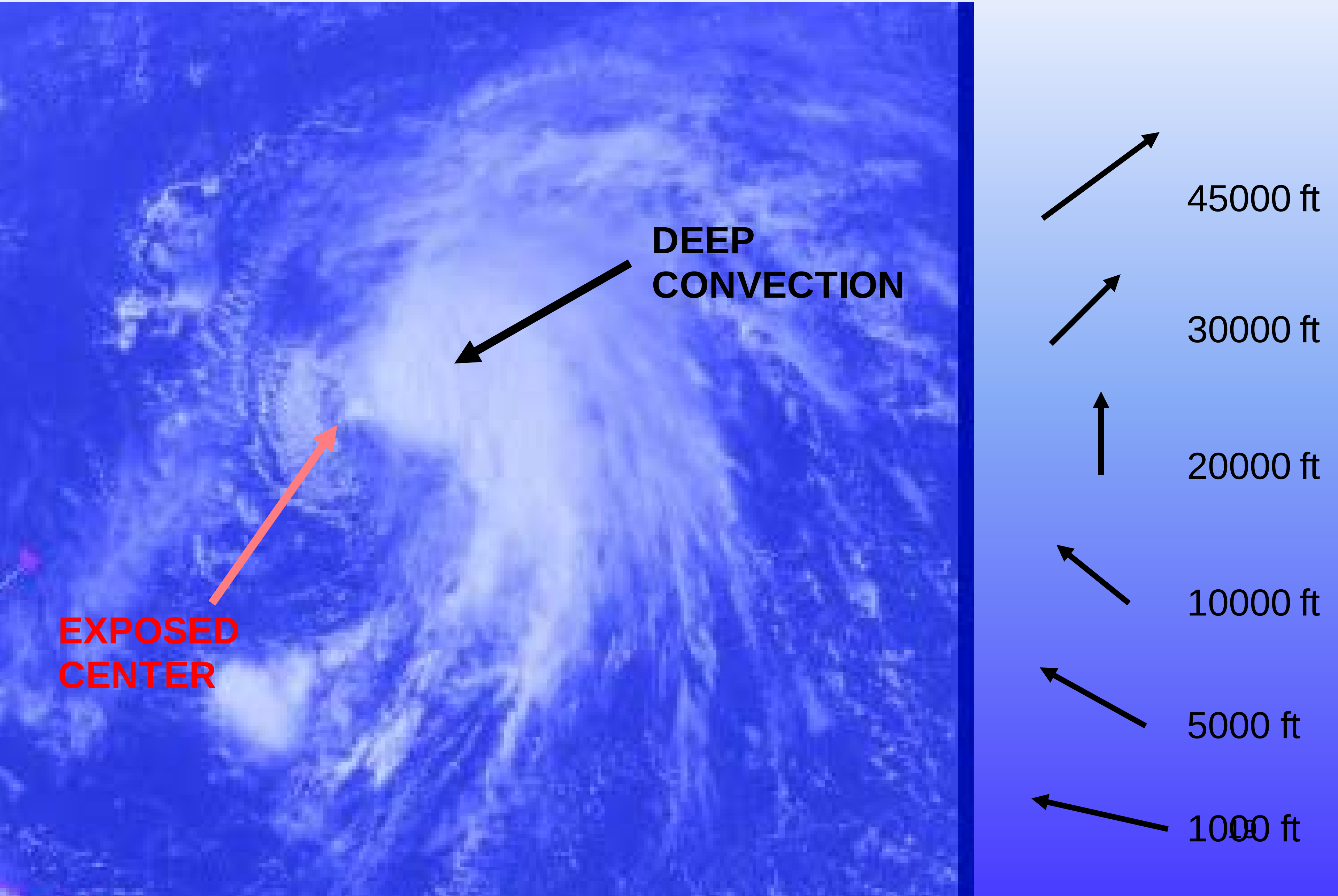
only provides a view of the very top layer of the ocean.

Ocean Heat Content

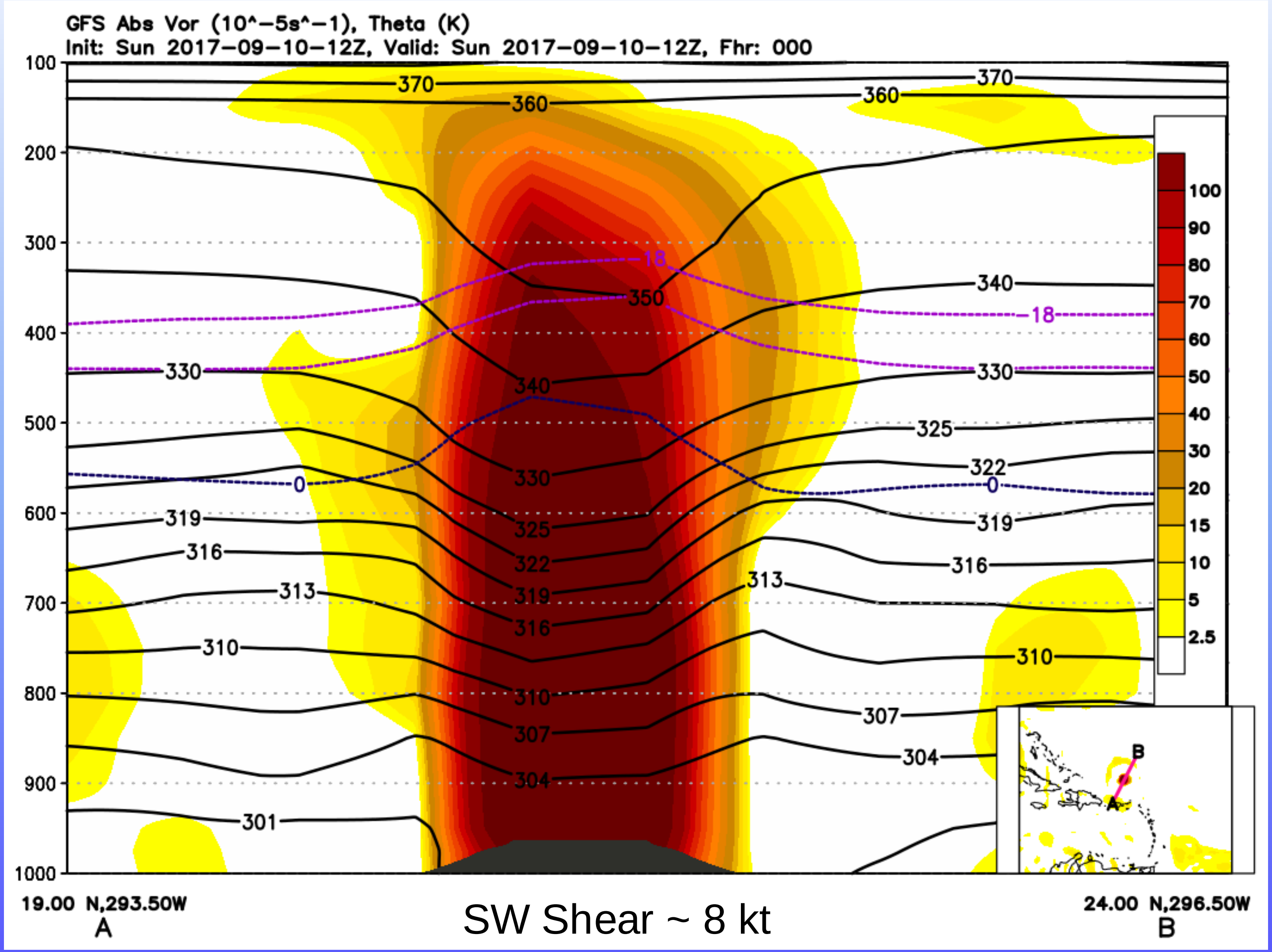
estimates the amount of heat available over a depth of warm water.

the greater the depth the more available heat that can be potentially converted to energy

Vertical Wind Shear

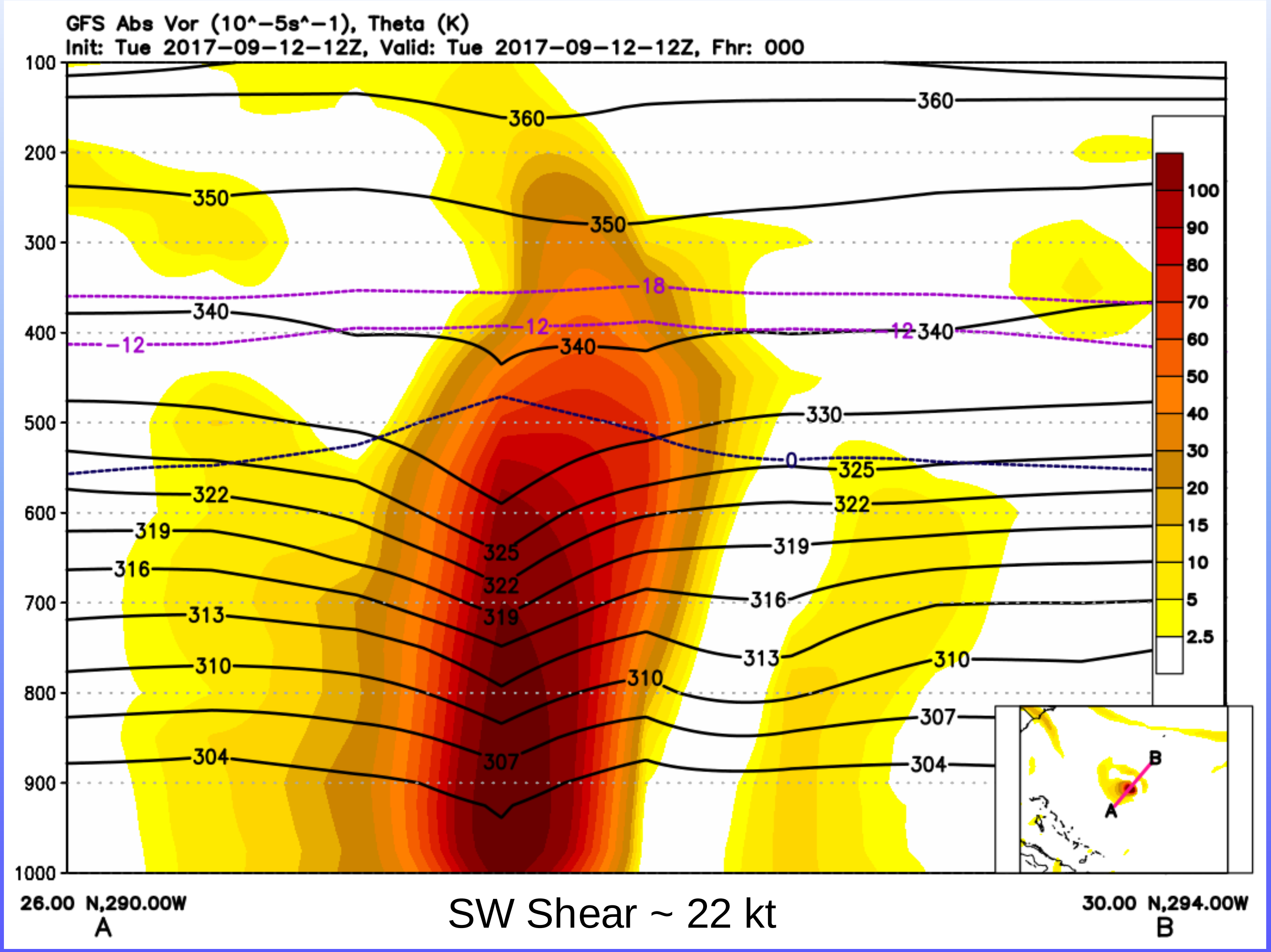


Hurricane Jose 12 UTC 10 Sept 2017



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

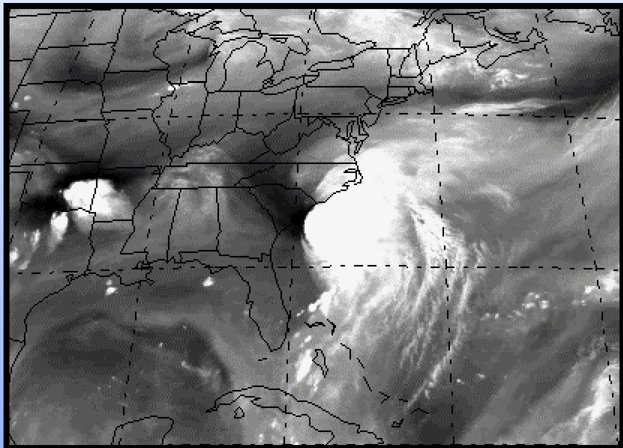
Hurricane Jose 12 UTC 12 Sept 2017

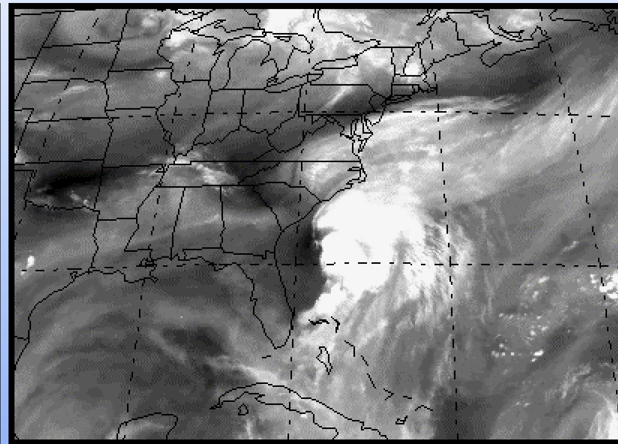


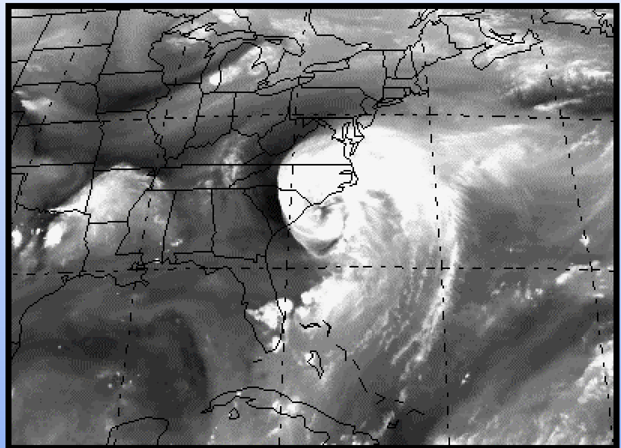
Vertical cross-section of vorticity and potential temperature anomaly from the GFS model for the initialization of the 1200 UTC forecast on September 10

Hurricane-Trough Interaction

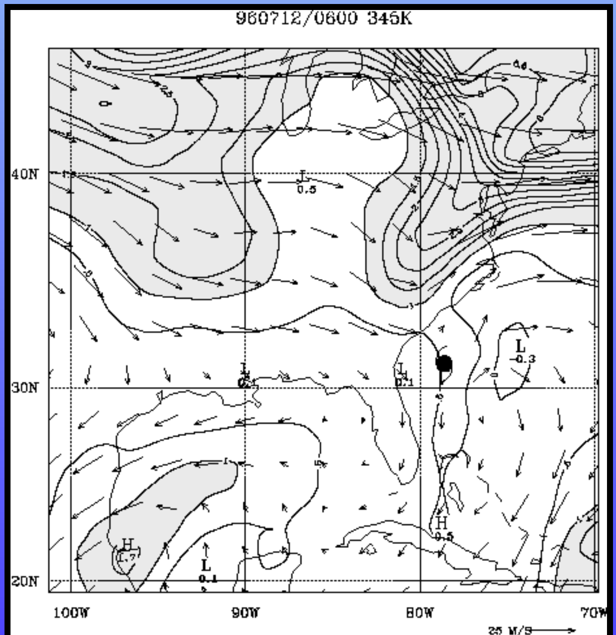
Hurricane Bertha (1996)

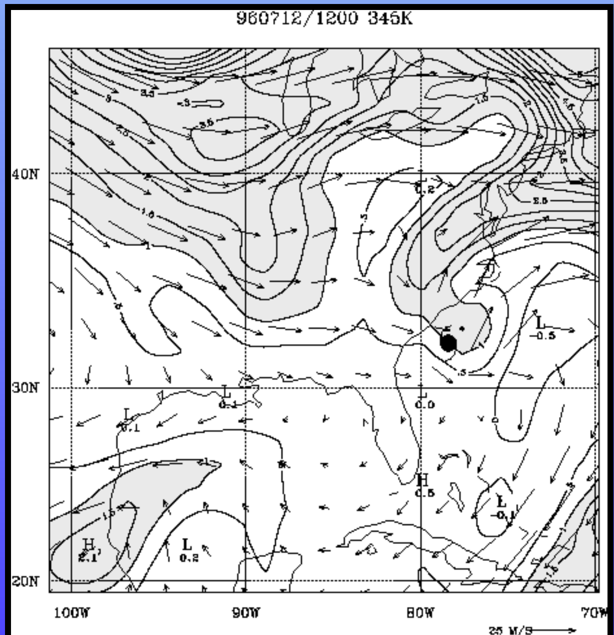


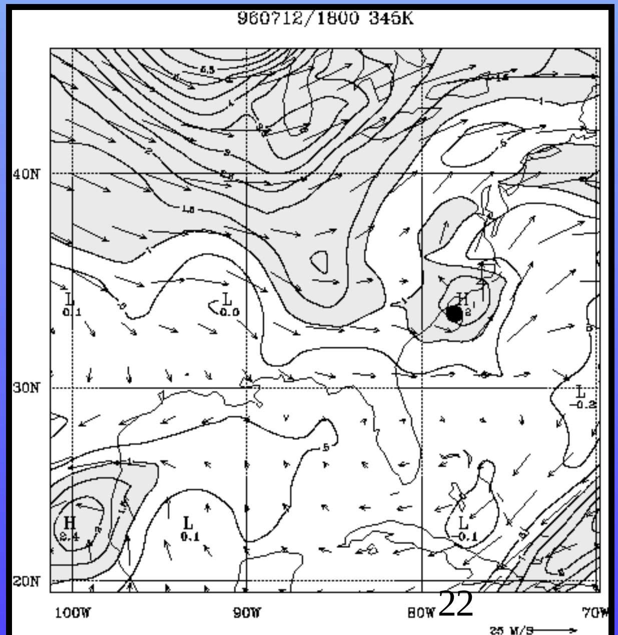




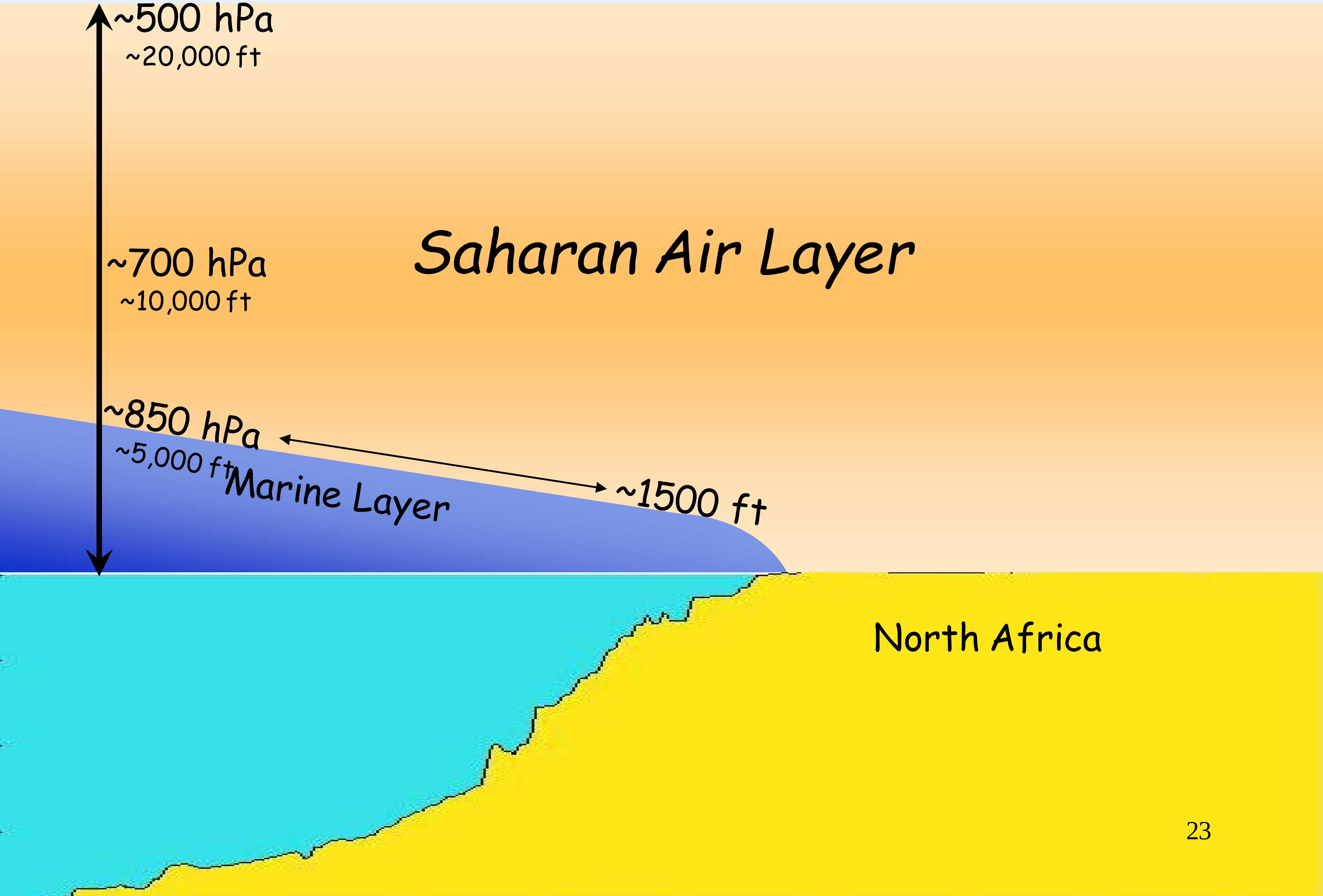
12 July 1995 06 UTC **12 July 1995 12 UTC** **12 July 1995 18 UTC**



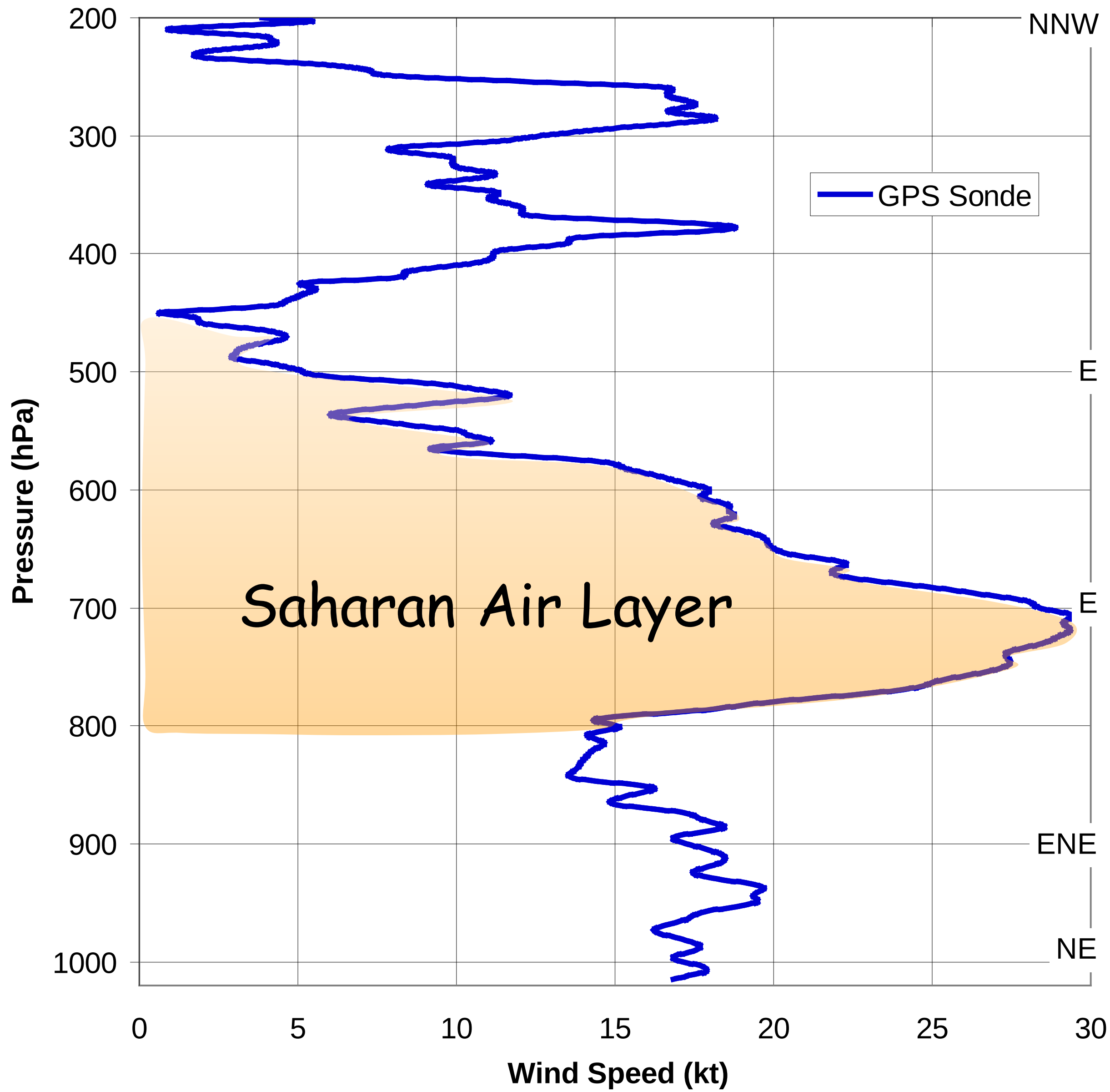




Saharan Air Layer

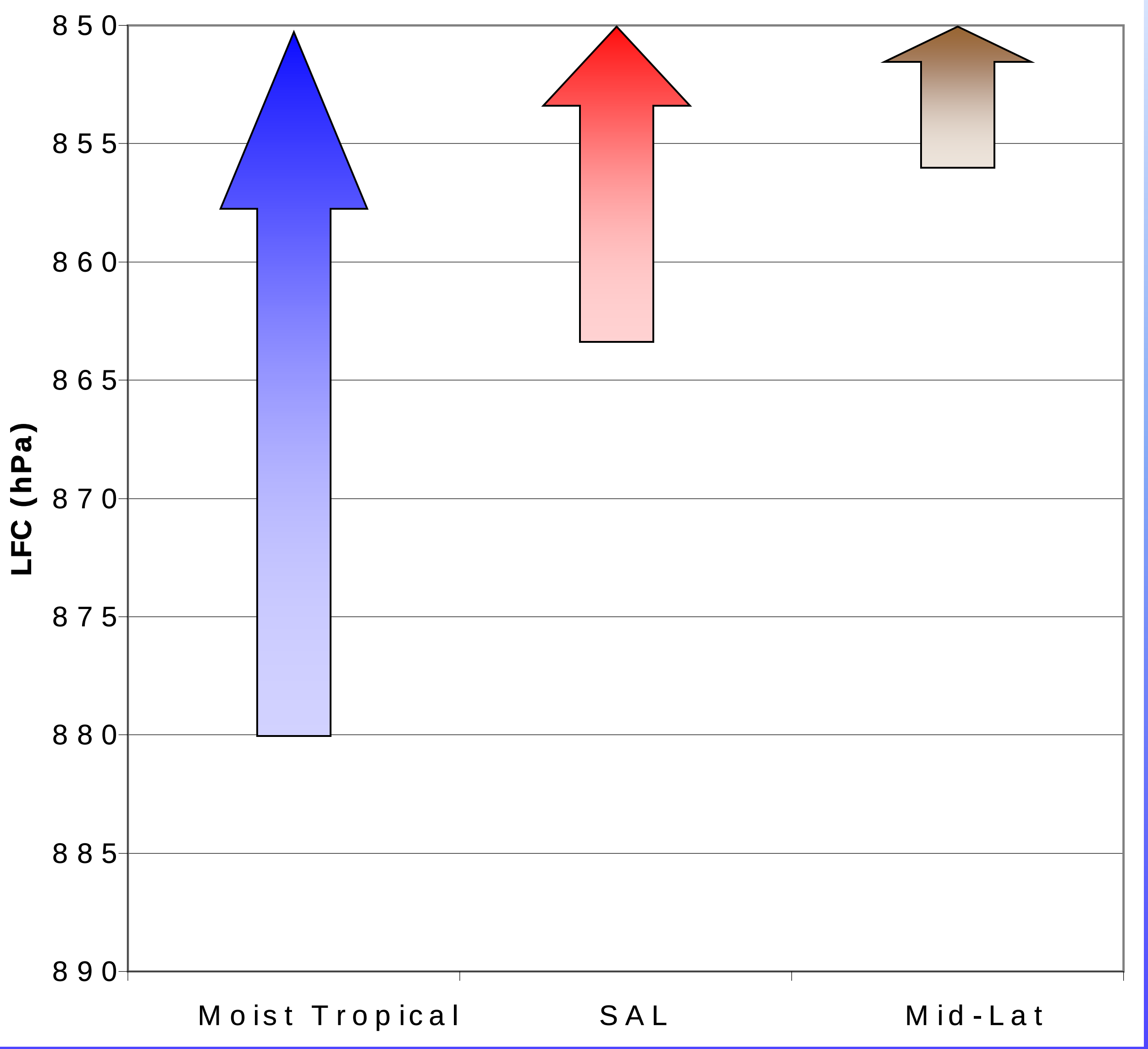


Getting Dry Air into the TC Circulation

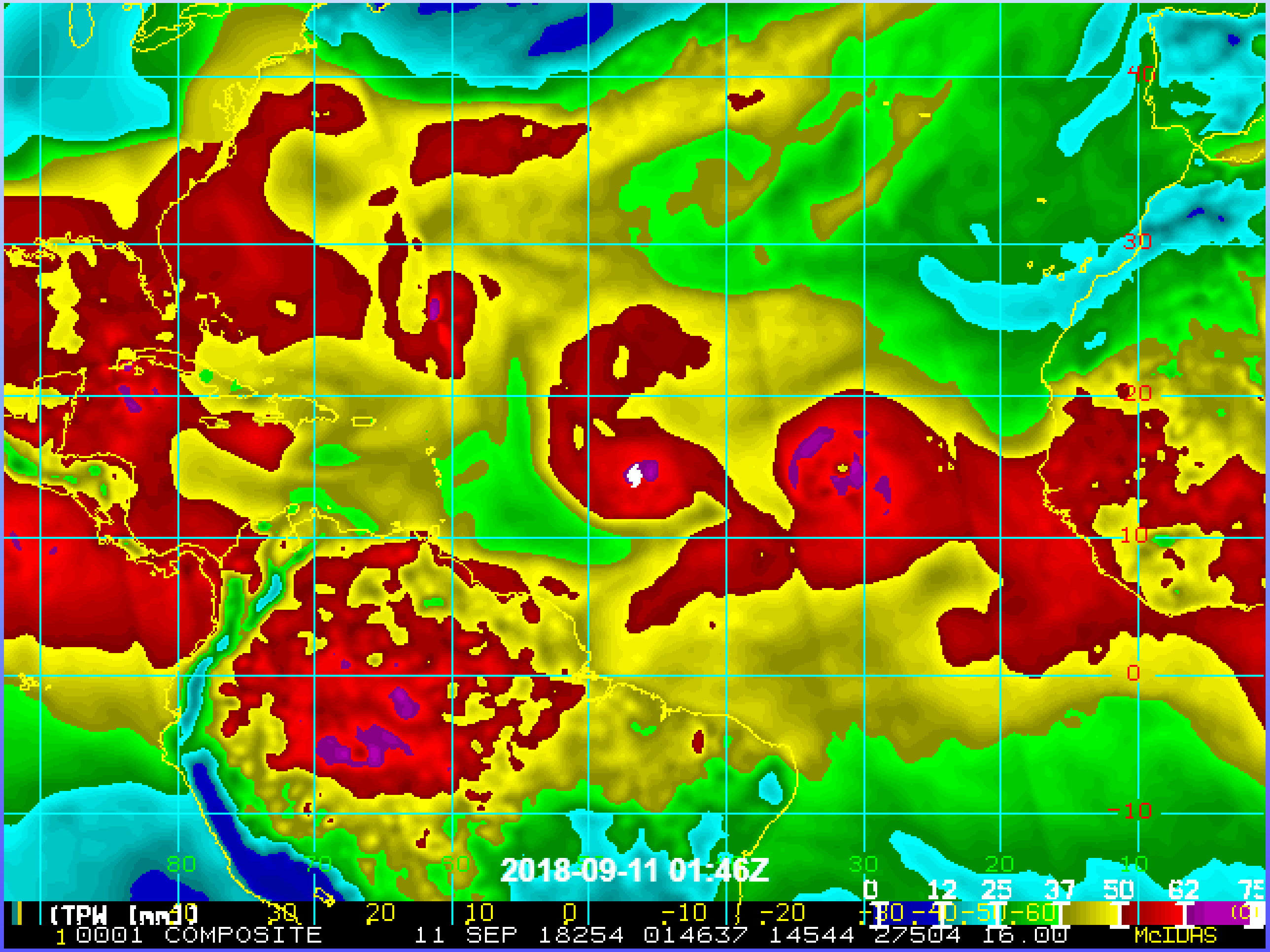


How Moisture Affects Stability

LCL and LFC



Satellite TPW Products Useful for Tracking Dry Air Intrusions



TC-centered TPW Loop for Hurricane Isaac Sept 2018

Eyewall Replacement Cycles

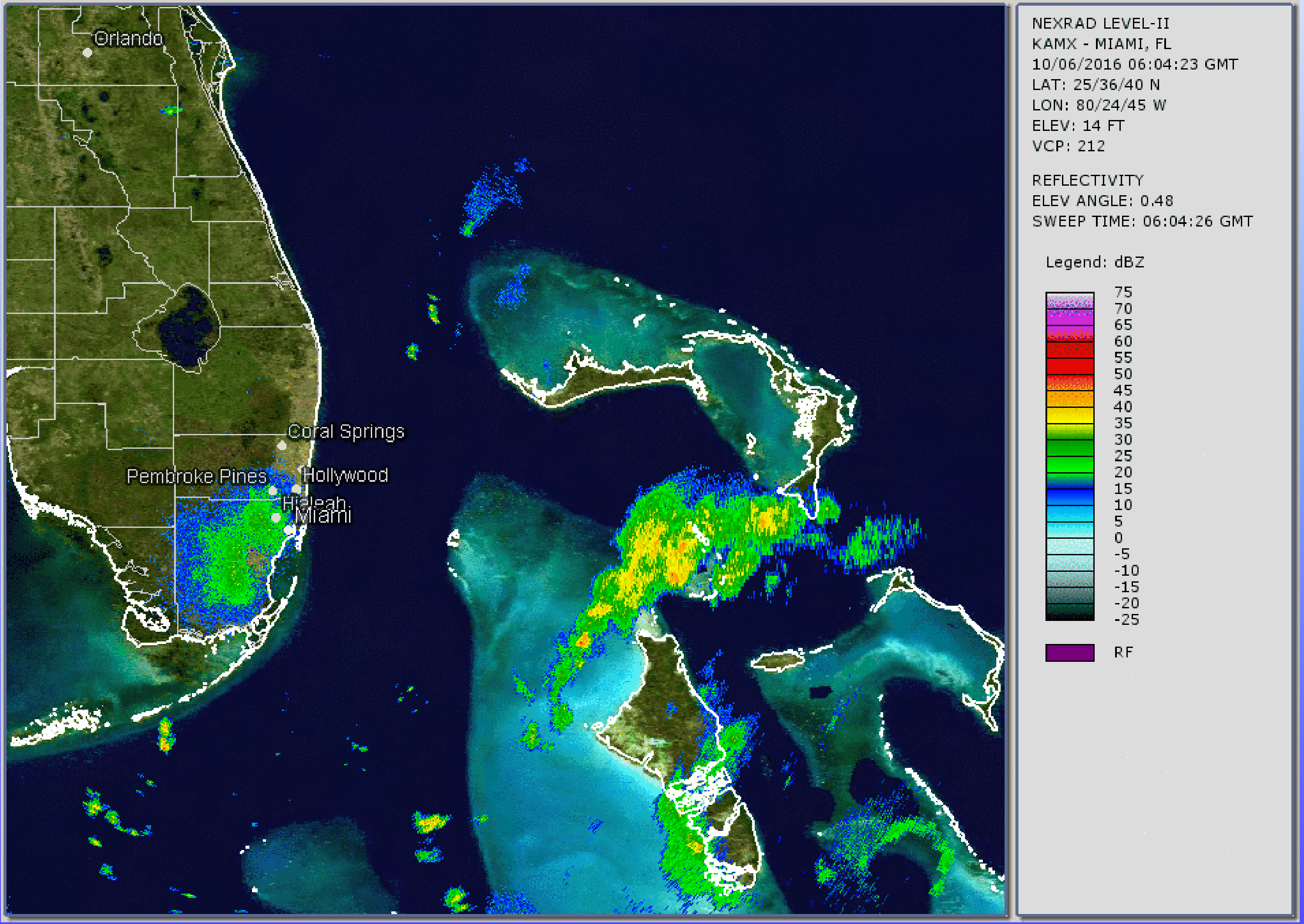
In addition to large-scale environmental influences, tropical cyclone intensity change can be caused by inner-core processes, such as eyewall replacement cycles:

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

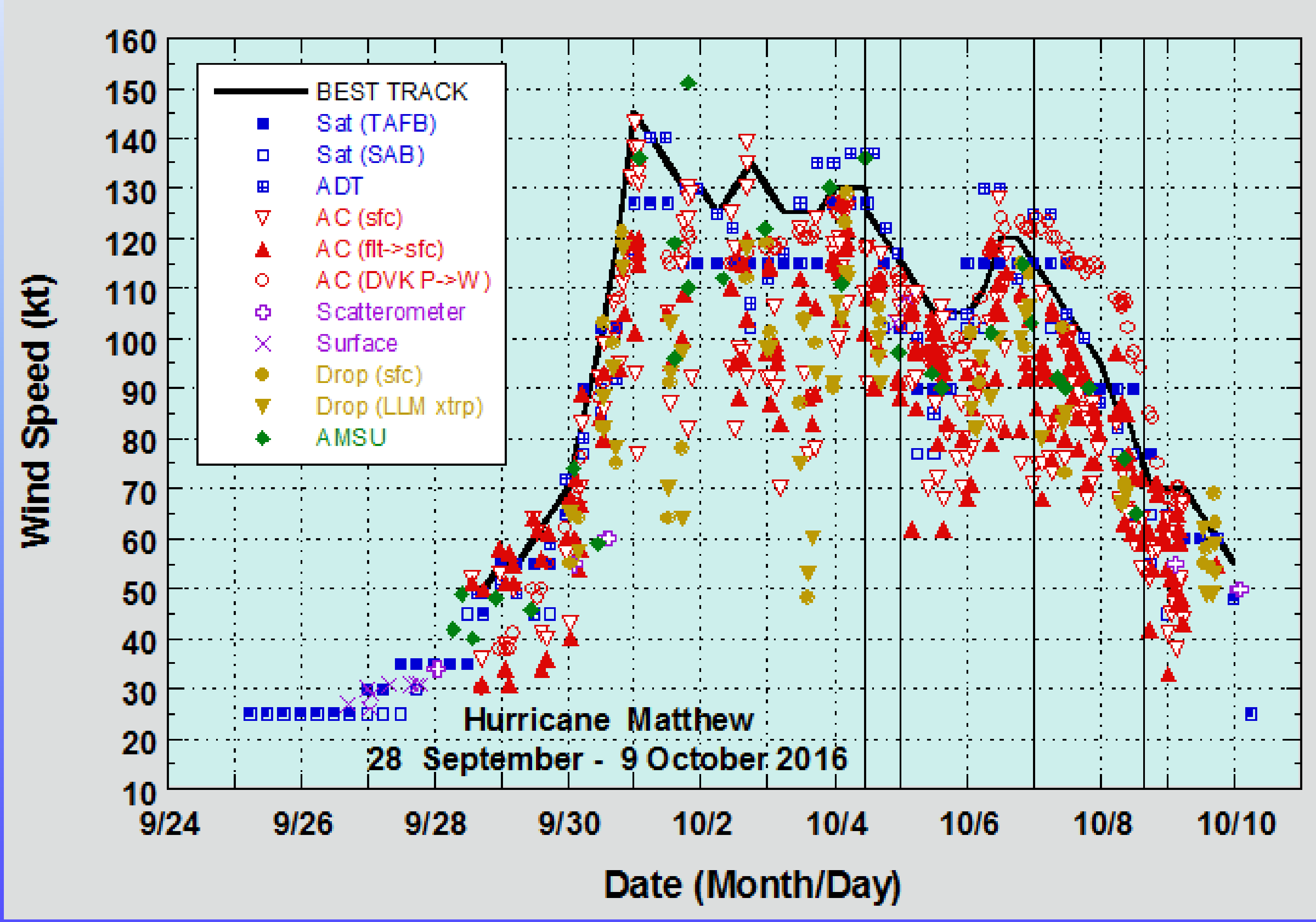
When this outer eyewall becomes dominant, some weakening usually occurs.

However, this outer eyewall could contract, in which case the hurricane would re-intensify.

Hurricane Matthew Radar Loop



Hurricane Matthew Maximum Wind



Land Interaction

- In general, winds weaken over land due to lack of latent heating and increased friction

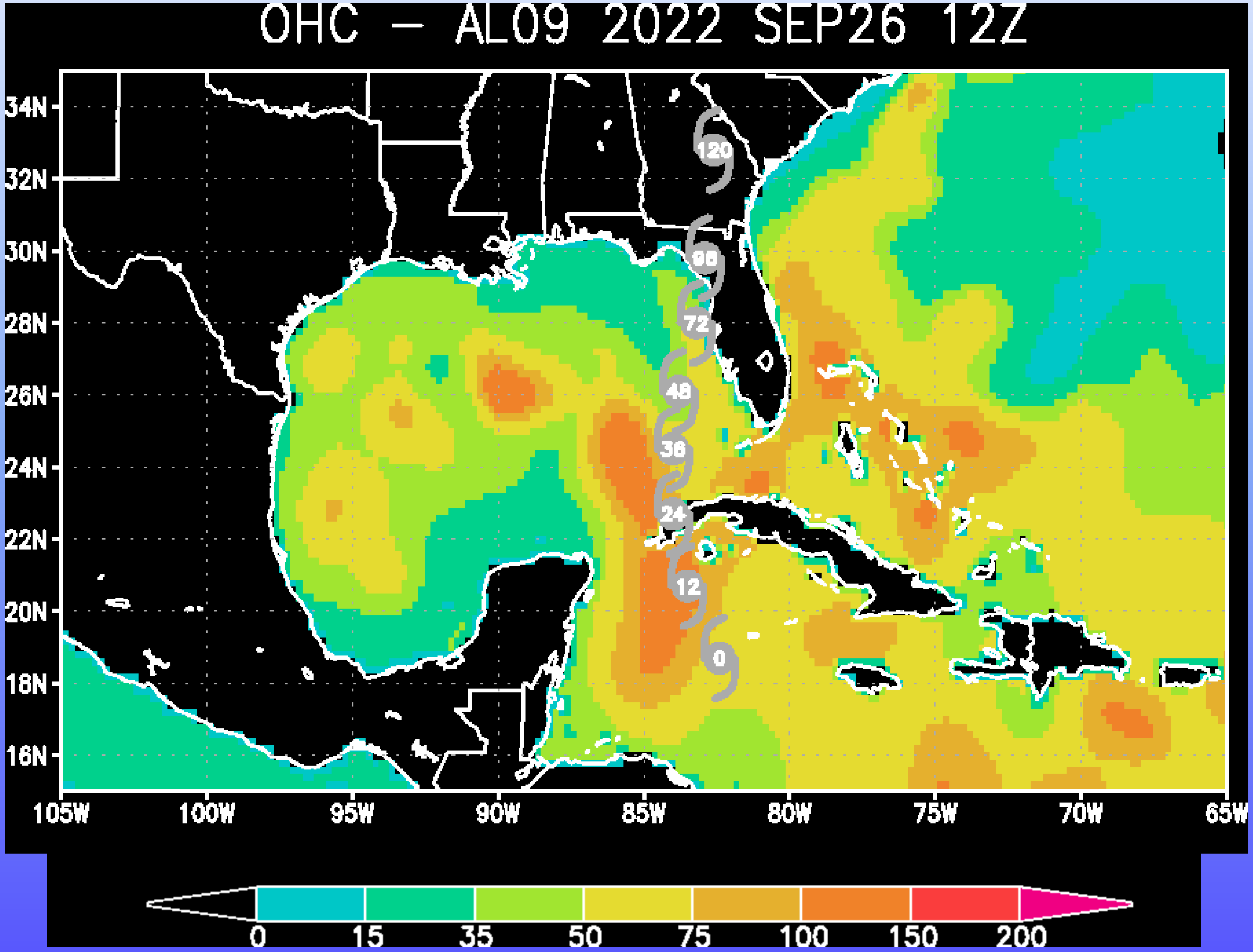
- Strong winds move inland farther if the TC is moving faster

- 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[1]

- 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

[1]From Wilks (2006) and Kalnay (2003)

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., 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**

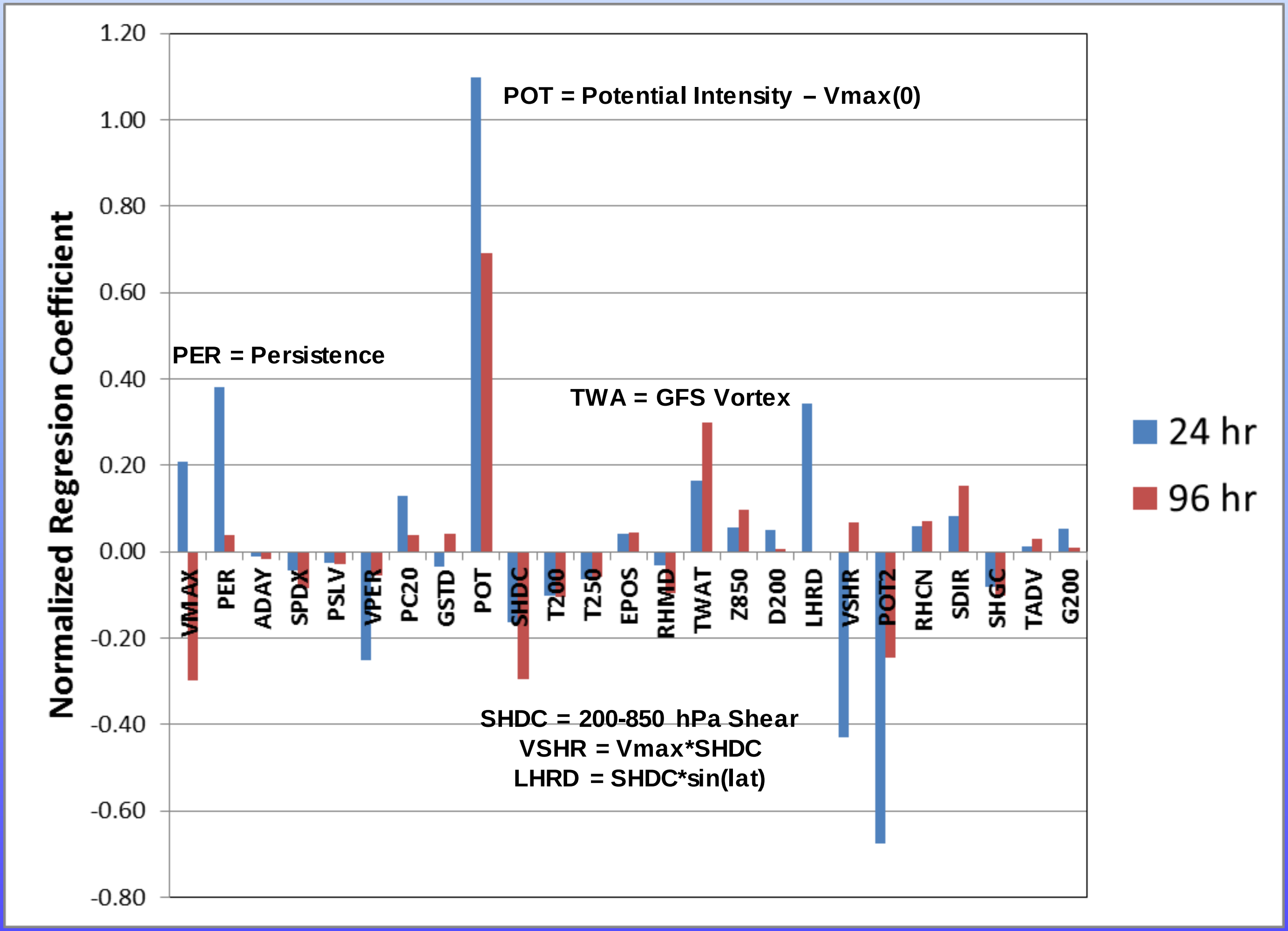
Overview of the SHIPS Model

- Multiple linear regression
  - $y = a_0 + a_1x_1 + \ldots a_Nx_N$
    - y = intensity change at given forecast time
      - (V_6-V_0), $(V_{12}-V_0)$, …, $(V_{120}-V_0)$
    - 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_{max} at t= 0 hr)
3. Persistence (V_0-V_{-12})
4. V_0 * Per
5. Zonal storm motion
6. Steering layer pressure
7. %IR pixels < -20^{o}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. θ_e of sfc parcel - θ_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



Impact of Land

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

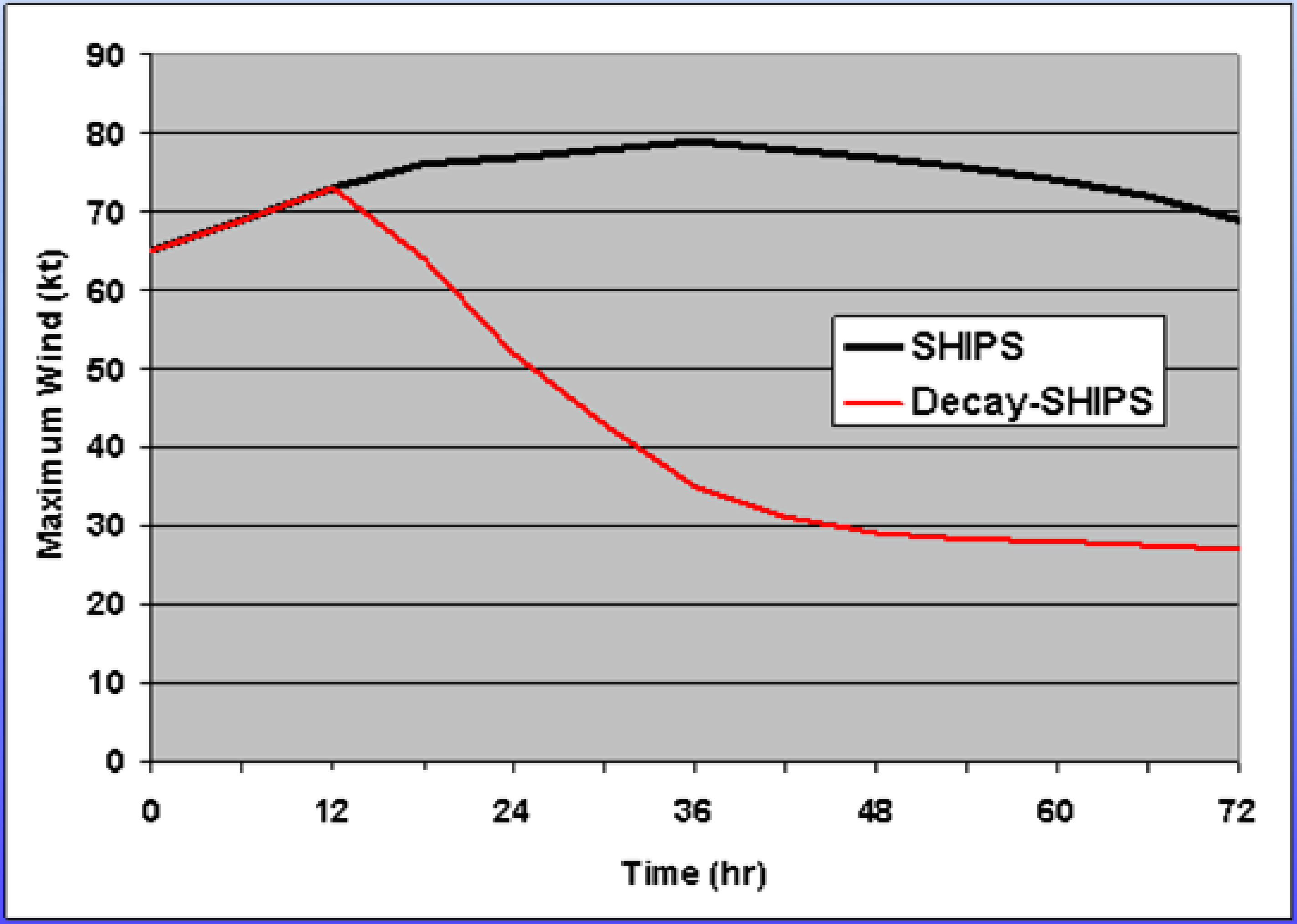
$$dV/dt = -\mu(V-V_b)$$

μ = climatological decay rate ~ 1/10 hr^{-1}

V_b = 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

$$dV/dt = \kappa V - \beta(V/V_{mpi})^n V$$
(A) (B)

V_{mpi} = Maximum Potential Intensity estimate

κ = Max wind growth rate (from SHIPS predictors)

β, n = empirical constants = 1/24 hr, 2.5

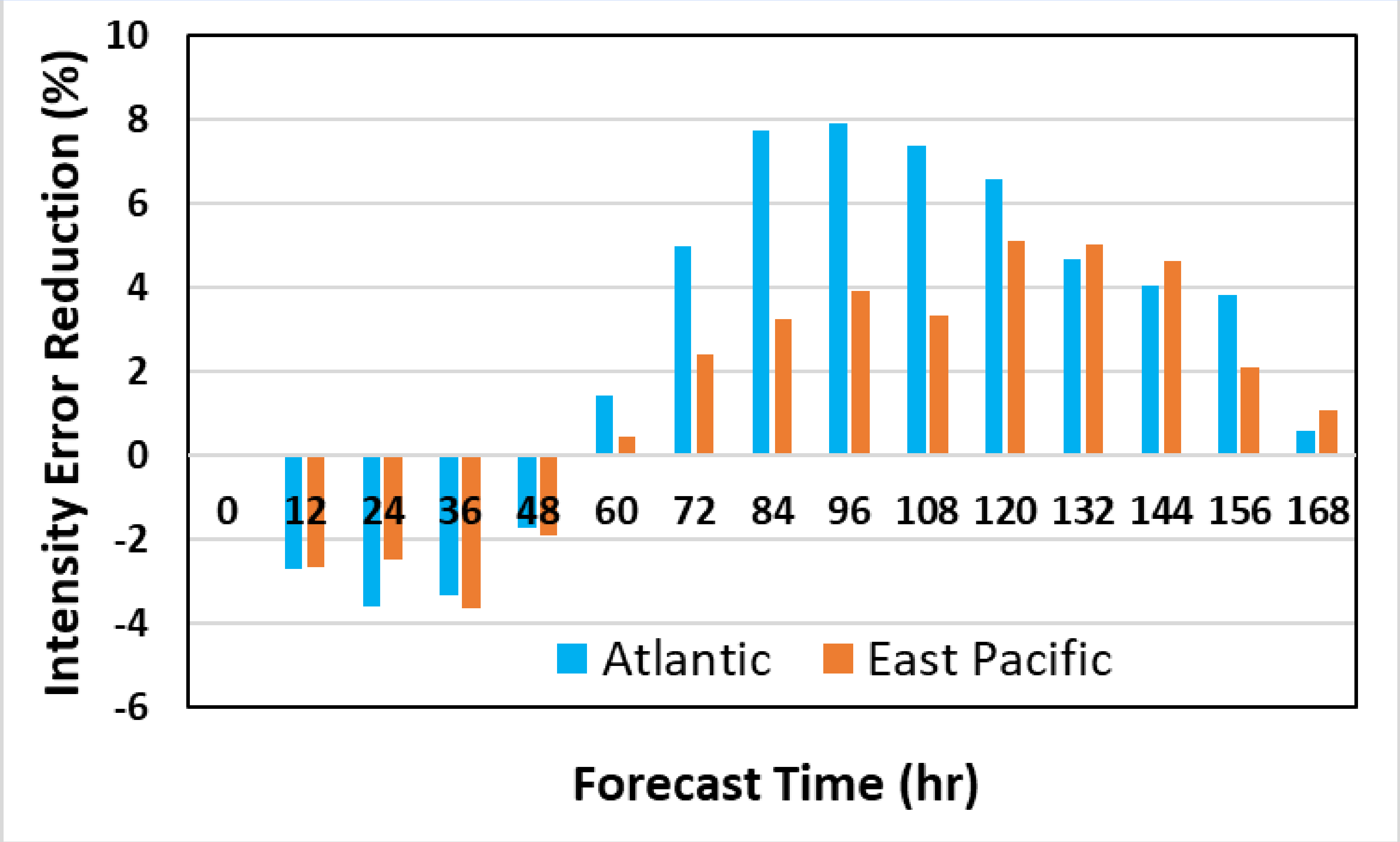
Steady State Solution: $V_s = V_{mpi}(\beta/\kappa)^{1/n}$

LGEM versus SHIPS

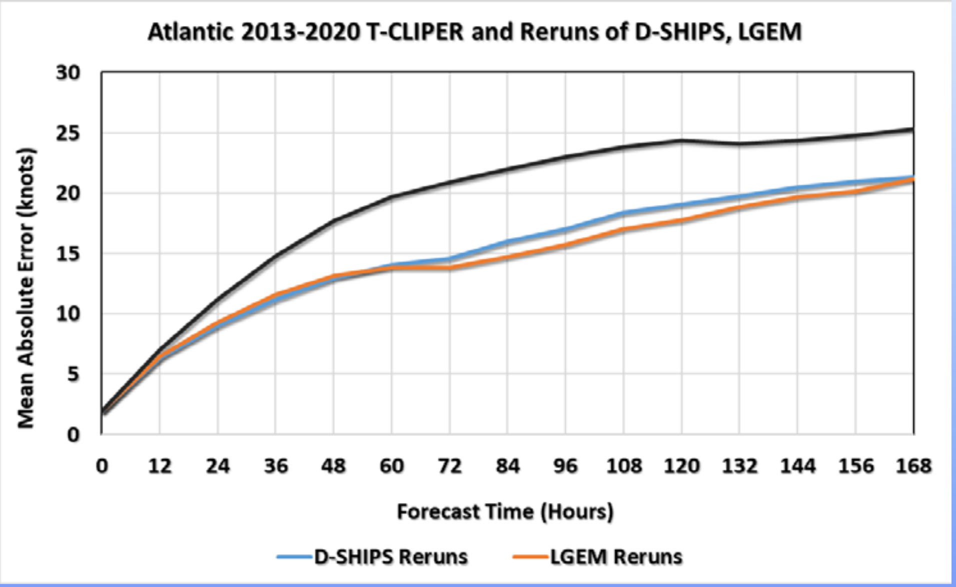
- Advantages
  - Prediction equation bounds the solution between 0 and V_{mpi}
  - Time evolution of predictors (Shear, etc) better accounted for
  - Movement between water and land handled better because of time stepping
- Disadvantages
  - Model fitting more involved
  - Inclusion of persistence more difficult
  - SHIPS forecasts easier to interpret

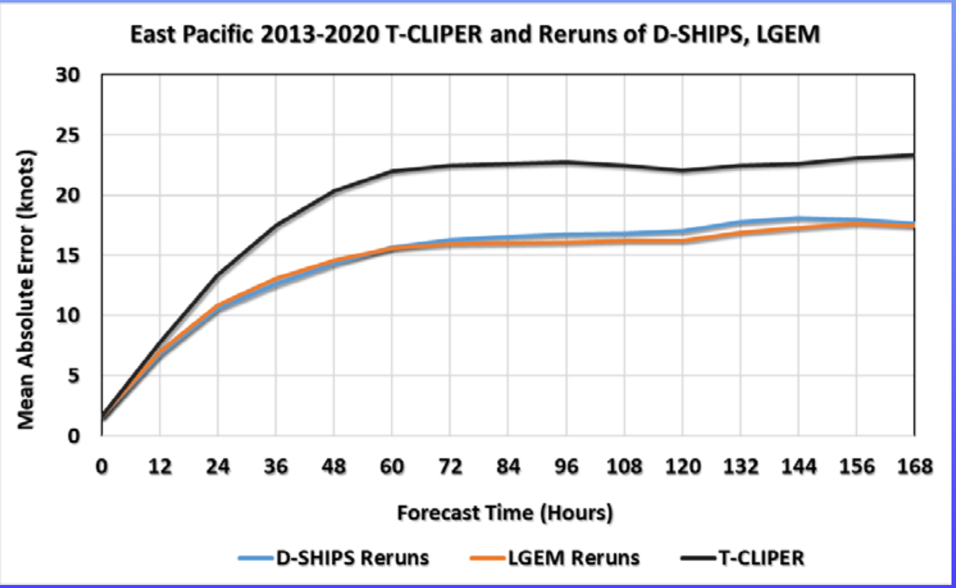
LGEM Improvement over SHIPS

Retrospective runs with 2021 Models
2013-2020 Sample



SHIPS/LGEM extended from 5 to 7days starting in 2020





SHIPS Diagnostic File

```
                   *   ATLANTIC     2021 SHIPS INTENSITY FORECAST     *
                   *   IR SAT DATA AVAILABLE,        OHC AVAILABLE     *
                   *   DORIAN       AL052019  08/30/19  00 UTC         *

TIME (HR)          0     6    12    18    24    36    48    60    72    84    96   108   120   132   144   156   168
V (KT) NO LAND    80    83    87    90    94    97   102   102   105   102   106   103   103    97    95    91    90
V (KT) LAND       80    83    87    90    94    97   102   102   105   102   106    62    40    31    28    27    27
V (KT) LGEM       80    83    86    89    92    99   105   105   104   104   103    62    39    31    28    27    27
Storm Type      TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP  TROP

SHEAR (KT)         9     8     4     3     8    12    12    15    11    11    11    16    15    16    16    14    21
SHEAR ADJ (KT)    -1    -2    -1    -1    -4    -1    -5    -2    -4     0     0     0    -2     2     1     3     2
SHEAR DIR        200   232   250   243   275   334   299   320   290   293   266   289   267   279   252   255   212
SST (C)         29.4  29.4  29.3  29.4  29.4  29.3  29.3  29.5  29.8  29.9  29.8  29.9  29.7  29.8  29.6  29.4  29.6
POT. INT. (KT)   159   159   157   158   158   156   156   159   164   166   163   165   161   164   159   156   159
ADJ. POT. INT.   147   144   141   142   141   138   136   138   141   141   137   138   135   137   131   127   129
200 MB T (C)   -53.3 -53.3 -53.4 -53.1 -53.0 -53.2 -52.8 -52.9 -52.6 -52.5 -52.1 -52.0 -51.7 -52.1 -51.8 -52.2 -51.4
200 MB VXT (C)  -0.1   0.1   0.2   0.2   0.6   0.6   0.6   0.7   1.0   0.9   1.0   1.3   0.9   0.8   0.7   0.7   0.6
TH_E DEV (C)      11    10    10    10    10    10    10     9     9     9     9     9    10     8    10     7     8
700-500 MB RH     56    56    57    59    59    58    63    61    68    64    65    60    62    56    55    50    50
MODEL VTX (KT)    12    13    14    14    16    17    20    21    23    22    27    26    28    26    27    27    28
850 MB ENV VOR   -43   -46   -45   -32   -22   -24     9    -1    23    -2    17   -15    11   -25    -2    -4    31
200 MB DIV        36    30    14    49    30    13    14    -3    25    -3    25    10    60    23    63    49    89
700-850 TADV       0     1     0     2     1    -6     0    -1    -1    -1    -1    -1     2     4     1     6     0
LAND (KM)        397   444   513   565   622   617   503   332   184    84     4   -46   -78   -77   -61   -46   -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
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 xxx.x xxx.x xxx.x xxx.x
STM SPEED (KT)    11    10    10    10     9     9     8     7     6     5     4     4     5     5     4     4     4
HEAT CONTENT      45    45    50    58    46    50    57    53    53    56    44    40    32    15    10    16     7

  FORECAST TRACK FROM OFCI      INITIAL HEADING/SPEED (DEG/KT):330/ 11      CX,CY:  -4/ 10
  T-12 MAX WIND:  75            PRESSURE OF STEERING LEVEL (MB):  623  (MEAN=620)
  GOES IR BRIGHTNESS TEMP. STD DEV.  50-200 KM RAD:  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

                       INDIVIDUAL CONTRIBUTIONS TO INTENSITY CHANGE
                        6    12    18    24    36    48    60    72    84    96   108   120   132   144   156   168
                       ----------------------------------------------------------------------------------------------
  SAMPLE MEAN CHANGE    1.    2.    3.    4.    6.    8.    9.   10.   11.   12.   12.   13.   14.   15.   15.   16.
  SST POTENTIAL         1.    3.    4.    5.    4.    2.   -1.   -2.   -3.   -4.   -4.   -5.   -7.   -8.  -10.  -11.
  VERTICAL SHEAR MAG   -0.    0.    1.    1.    1.    3.    4.    5.    7.    8.    8.    8.    9.    9.    9.    8.
  VERTICAL SHEAR ADJ    0.    0.    1.    1.    2.    3.    4.    5.    4.    4.    3.    3.    3.    2.    2.    1.
  VERTICAL SHEAR DIR   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.    0.    0.    0.    1.    1.    1.
  PERSISTENCE           1.    1.    1.    0.    0.    0.    0.    0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.
  200/250 MB TEMP.     -0.   -1.   -1.   -1.   -1.   -1.   -1.   -2.   -2.   -2.   -3.   -3.   -4.   -4.   -4.   -5.
  THETA_E EXCESS        0.    0.    0.    1.    1.    1.    1.    1.    1.    0.    0.    0.   -0.   -0.   -0.   -0.
  700-500 MB RH        -0.   -0.   -0.   -0.   -0.   -1.   -1.   -2.   -3.   -3.   -3.   -4.   -4.   -4.   -4.   -3.
  MODEL VTX TENDENCY    0.    1.    1.    2.    3.    7.    8.   11.   10.   15.   14.   15.   11.   11.   10.   10.
  850 MB ENV VORTICITY -0.   -1.   -1.   -1.   -1.   -2.   -2.   -2.   -2.   -2.   -2.   -3.   -3.   -3.   -3.   -3.
  200 MB DIVERGENCE    -0.   -0.   -0.   -0.   -0.   -0.   -1.   -1.   -1.   -1.   -0.    0.    0.    0.    0.   -0.
  850-700 T ADVEC       0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.
  ZONAL STORM MOTION   -0.   -0.    0.    0.    0.    0.    0.   -0.   -0.   -0.   -0.   -0.   -1.   -1.   -1.   -1.
  STEERING LEVEL PRES  -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.
  DAYS FROM CLIM. PEAK  0.   -0.   -0.   -0.    0.    0.    0.    0.    0.   -0.   -0.   -0.   -0.   -0.   -1.   -0.
  GOES PREDICTORS      -0.   -0.   -0.   -0.   -0.    0.    1.    1.    1.    1.    1.    1.    0.   -0.   -0.   -0.
  OCEAN HEAT CONTENT    0.    0.    0.    0.    0.    0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.   -0.
  RI POTENTIAL          0.    1.    2.    2.    3.    3.    2.    1.    0.   -1.   -1.   -2.   -2.   -2.   -2.   -2.
                       ----------------------------------------------------------------------------------------------
  TOTAL CHANGE          3.    7.   10.   14.   17.   22.   22.   25.   22.   26.   23.   23.   17.   15.   11.   10.
```

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

SHIPS Diagnostic File

* ATLANTIC 2021 SHIPS INTENSITY FORECAST *
* IR SAT DATA AVAILABLE, OHC AVAILABLE *
* DORIAN AL052019 08/30/19 00 UTC *

TIME (HR)	0	6	12	18	24	36	48	60	72	84	96	108	120	132	144	156	168
V (KT) NO LAND	80	83	87	90	94	97	102	102	105	102	106	103	103	97	95	91	90
V (KT) LAND	80	83	87	90	94	97	102	102	105	102	106	62	40	31	28	27	27
V (KT) LGEM	80	83	86	89	92	99	105	105	104	104	103	62	39	31	28	27	27
Storm Type	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP
SHEAR (KT)	9	8	4	3	8	12	12	15	11	11	11	16	15	16	16	14	21
SHEAR ADJ (KT)	-1	-2	-1	-1	-4	-1	-5	-2	-4	0	0	0	-2	2	1	3	2
SHEAR DIR	200	232	250	243	275	334	299	320	290	293	266	289	267	279	252	255	212
SST (C)	29.4	29.4	29.3	29.4	29.4	29.3	29.3	29.5	29.8	29.9	29.8	29.9	29.7	29.8	29.6	29.4	29.6
POT. INT. (KT)	159	159	157	158	158	156	156	159	164	166	163	165	161	164	159	156	159
ADJ. POT. INT.	147	144	141	142	141	138	136	138	141	141	137	138	135	137	131	127	129
200 MB T (C)	-53.3	-53.3	-53.4	-53.1	-53.0	-53.2	-52.8	-52.9	-52.6	-52.5	-52.1	-52.0	-51.7	-52.1	-51.8	-52.2	-51.4
200 MB VXT (C)	-0.1	0.1	0.2	0.2	0.6	0.6	0.6	0.7	1.0	0.9	1.0	1.3	0.9	0.8	0.7	0.7	0.6
TH_E DEV (C)	11	10	10	10	10	10	10	9	9	9	9	9	10	8	10	7	8
700-500 MB RH	56	56	57	59	59	58	63	61	68	64	65	60	62	56	55	50	50
MODEL VTX (KT)	12	13	14	14	16	17	20	21	23	22	27	26	28	26	27	27	28
850 MB ENV VOR	-43	-46	-45	-32	-22	-24	9	-1	23	-2	17	-15	11	-25	-2	-4	31
200 MB DIV	36	30	14	49	30	13	14	-3	25	-3	25	10	60	23	63	49	89
700-850 TADV	0	1	0	2	1	-6	0	-1	-1	-1	-1	-1	2	4	1	6	0
LAND (KM)	397	444	513	565	622	617	503	332	184	84	4	-46	-78	-77	-61	-46	-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
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	xxx.x	xxx.x	xxx.x	xxx.x
STM SPEED (KT)	11	10	10	10	9	9	8	7	6	5	4	4	5	5	4	4	4
HEAT CONTENT	45	45	50	58	46	50	57	53	53	56	44	40	32	15	10	16	7

FORECAST TRACK FROM OFCI INITIAL HEADING/SPEED (DEG/KT):330/ 11 CX,CY: -4/ 10
T-12 MAX WIND: 75 PRESSURE OF STEERING LEVEL (MB): 623 (MEAN=620)
GOES IR BRIGHTNESS TEMP. STD DEV. 50-200 KM RAD: 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

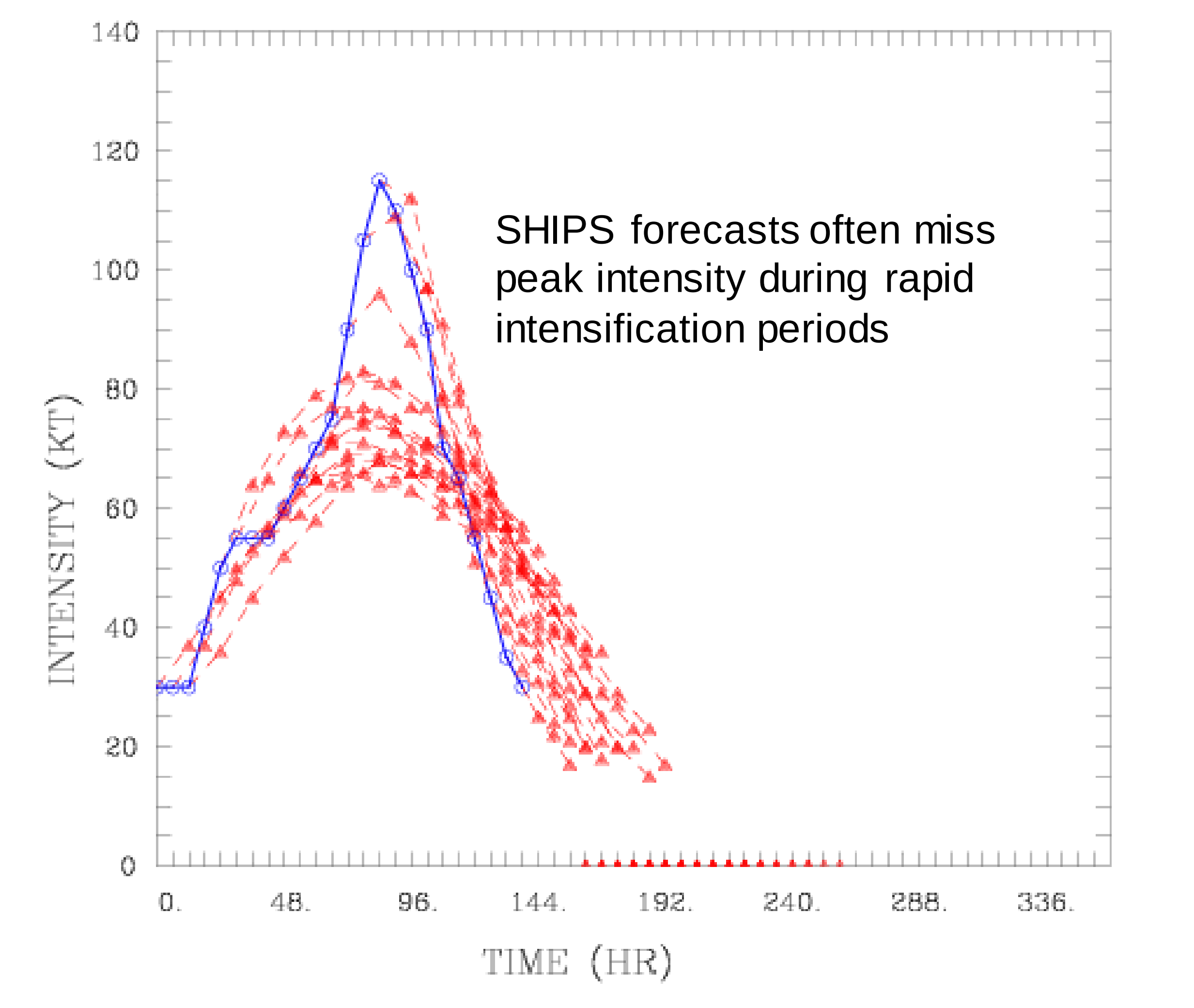
Mean=15 kt
σ=10 kt

Mean=55%
σ=10%

Mean=30kJ/cm^2
σ=10kJ/cm^2

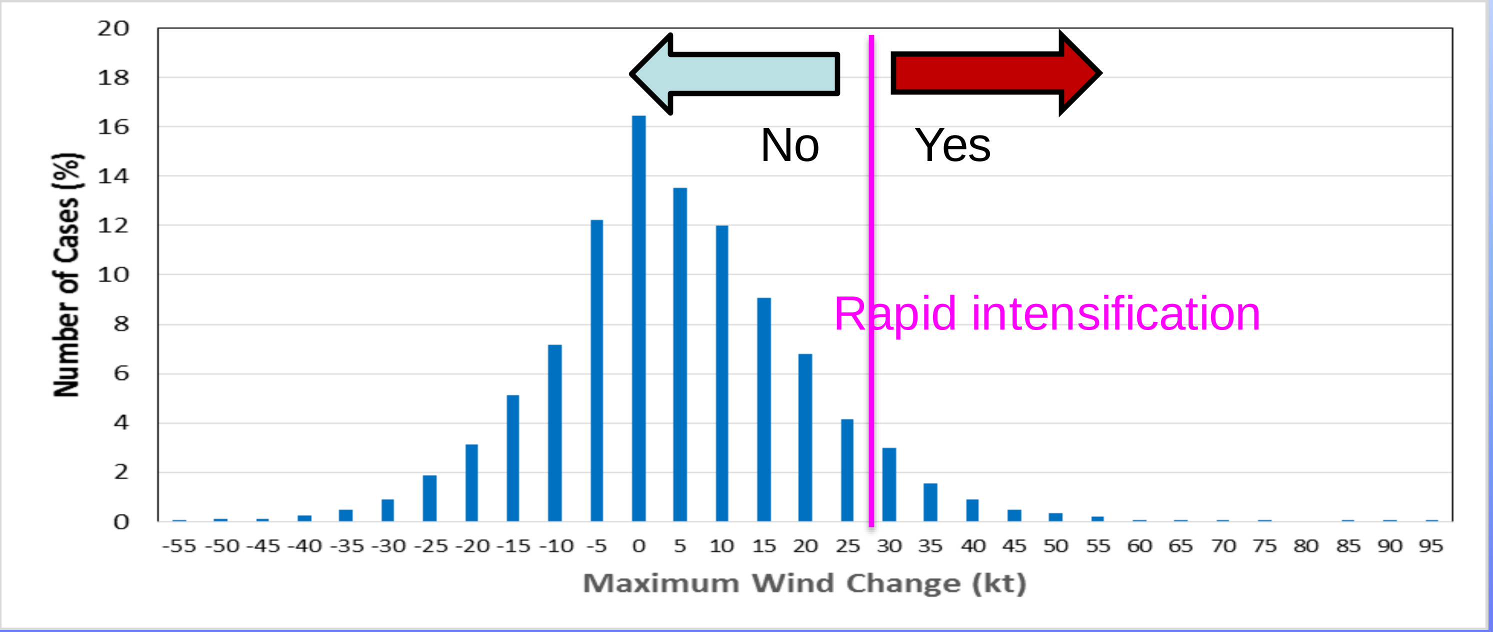
Available in real time from ftp://ftp.nhc.noaa.gov/atcf/stext

SHIPS Forecasts For East Pacific Hurricane Georgette (2016)



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)

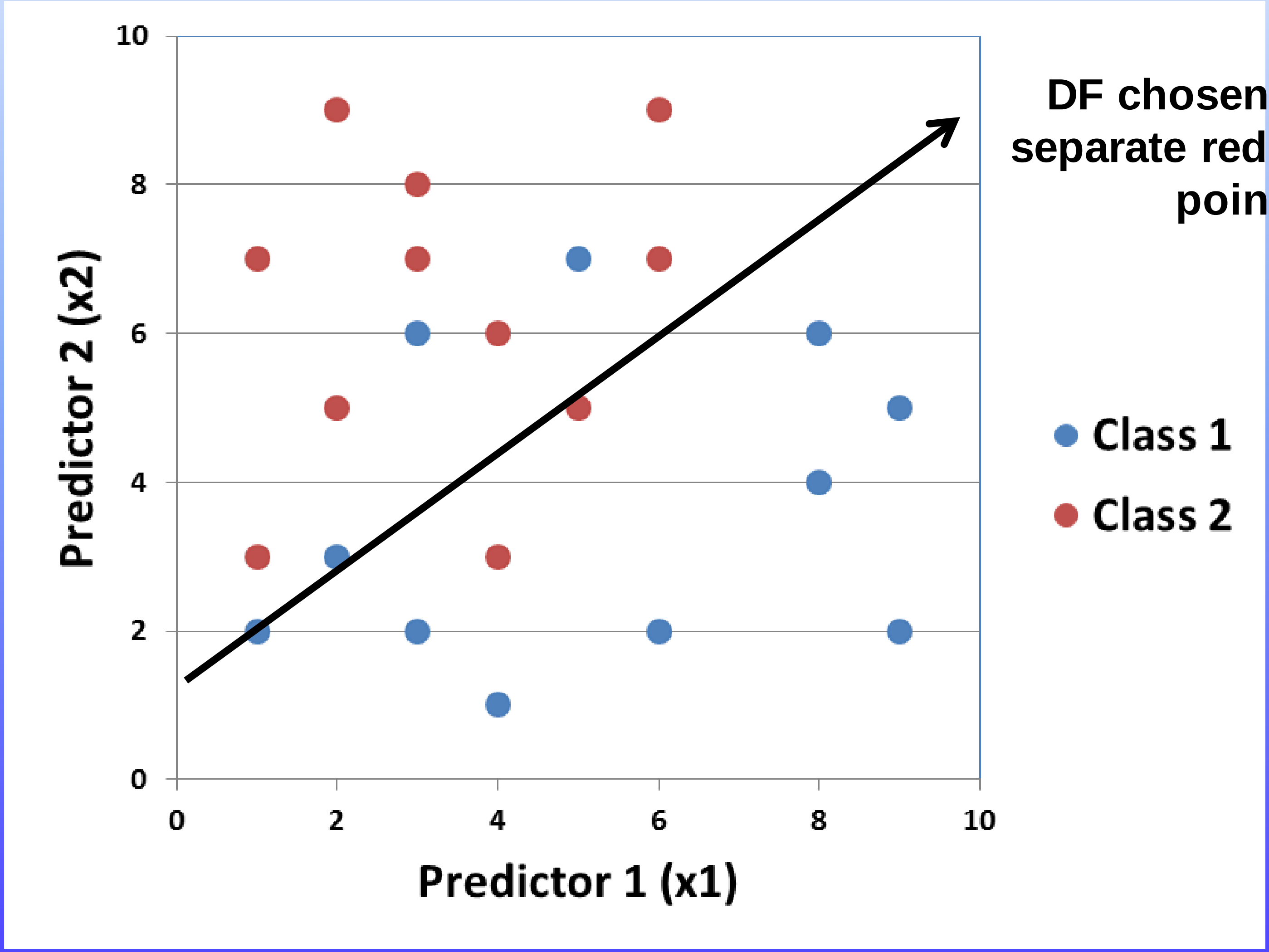
Linear Discriminant Analysis

- 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

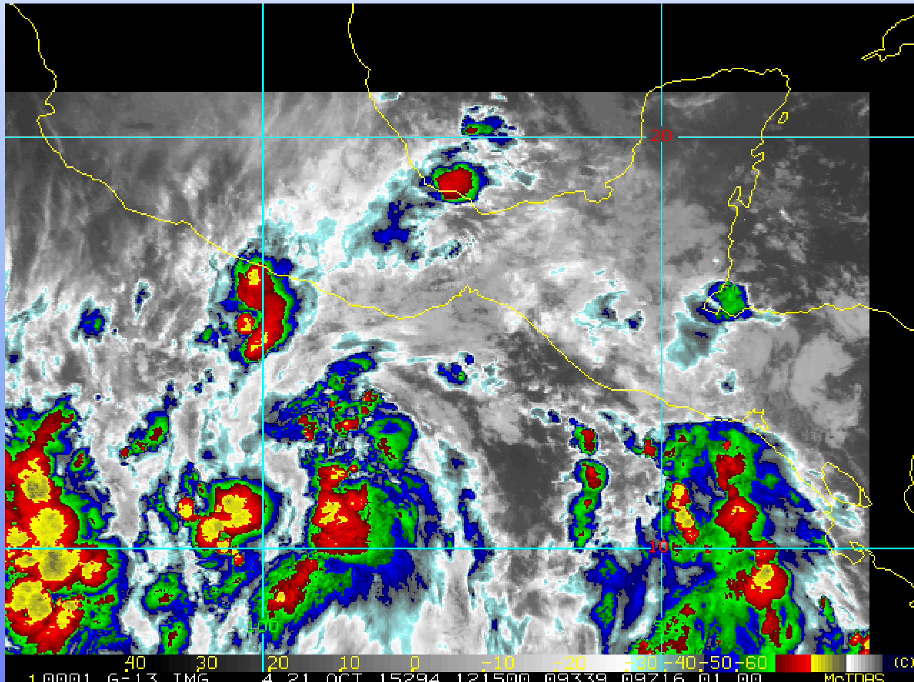
Graphical Interpretation of the Discriminant Function



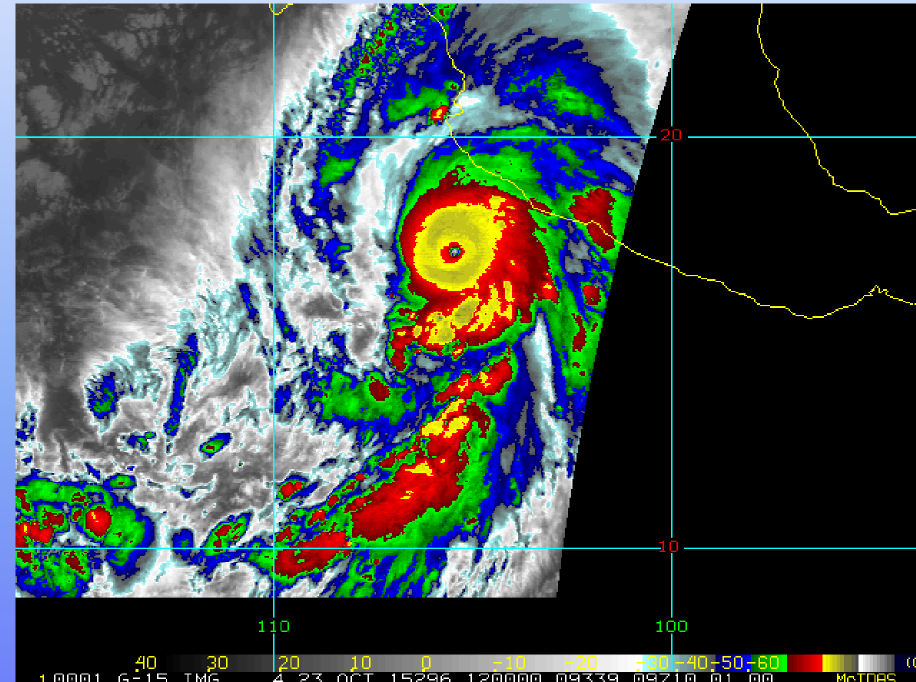
RII Discriminators

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)

* EAST PACIFIC 2021 SHIPS INTENSITY FORECAST *
* IR SAT DATA AVAILABLE, OHC AVAILABLE *
* PATRICIA EP202015 10/22/15 06 UTC *

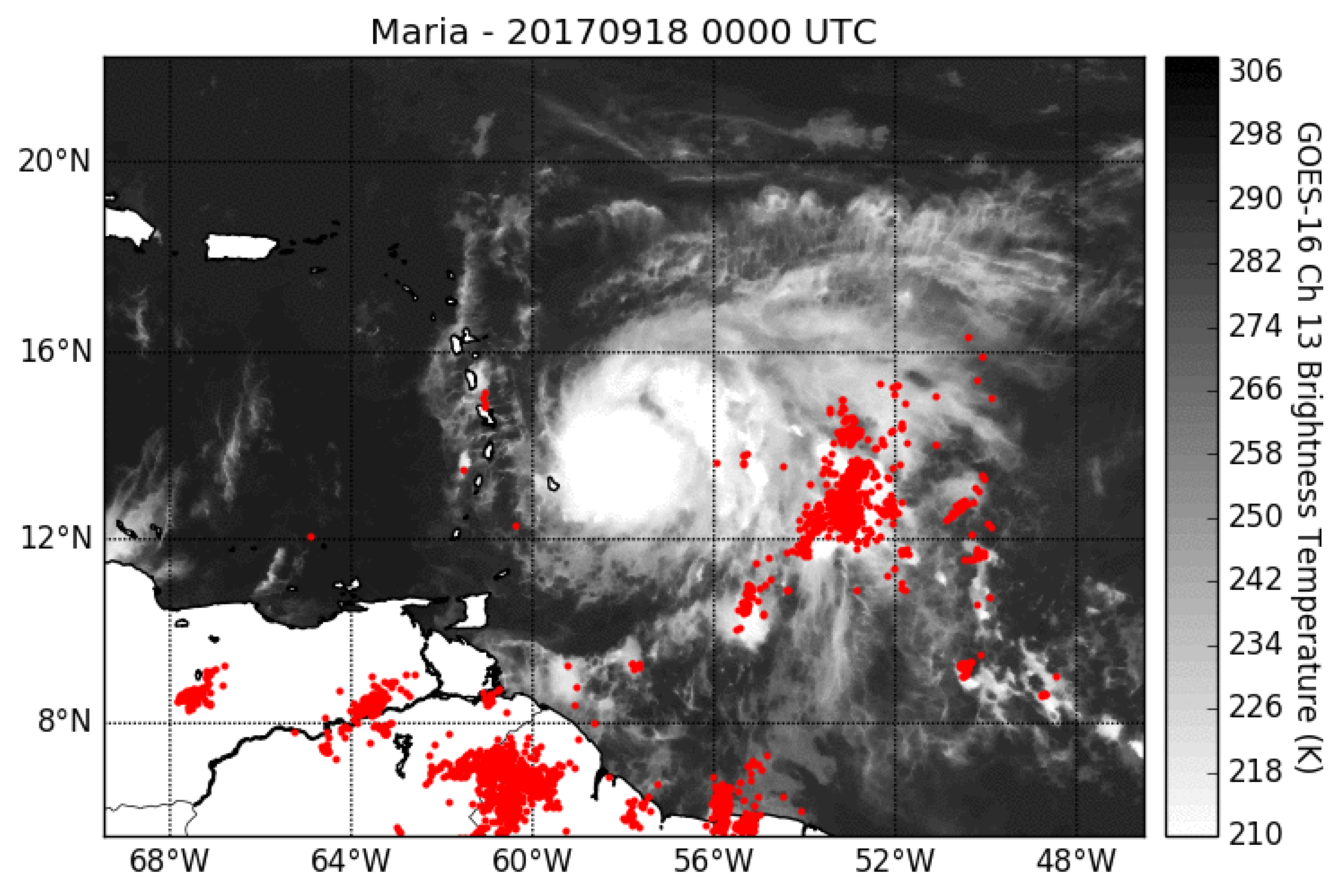
TIME (HR)	0	6	12	18	24	36	48	60	72	84	96	108	120	132	144	156	168
V (KT) NO LAND	70	82	94	105	113	124	117	89	70	59	50	44	41	38	35	32	28
V (KT) LAND	70	82	94	105	113	124	95	52	35	29	28	27	27	27	27	27	27
V (KT) LGEM	70	83	95	106	115	122	91	50	34	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Storm Type	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SHEAR (KT)	2	1	6	11	11	12	24	31	46	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SHEAR ADJ (KT)	0	0	-3	-5	-5	-2	4	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SHEAR DIR	42	229	228	197	178	189	195	219	232	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SST (C)	30.3	30.4	30.5	30.3	30.1	30.5	30.6	28.5	28.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

** 2021 E. Pacific RI INDEX EP202015 PATRICIA 10/22/15 06 UTC **
(SHIPS-RII PREDICTOR TABLE for 30 KT OR MORE MAXIMUM WIND INCREASE IN NEXT 24-h)

Predictor	Value	RI Predictor Range	Scaled Value(0-1)	% Contribution
POT = MPI-VMAX (KT)	98.7	40.5 to 149.3	0.53	13.6
12 HR PERSISTENCE (KT)	25.0	-22.0 to 44.0	0.71	20.8
D200 (10**7s-1)	116.8	-33.0 to 159.5	0.78	18.5
850-200 MB SHEAR (KT)	6.3	19.6 to 1.3	0.73	16.6
MAXIMUM WIND (KT)	70.0	22.5 to 132.0	0.83	14.9
STD DEV OF IR BR TEMP	6.3	37.8 to 2.1	0.88	14.2
BL DRY-AIR FLUX (W/M2)	120.8	800.8 to -82.5	0.77	-13.8
HEAT CONTENT (KJ/CM2)	61.6	2.7 to 106.7	0.57	7.6
%area of TPW <45 mm upshear	0.0	56.6 to 0.0	1.00	5.0
2nd PC OF IR BR TEMP	-0.3	2.2 to -2.3	0.55	1.6

SHIPS Prob RI for 20kt/ 12hr RI threshold= 100% is 15.9 times climatological mean (6.3%)
SHIPS Prob RI for 25kt/ 24hr RI threshold= 100% is 8.0 times climatological mean (12.5%)
SHIPS Prob RI for 30kt/ 24hr RI threshold= 99% is 11.6 times climatological mean (8.6%)
SHIPS Prob RI for 35kt/ 24hr RI threshold= 98% is 16.1 times climatological mean (6.2%)
SHIPS Prob RI for 40kt/ 24hr RI threshold= 82% is 19.5 times climatological mean (4.2%)
SHIPS Prob RI for 45kt/ 36hr RI threshold= 94% is 14.0 times climatological mean (6.7%)
SHIPS Prob RI for 55kt/ 48hr RI threshold= 58% is 9.9 times climatological mean (5.9%)
SHIPS Prob RI for 65kt/ 72hr RI threshold= 13% is 2.7 times climatological mean (4.7%)

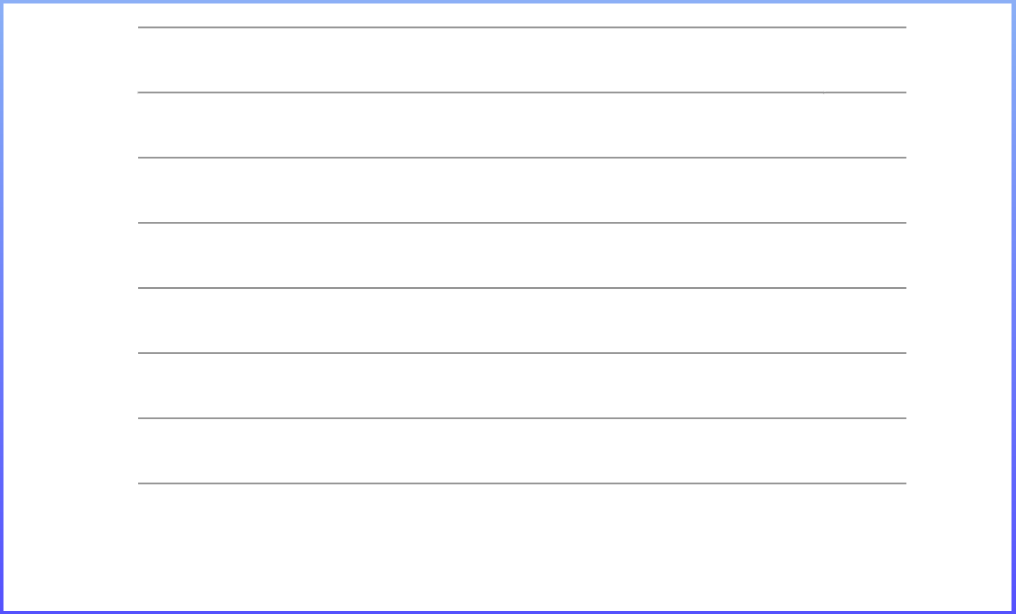
GOES-16 Imagery and Lightning Locations



Using GLM to Improve the RII

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

<u>RII PREDICTORS</u>
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



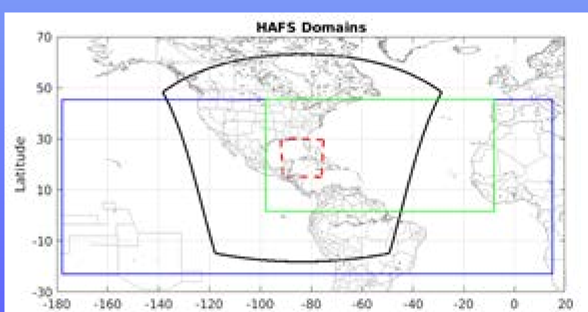
Stevenson et al. (2014, MWR)

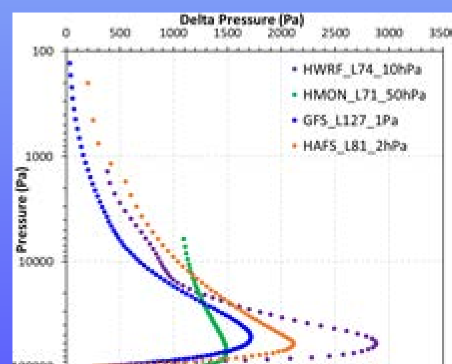
Tropical Cyclone Intensity Dynamical Forecast Models

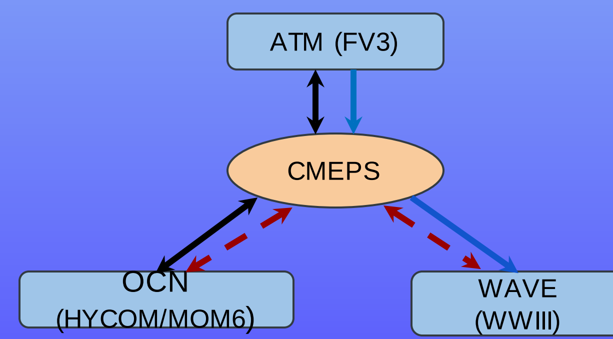
- Regional Models: HWRF, HMON, COAMPS-TC
- Global Models: NCEP GFS, UKMET, ECMWF, Navy NAVGEM, Canadian
- These models have forecast errors due to…
  - sparse observations
  - inadequate resolution (need to go down to a few km grid spacing; the HMON and HWRF, our highest-resolution operational hurricane 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 to due improved resolution, physics and data assimilation

HWRF and HMON being Replaced by HAFS in 2023
Two Configurations for HAFS IOC

HAFSv1.0	Domain*	Resolution*	DA/VI	Ocean/Wave Coupling	Physics	Basins
HFSA	Storm-centric with one moving nest, parent: ~78x75 degree, nest: ~12x12 degree	Regional (ESG)), ~6/2 km, ~L81, ~2 hPa model top	Vmax > 50 kt warm-cycling VI and 4DEnVar DA	Two-way HYCOM, one-way WW3 coupling for NHC AOR	Physics suite-1	All global Basins NHC/CPHC/JTWC Max 7 Storms Replace HWRF
HFSB	Storm-centric with one moving nest, parent: ~75x75 degree, nest: ~12x12 degree	Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top	Vmax > 40 kt warm-cycling VI and 4DEnVar DA	Two-way HYCOM No Wave	Physics suite-2	NHC/CPHC Max 5 Storms Replace HMON





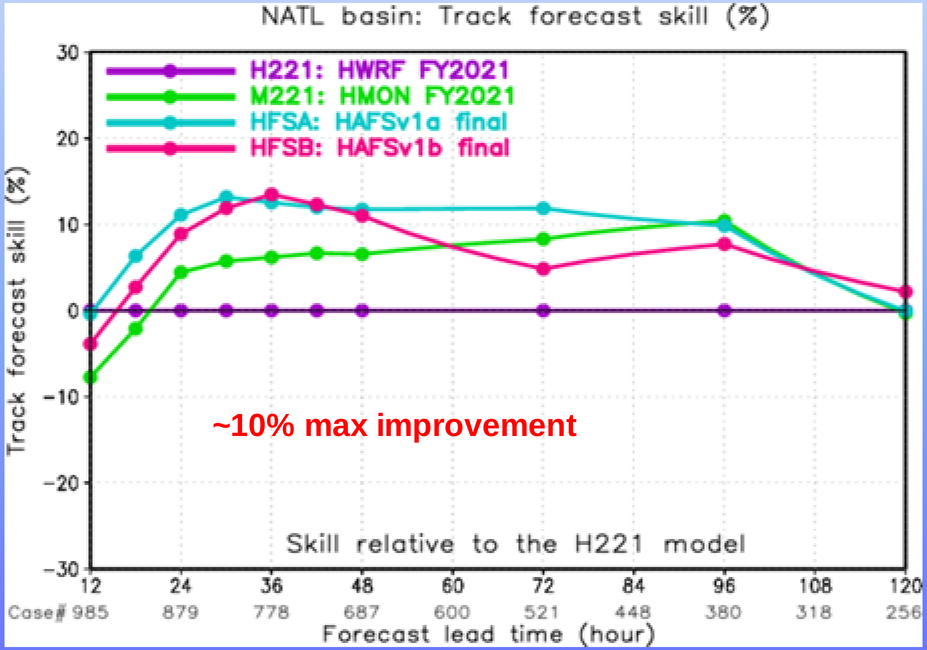


HAFS Physics Schemes

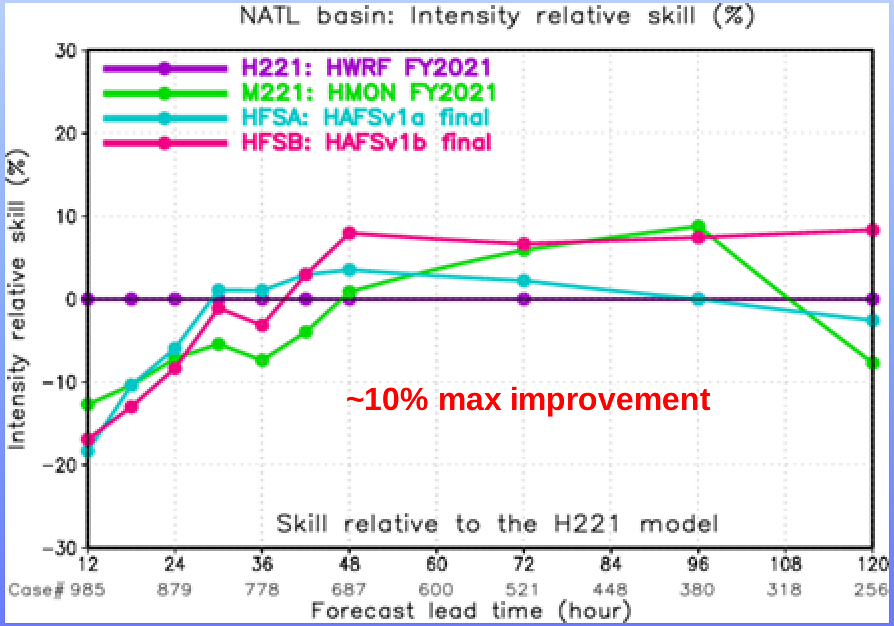
	Suite 1	Suite 2	Reference
Land/ocean Surface	NOAH LSM VIIRS veg type, HYCOM	NOAH LSM VIIRS veg type HYCOM	Ek et al. (2003) …
Surface Layer	GFS, HWRF TC-specific sea surface roughnesses	GFS, HWRF TC-specific sea surface roughnesses	Miyakoda and Sirutis (1986); Long (1984, 1986)
Boundary Layer	Sa-TKE-EDMF, TC-related calibration, **mixing length tuning**	Sa-TKE-EDMF, TC-related calibration, **tc_pbl=1*, mixing length tuning**	Han et al. (2019) *Chen et al. (2022)
Microphysics	**GFDL single-moment**	**Thompson double-moment**	Lin et al. (1983) Chen and Lin (2013)
Radiation	RRTMG Calling frequency **720 s**	RRTMG Calling frequency **1800 s**	Iacono et al. (2008)
Cumulus convection (deep & shallow)	Scale-aware-SAS **calibrated entrainment**	Scale-aware-SAS	Han et al. (2017)
Gravity wave drag	Unified GWD (orographic on/convective off)	Unified GWD (orographic on/convective off)	Alpert et al. (1988)

Final configurations: Track/intensity forecast skills (NATL)
Late Model Verification

Track



Intensity



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**

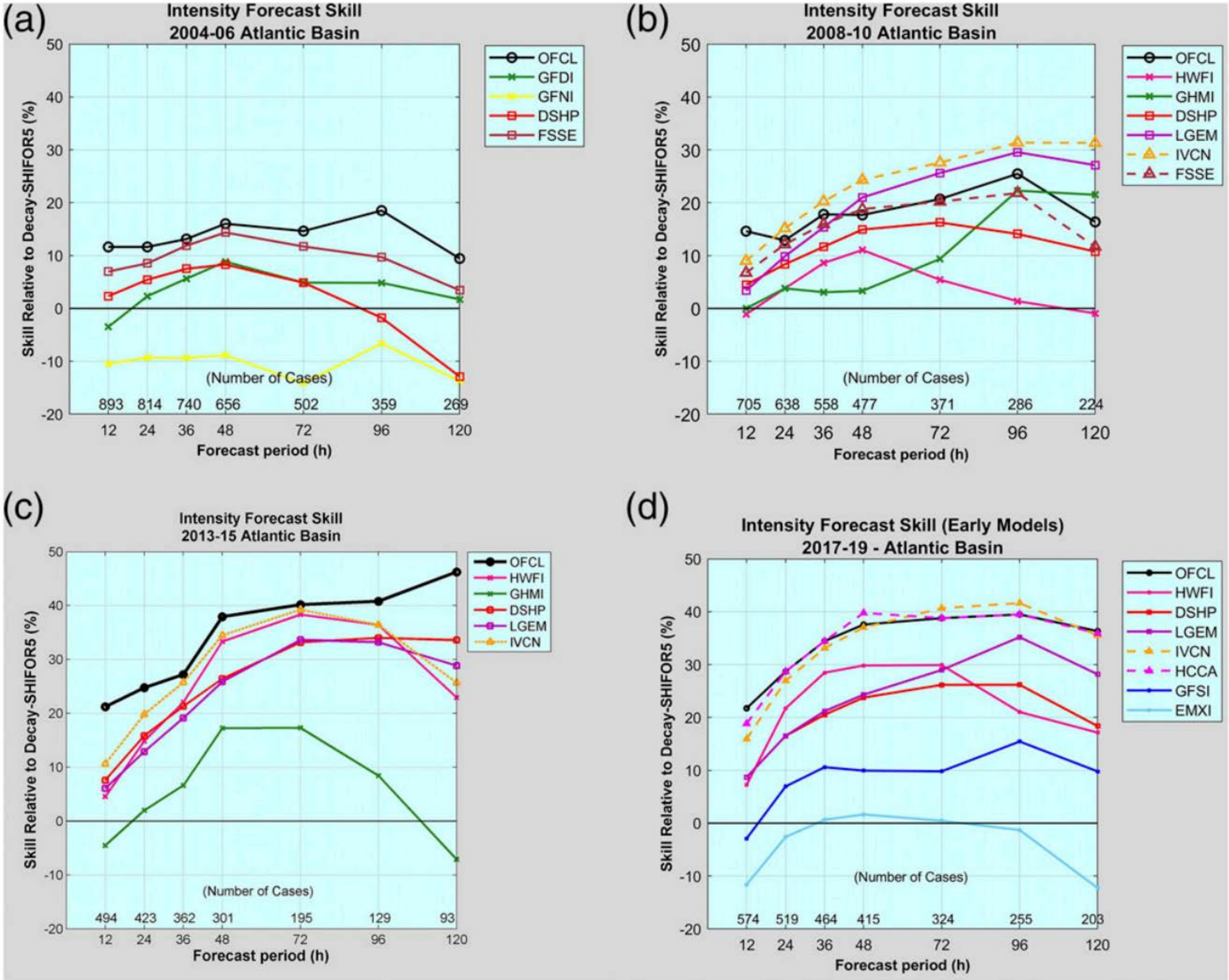
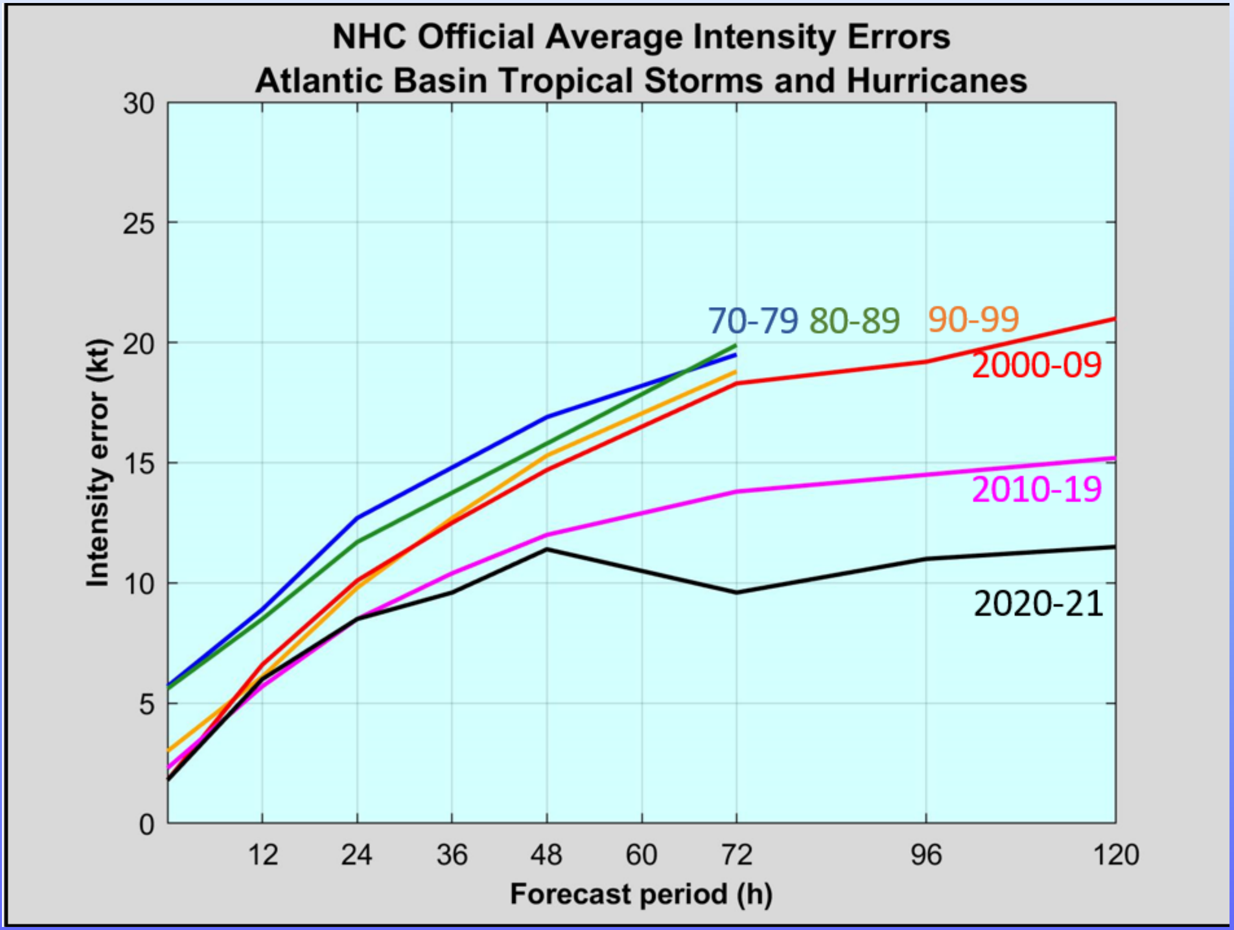


FIG. 5. NHC and intensity model skill for (a) 2004–06, (b) 2008–10, (c) 2013–15, and (d) 2017–19. NHC skill is shown in black, and the various models are depicted in the other colors. The number of verifying events at each forecast lead time is shown above the x axis. Models not previously defined: NHC 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



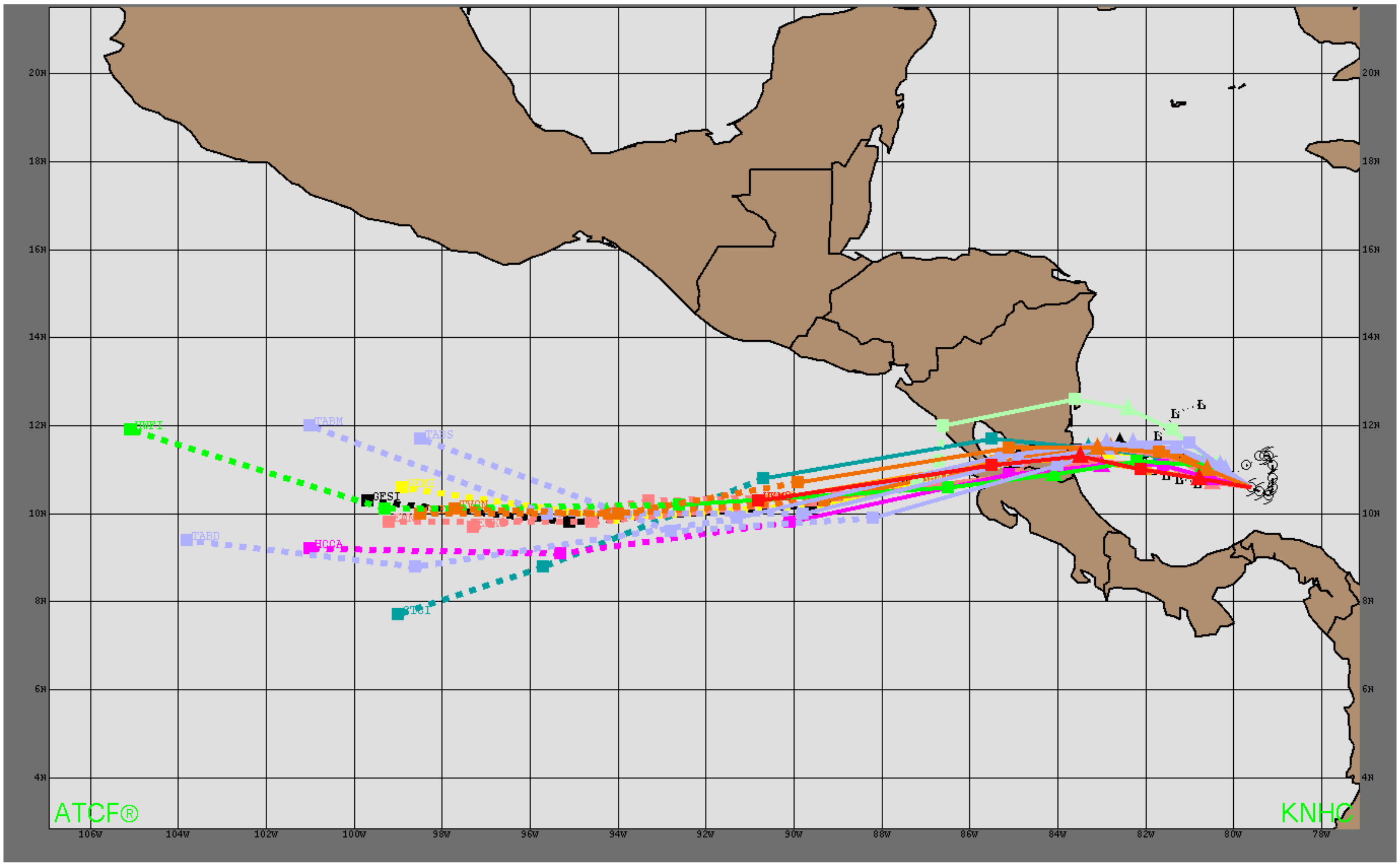
Only small improvements between 1970-2009, but errors have decreased more sharply this decade.

Figure from J. Cangialosi (2022)

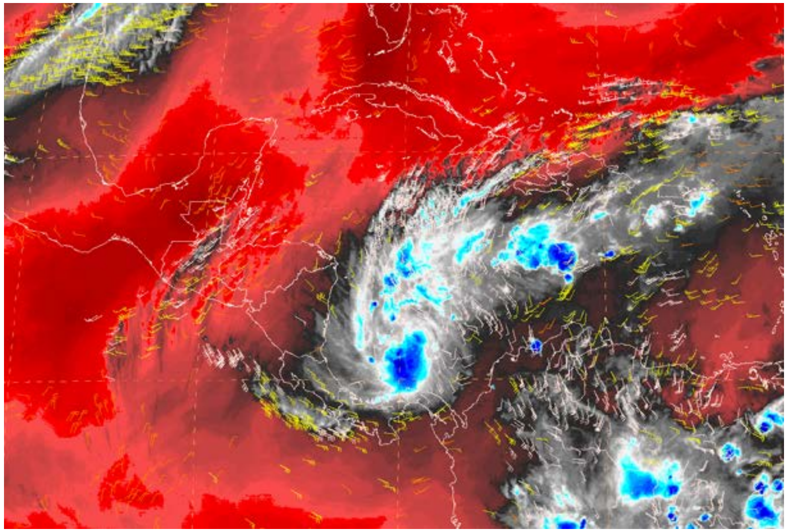
Poll Question 3
Intensity Forecast

Part 2: 36-Hour Forecast Intensity

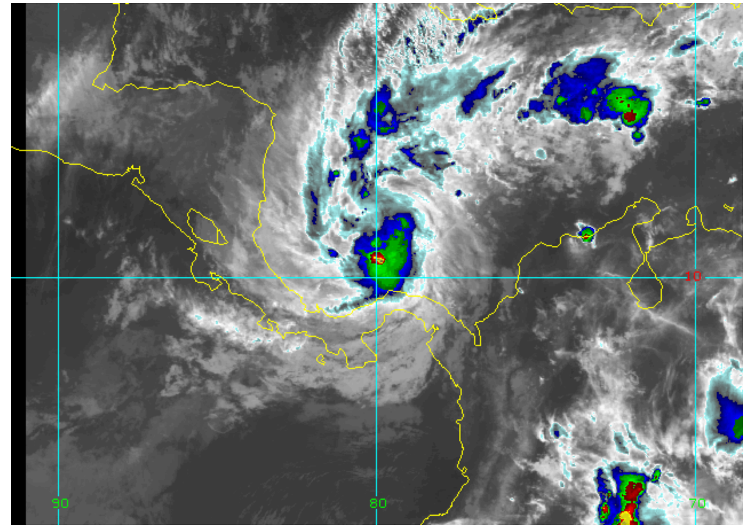
Model Track Guidance

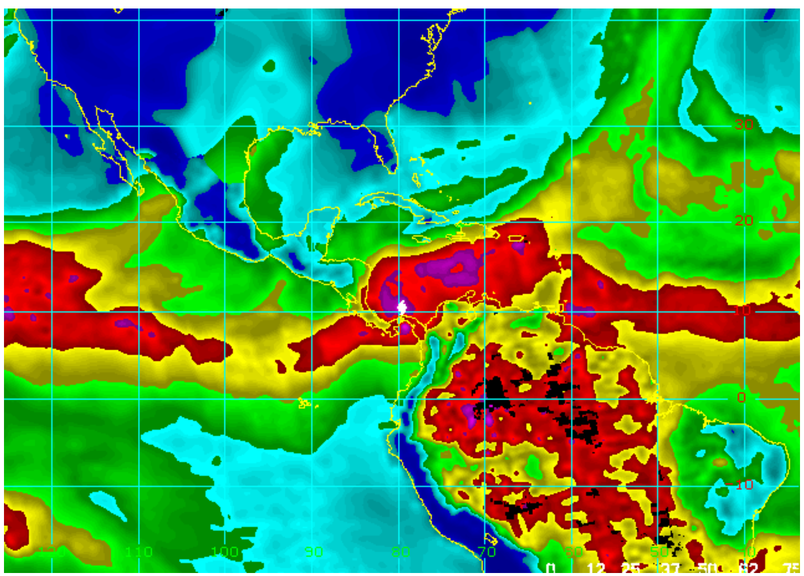


Water Vapor Imagery and Mid- to Upper Level Winds

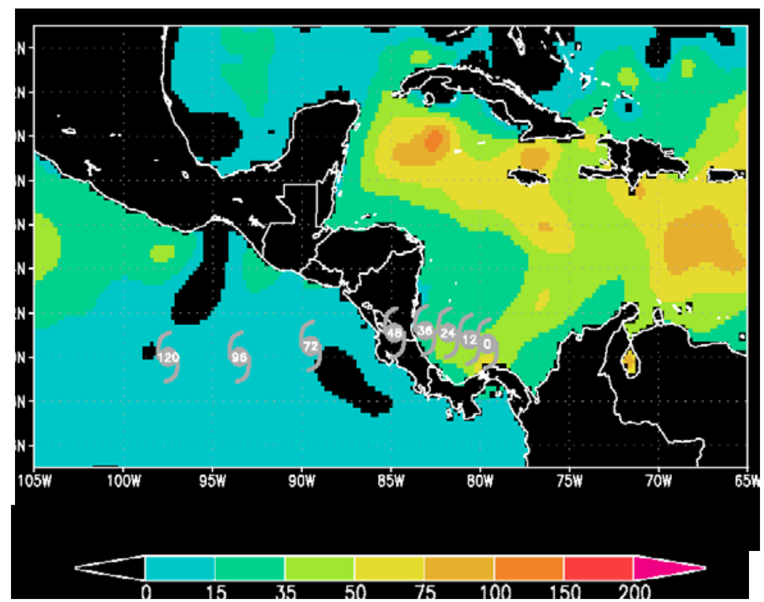


Infrared Imagery (Window Channel)



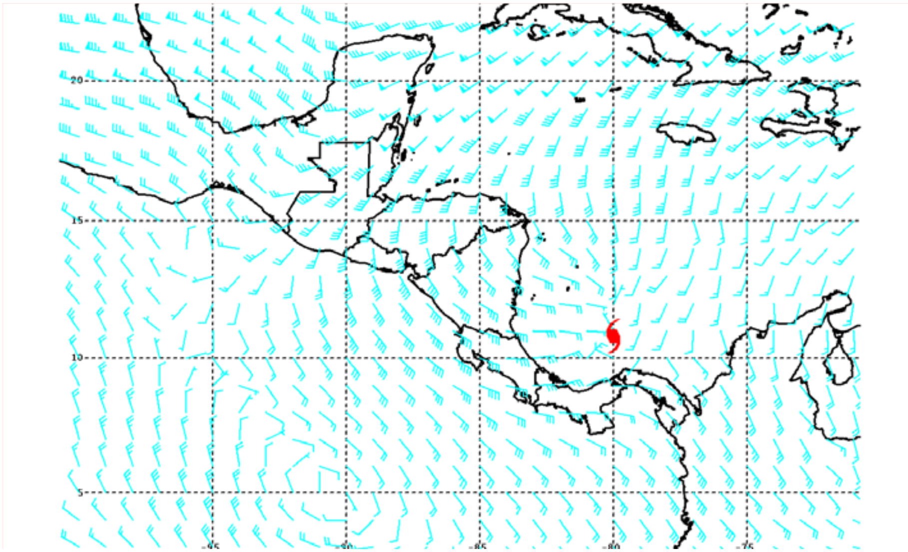


Total Precipitable Water

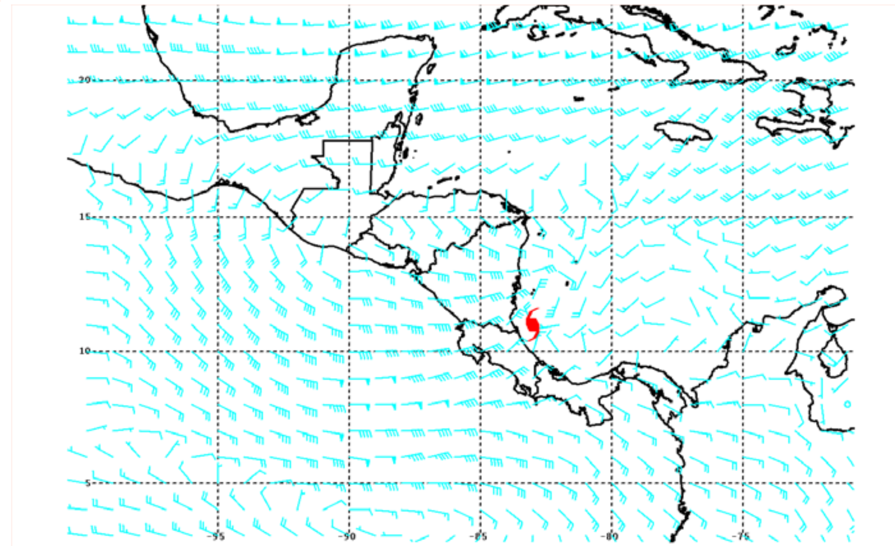


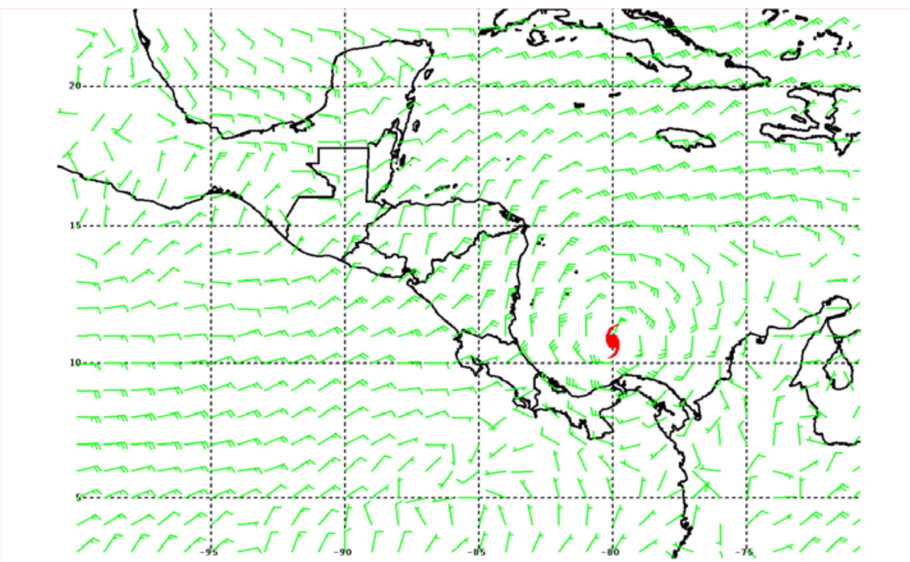
Oceanic Heat Content

200 hPa Wind 6 hr GFS forecast

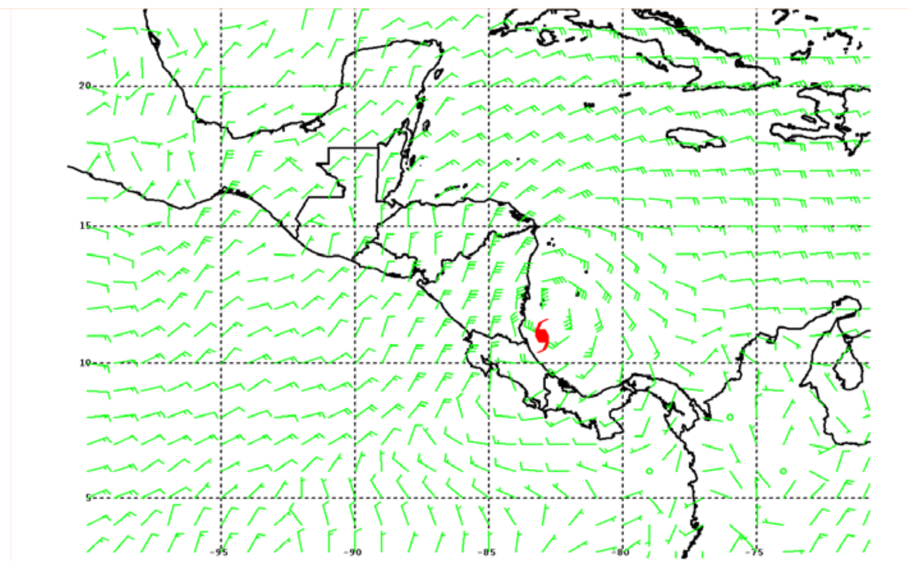


200 hPa Wind 42 hr GFS forecast



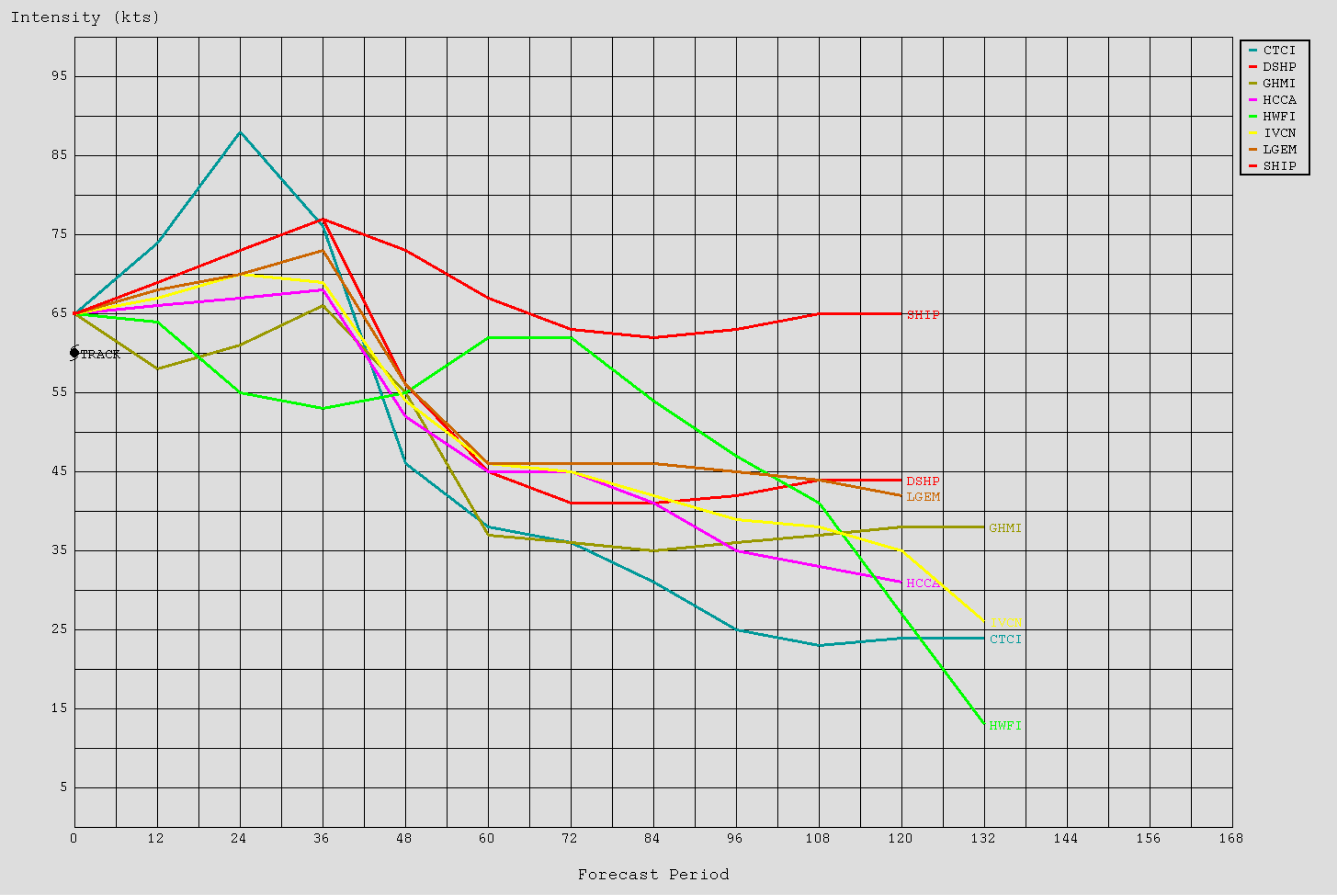


850 hPa Wind 6 hr GFS forecast



850 hPa Wind 42 hr GFS forecast

Intensity Model Guidance



SHIPS/LGEM Model Guidance

* ATLANTIC SHIPS INTENSITY FORECAST *
* IR SAT DATA AVAILABLE, OHC AVAILABLE *

TIME (HR)	0	6	12	18	24	36	48	60	72	84	96	108	120
V (KT) NO LAND	65	67	69	71	73	77	73	67	63	62	63	65	65
V (KT) LAND	65	67	69	71	73	77	56	45	41	41	42	44	44
V (KT) LGEM	65	67	68	69	70	73	56	46	46	46	45	44	42
Storm Type	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP
SHEAR (KT)	14	13	12	11	12	11	16	22	25	25	20	20	24
SHEAR ADJ (KT)	0	-1	-3	-4	-4	-2	-1	-1	0	1	4	8	7
SHEAR DIR	136	151	151	123	116	119	133	135	125	125	115	108	89
SST (C)	29.0	29.0	29.0	29.0	29.1	29.2	28.7	28.1	28.1	28.7	29.1	29.1	28.6
POT. INT. (KT)	148	148	149	150	152	154	147	139	138	146	152	154	147
ADJ. POT. INT.	141	142	144	147	149	151	146	140	139	144	152	160	153
200 MB T (C)	-52.9	-53.0	-53.2	-52.6	-52.8	-53.3	-53.0	-53.6	-53.3	-54.1	-53.8	-54.4	-54.1
200 MB VXT (C)	-0.2	-0.2	-0.1	0.0	0.1	0.1	0.1	0.2	0.3	0.1	0.0	0.0	0.0
TH_E DEV (C)	6	5	4	5	5	4	5	4	5	4	4	4	5
700-500 MB RH	63	66	67	69	70	74	75	74	71	65	67	60	58
MODEL VTX (KT)	17	18	18	18	17	20	15	11	8	10	11	11	10
850 MB ENV VOR	51	63	64	66	62	62	61	46	48	28	8	-6	-7
200 MB DIV	68	86	109	104	61	64	61	45	61	65	80	77	65
700-850 TADV	0	1	0	0	1	1	6	10	9	10	8	5	1
LAND (KM)	111	135	163	212	196	85	-55	83	311	412	463	559	695
LAT (DEG N)	10.6	10.8	10.9	11.0	11.1	11.1	11.1	10.8	10.3	10.0	9.9	9.8	9.5
LONG(DEG W)	79.6	79.9	80.2	80.8	81.5	82.9	84.4	86.6	89.1	91.1	92.2	94.3	97.1
STM SPEED (KT)	3	3	5	6	7	7	9	12	11	7	8	12	14
HEAT CONTENT	44	41	37	35	35	31	24	3	12	4	6	7	3

FORECAST TRACK FROM OFCI INITIAL HEADING/SPEED (DEG/KT):290/ 2 CX,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)

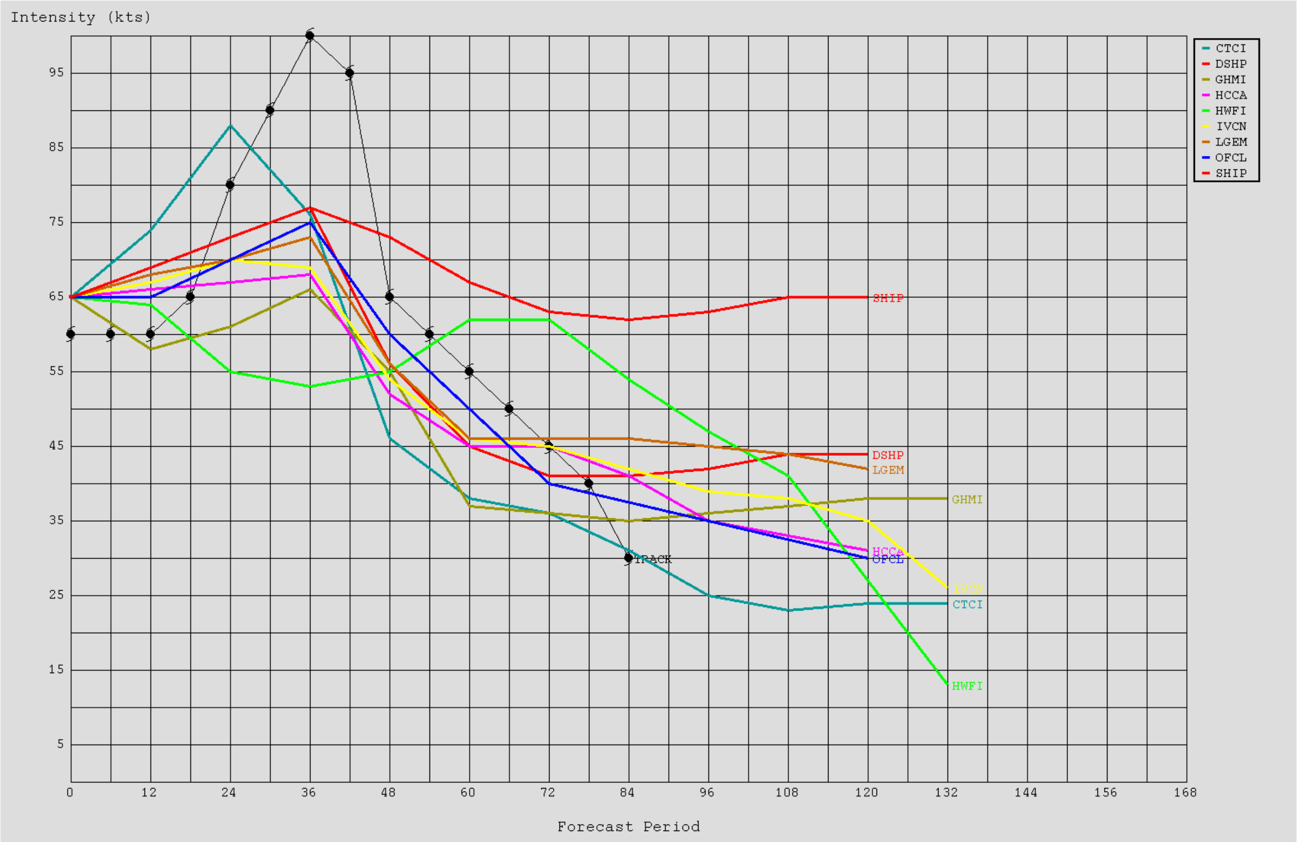
Predictor	Value	RI Predictor Range	Scaled Value(0-1)	% Contribution
12 HR PERSISTENCE (KT):	5.0	-49.5 to 33.0	0.66	6.3
850-200 MB SHEAR (KT) :	12.5	28.8 to 2.9	0.63	2.7
HEAT CONTENT (KJ/cm2) :	38.4	0.0 to 155.1	0.25	0.8
STD DEV OF IR BR TEMP :	10.1	37.5 to 2.9	0.79	3.3
2nd PC OF IR BR TEMP :	0.1	2.8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

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%)

What is your 36 hr Intensity Forecast?

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