Tropical Cyclone Intensity Analysis and Forecasting

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WMO RA-IV Workshop on
Hurricane Forecasting and Warning
Miami, Florida
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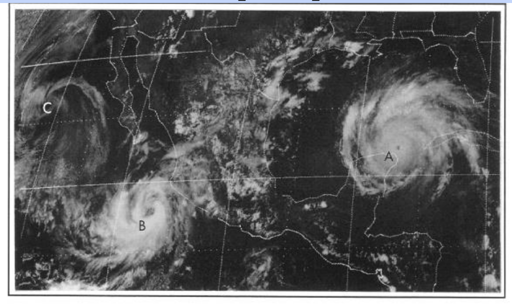
Outline

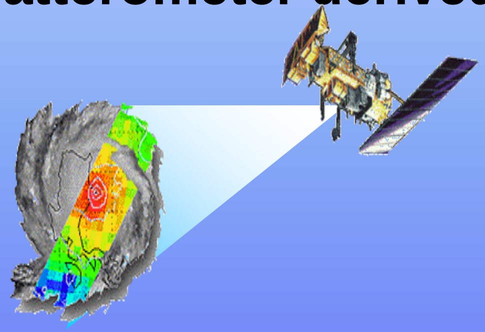
- Estimating the Current Intensity (with Exercise)
- Factors that Influence Intensity Change
- Intensity Forecasting Models
- Official Intensity Forecasts
- Intensity Forecast Exercise

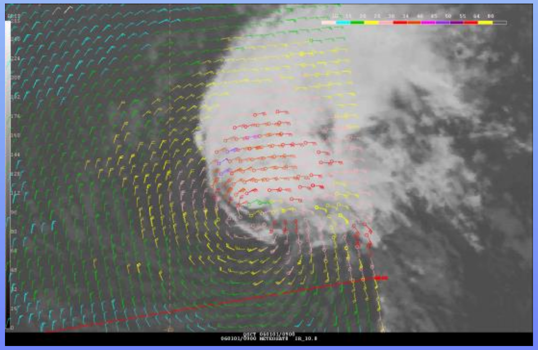
How Do We Estimate Intensity?

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

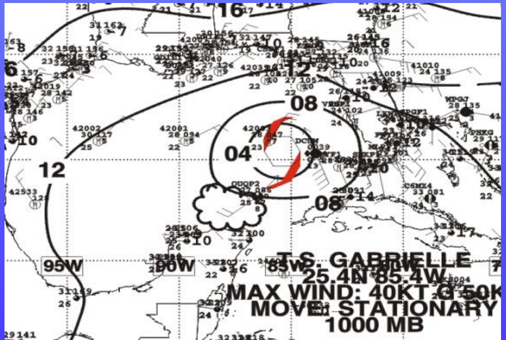


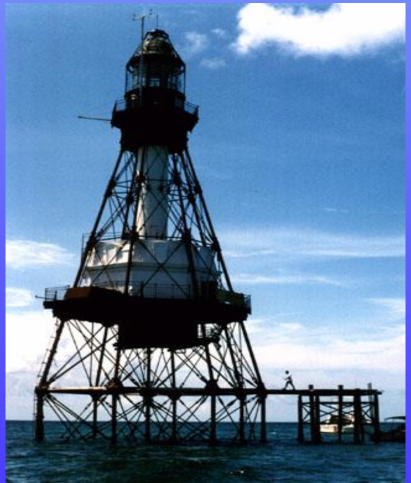
  - **Microwave soundings (AMSU)**
  - **Scatterometer derived surface winds (ASCAT)**





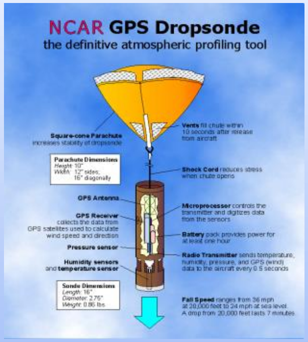
- **Surface observations**
  - **Ships, buoys, land stations (limited)**

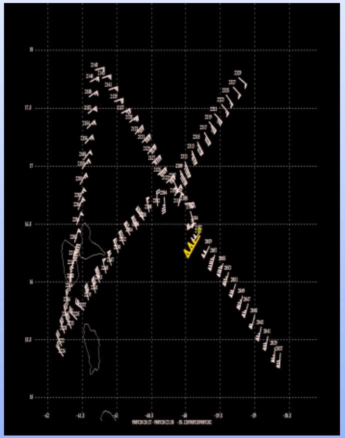


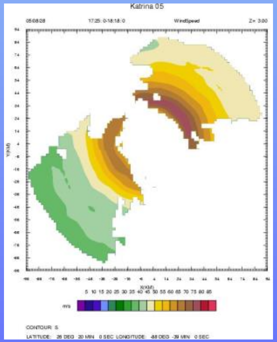


How Do We Estimate Intensity?

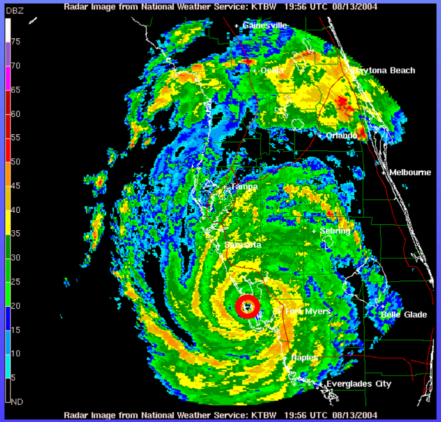
- **Aircraft reconnaissance**
  - **Flight-level winds**
  - **GPS dropsondes**
  - **Stepped-Frequency Microwave Radiometer (SFMR)**

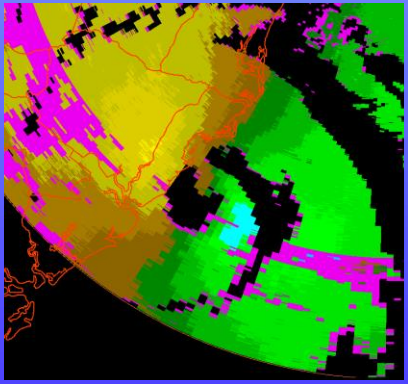




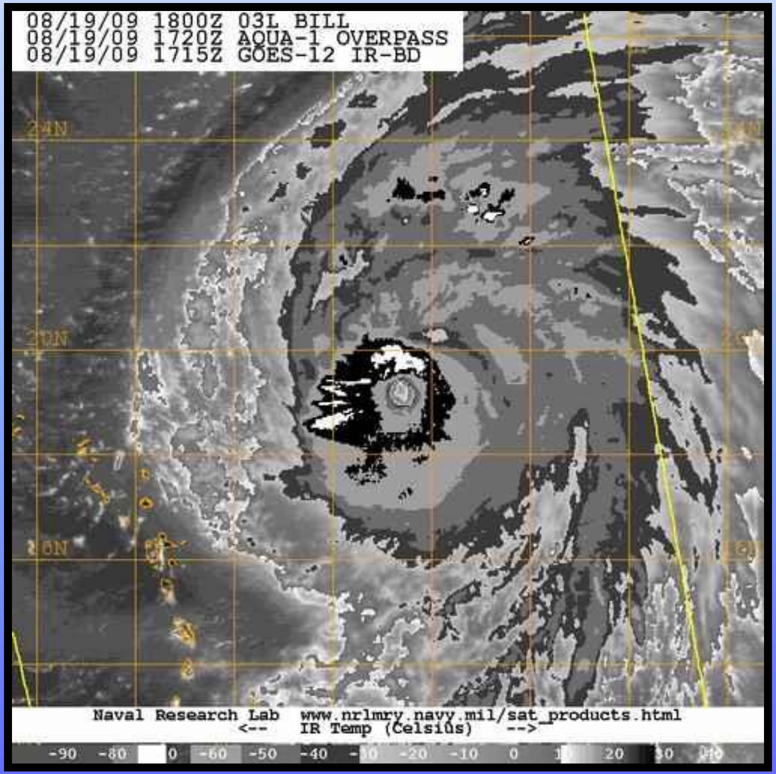


- **Doppler radar**
  - **Land-based (WSR-88D)**
  - **Airborne**





Exercise 1: 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

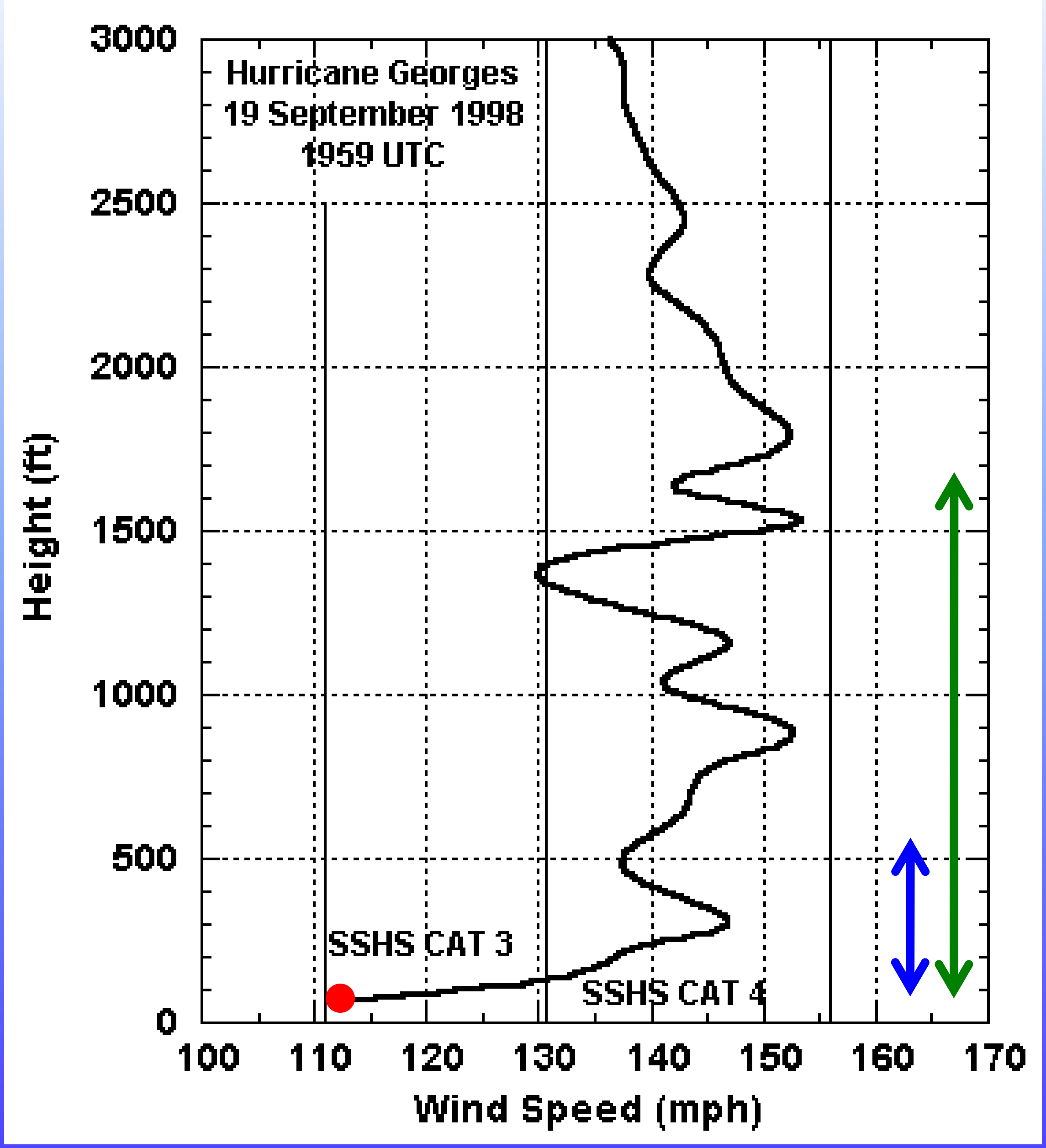
```
000
URNT12 KNHC 191819 CCA
VORTEX DATA MESSAGE   AL032009
A. 19/17:57:30Z
B. 19 deg 16 min N
   056 deg 55 min W
C. 700 mb 2665 m
D. 102 kt
E. 056 deg 24 nm
F. 134 deg 135 kt
G. 055 deg 27 nm
H. 947 mb
I. 11 C / 3045 m
J. 19 C / 3047 m
K. 6 C / NA
L. OPEN SW
M. C32
N. 12345 / 07
O. 0.02 / 0.5 nm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

Surface Wind

Dropsonde

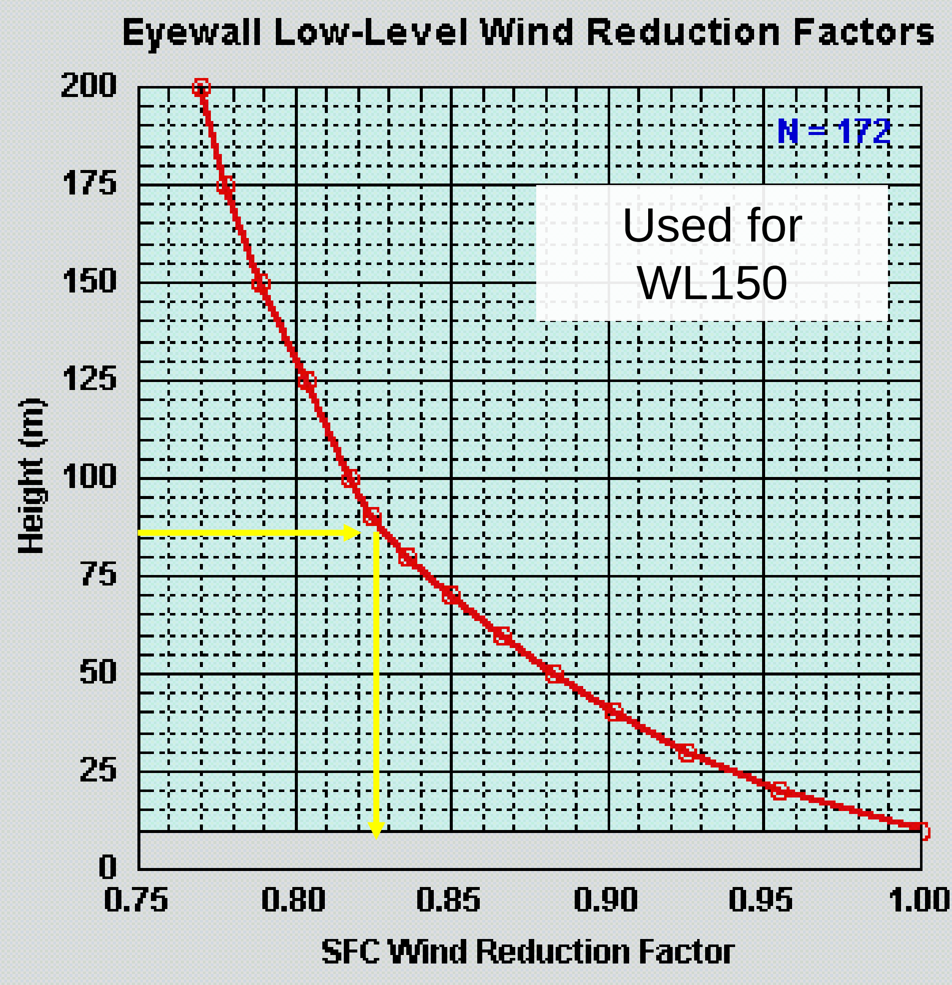
```
000
UZNT13 KNHC 192344
XXAA  69237 99203 70578 07807 99955 25600 09122 00912 ///// /////
92277 23801 10140 85016 20600 11641 70686 148// 14599 88999 77999
31313 09608 82322
61616 NOAA3 WX03A BILL4 OB 11
62626 REL 2033N05779W 232240 SPG 2042N05793W 232707 WL150 09134 0
86 DLM WND 12128 954696 MBL 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 × 0.8 = 111 kt

WL150 (lowest 150 mb) =
134 × 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

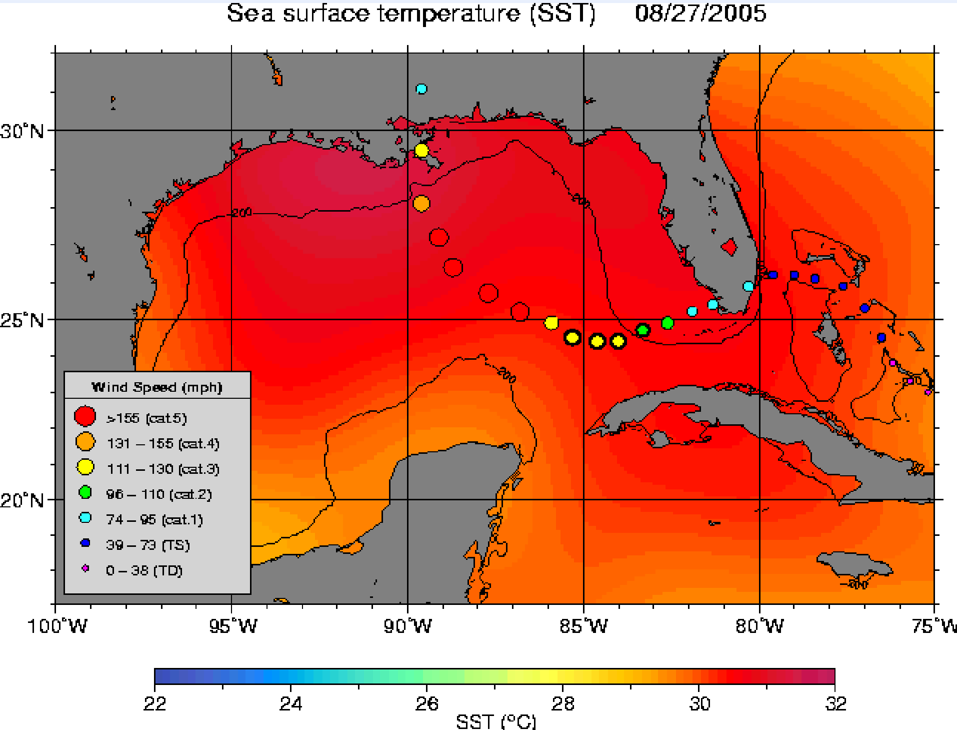
***representative* of the TC's circulation**

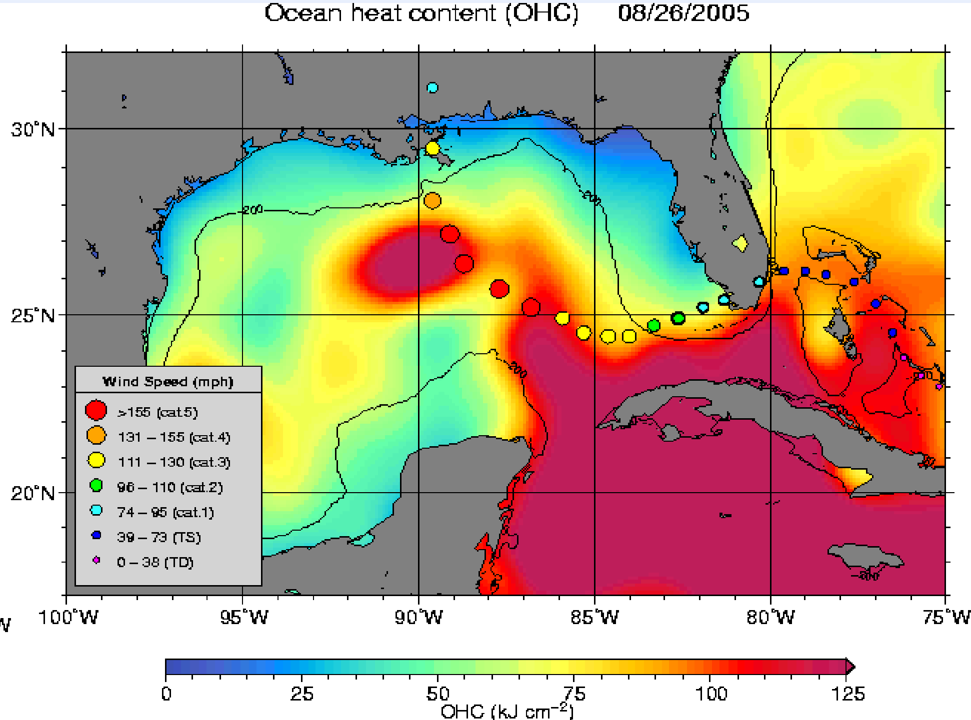
EXERCISE 1
Intensity Estimation

Factors Affecting
Tropical Cyclone Intensity

- **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

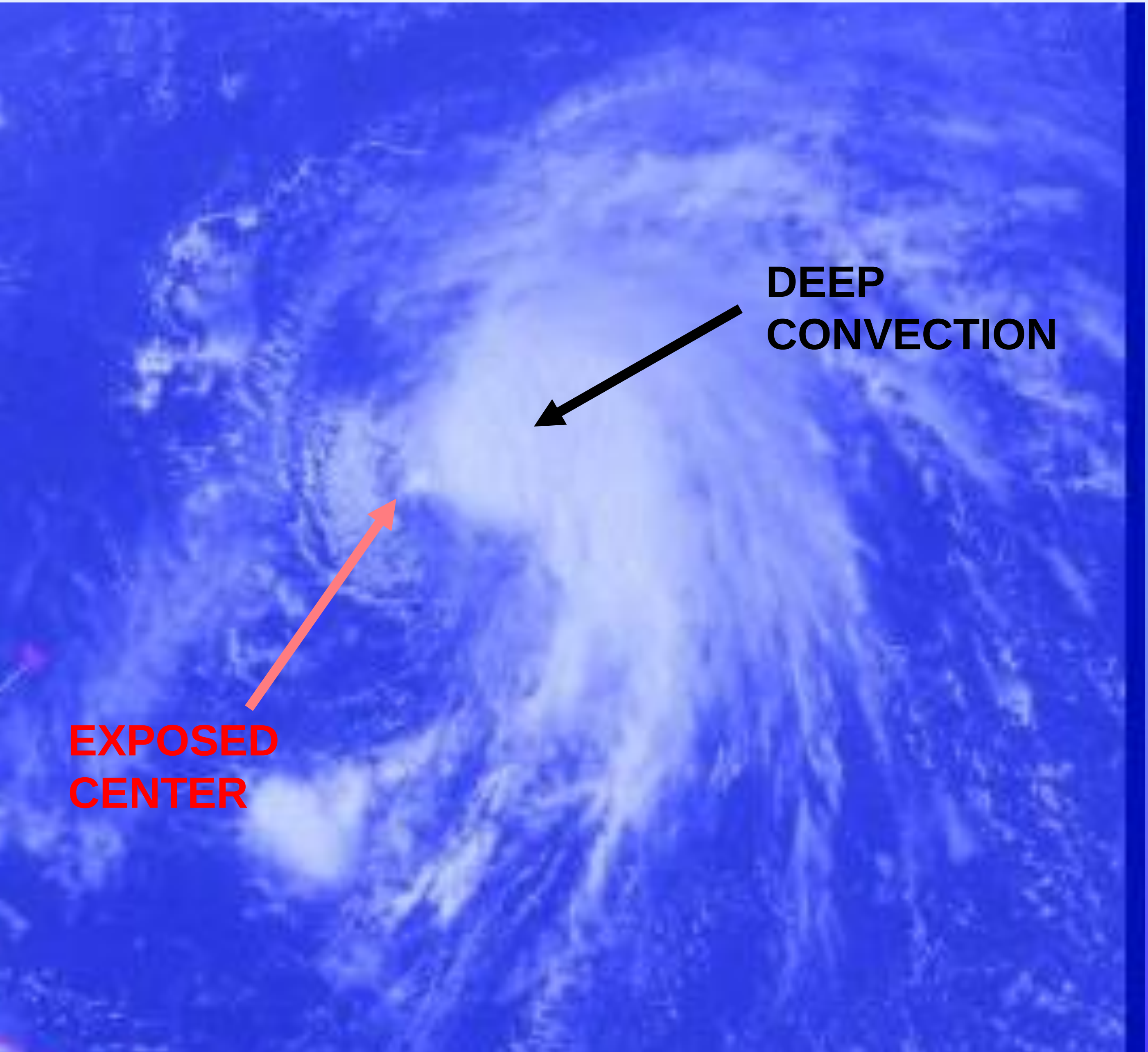
only provides a view of the very top layer of the ocean.

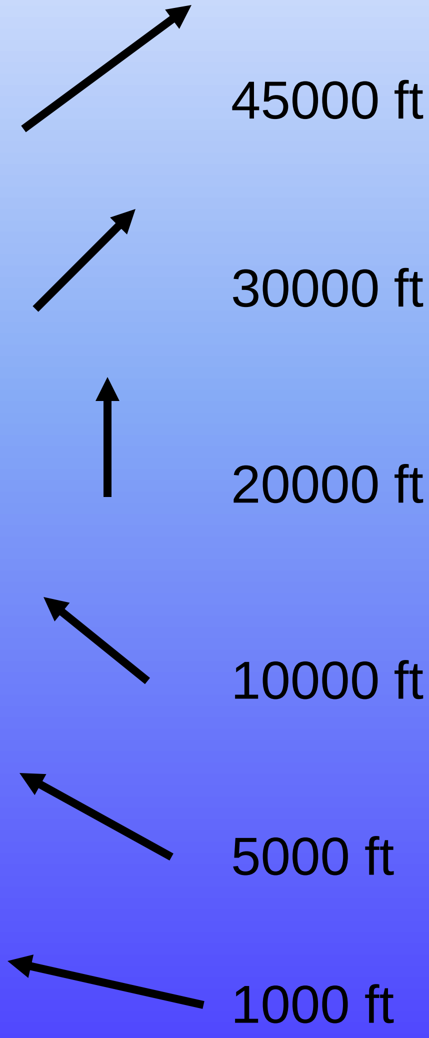
Ocean Heat Content

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

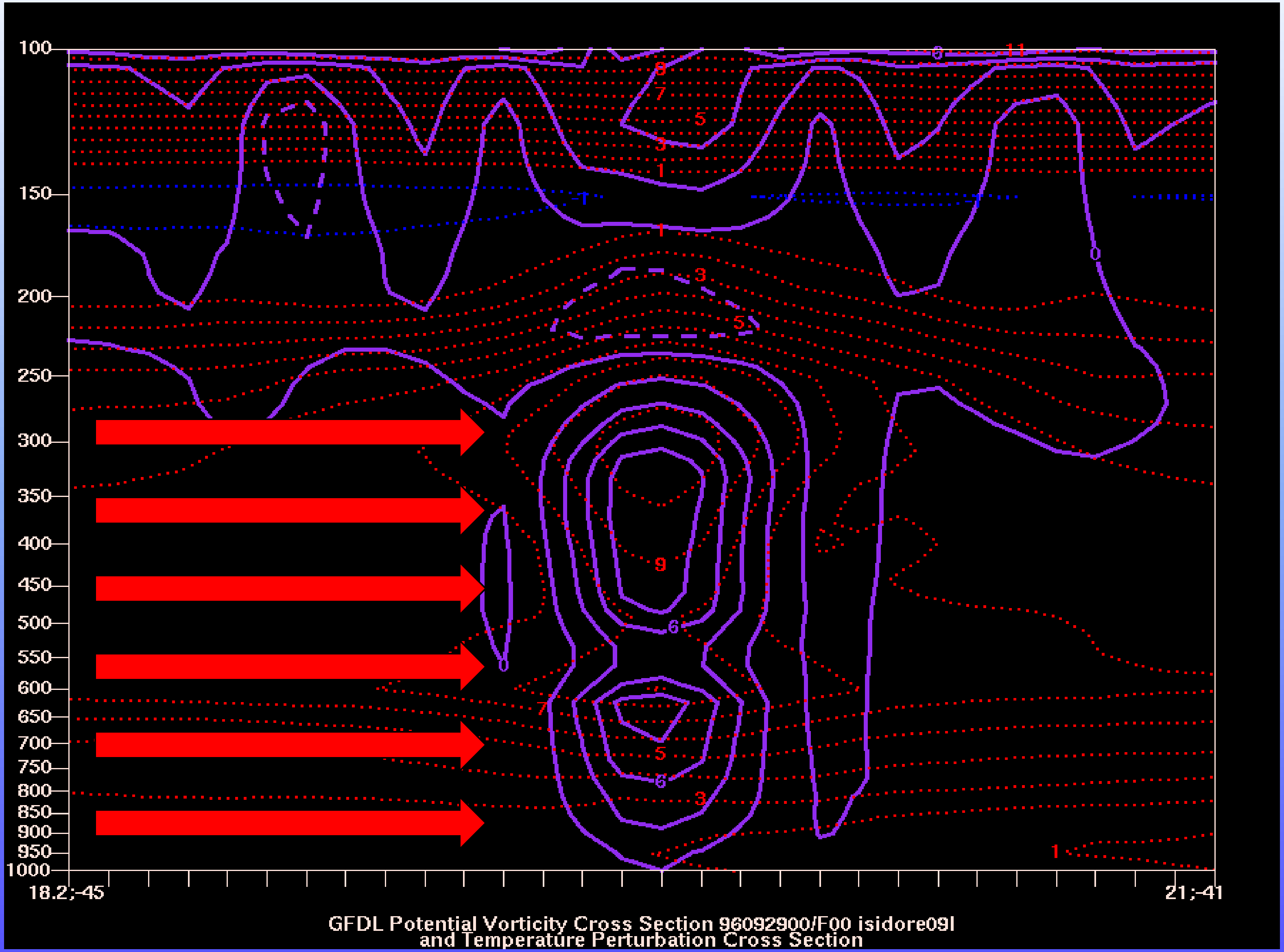
the greater the depth the more available heat that can be potentially converted to energy

Vertical Wind Shear



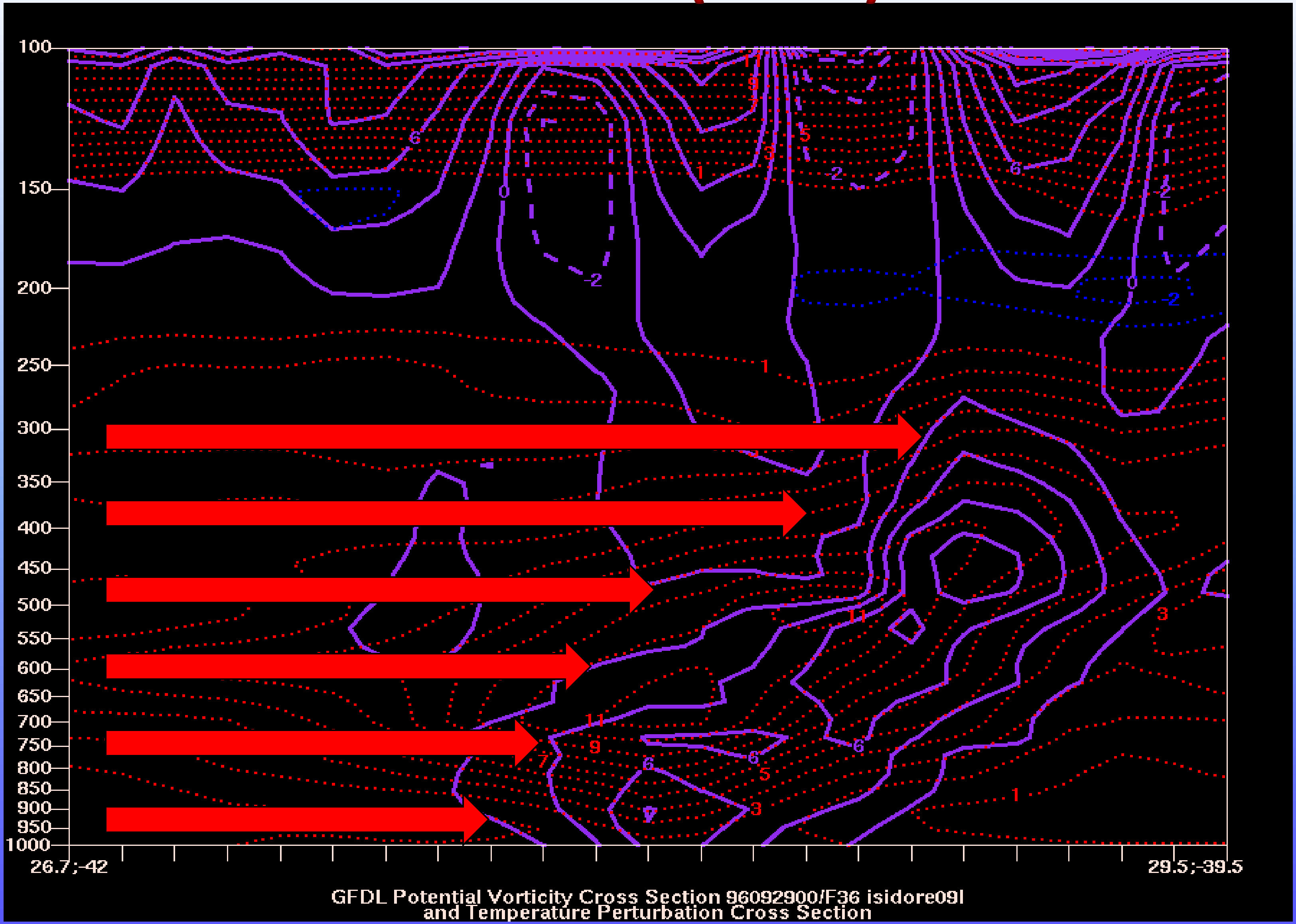


Isidore (1996)



Vertical cross-section of PV (purple) and temperature anomaly from the GFDL model for the initialization of the 0000 UTC forecast on September 29

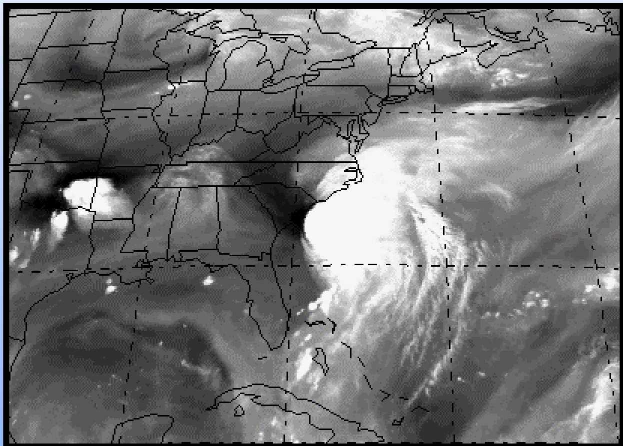
Isidore (1996)

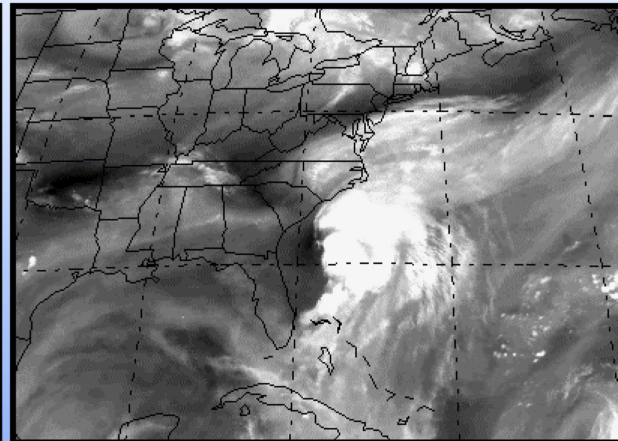


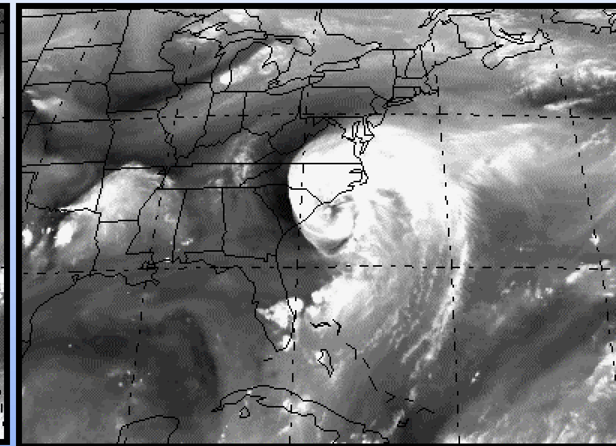
Vertical cross-section of PV (purple) and temperature anomaly from the 36-hour forecast GFDL model for the initialization of the 0000 UTC forecast on September 29

Hurricane-Trough Interaction

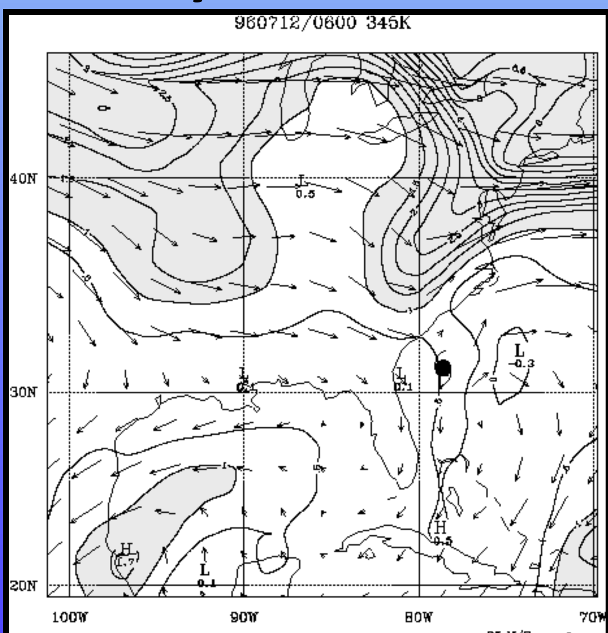
Hurricane Bertha (1996)

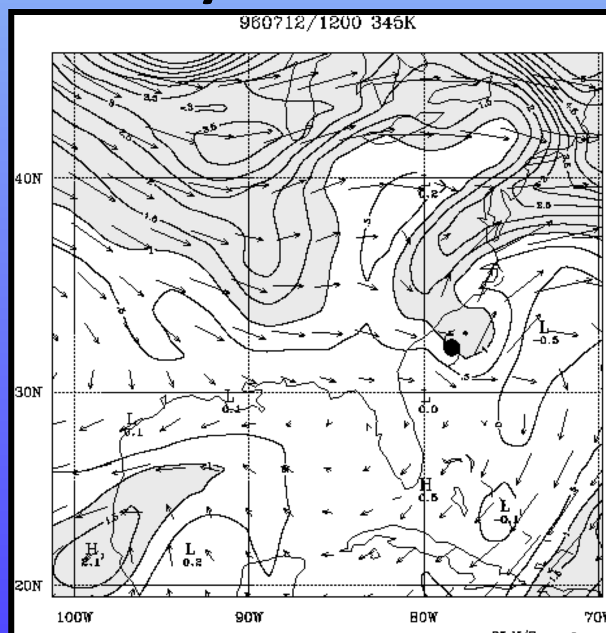


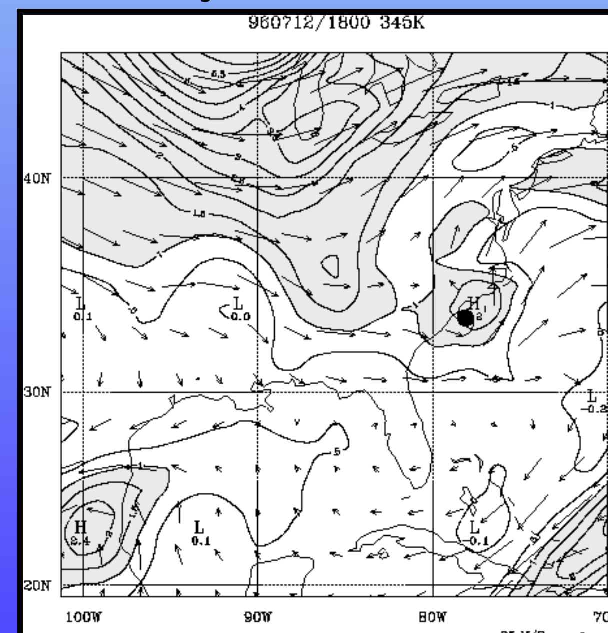




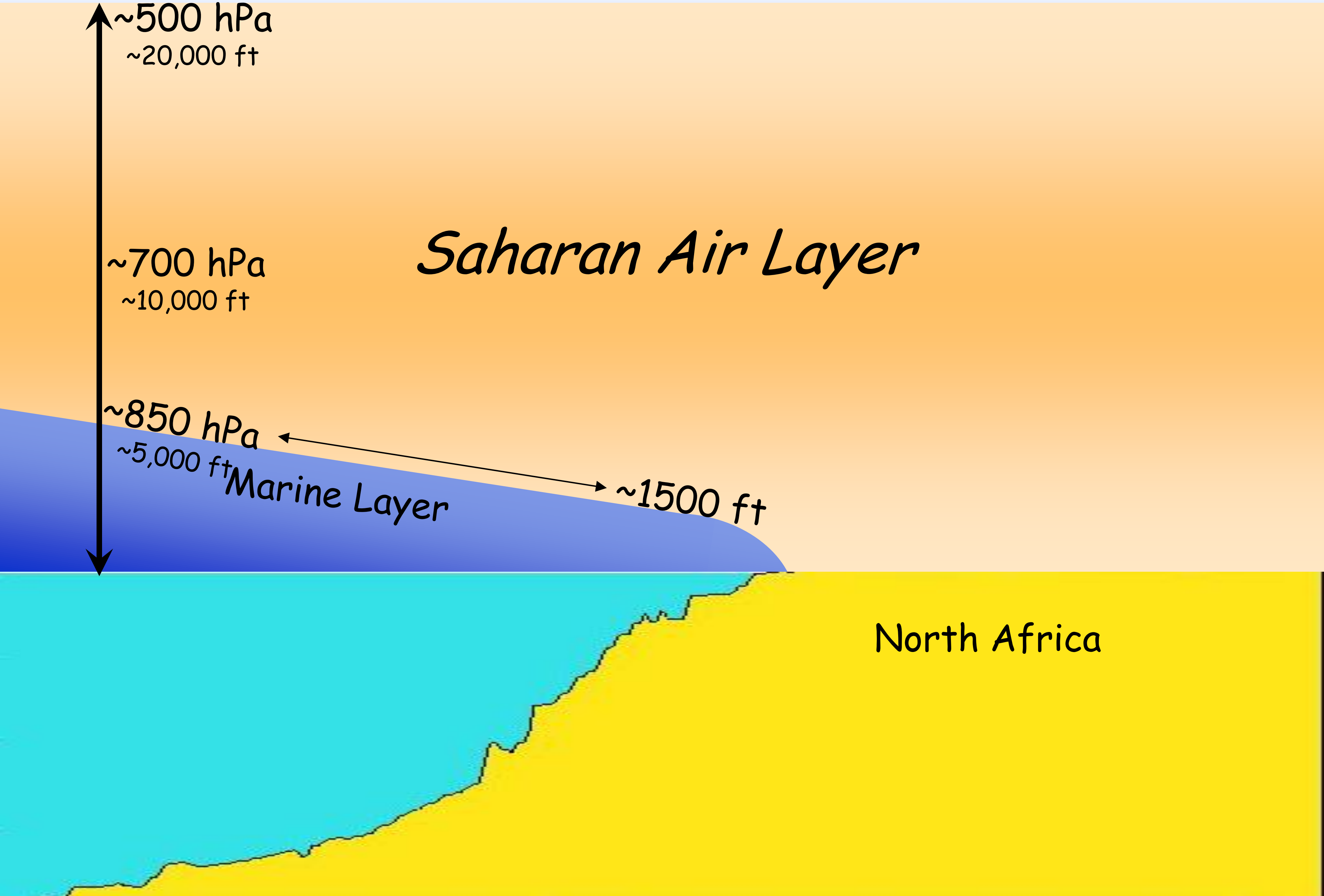
12 July 1995 06 UTC **12 July 1995 12 UTC** **12 July 1995 18 UTC**



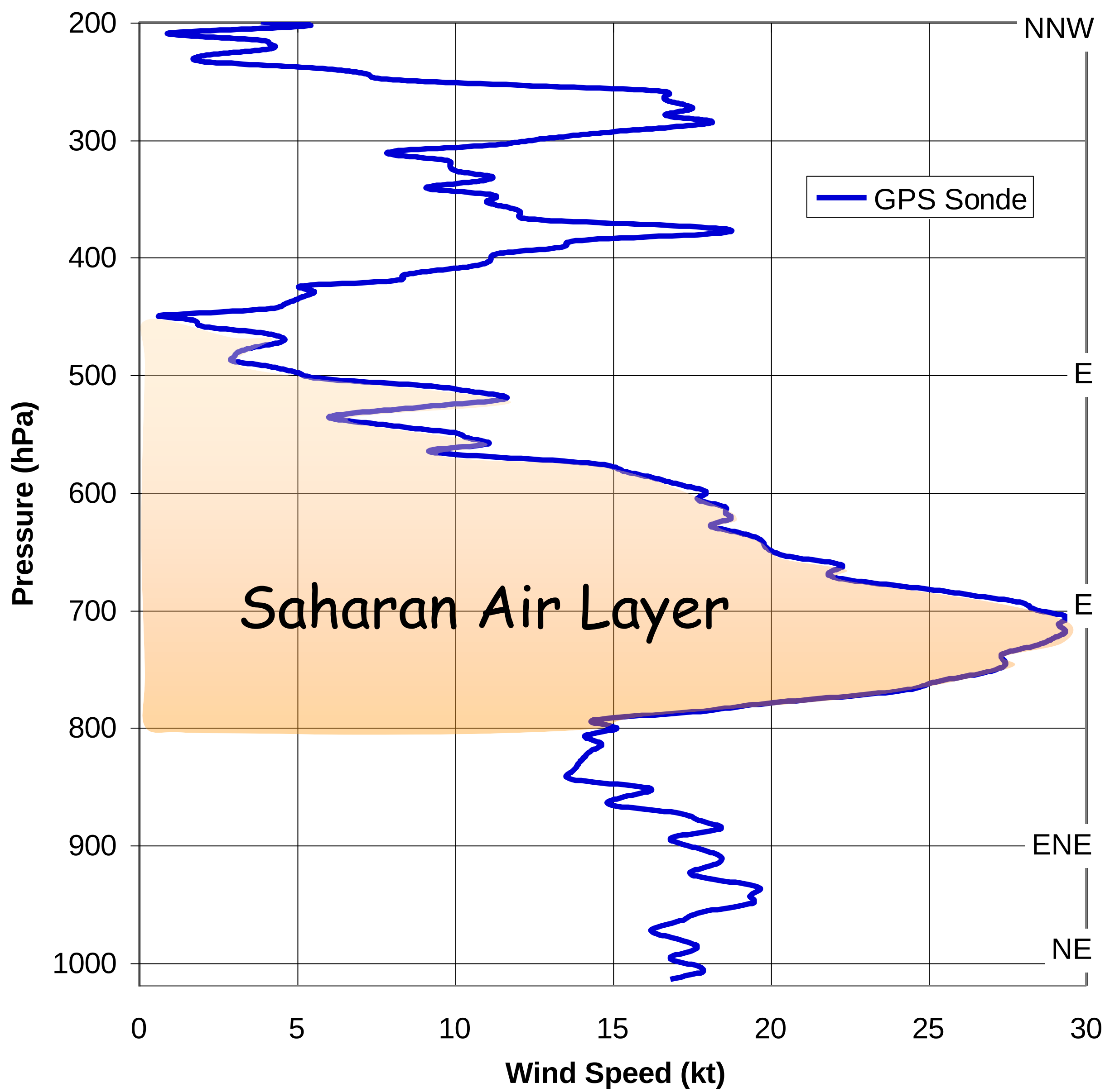




Saharan Air Layer

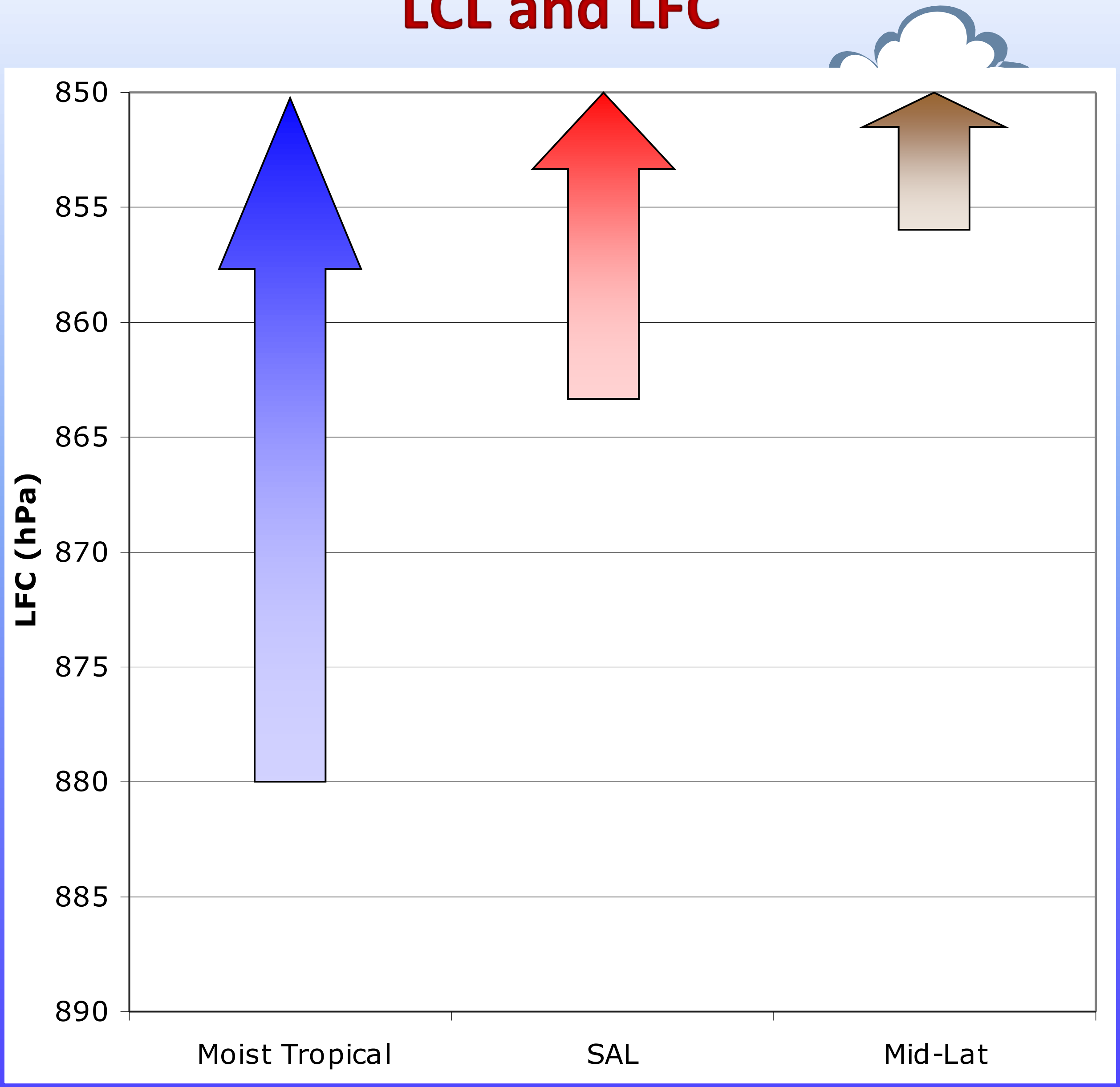


Getting Dry Air into the TC Circulation



How Moisture Affects Stability

LCL and LFC



Eyewall Replacement Cycles

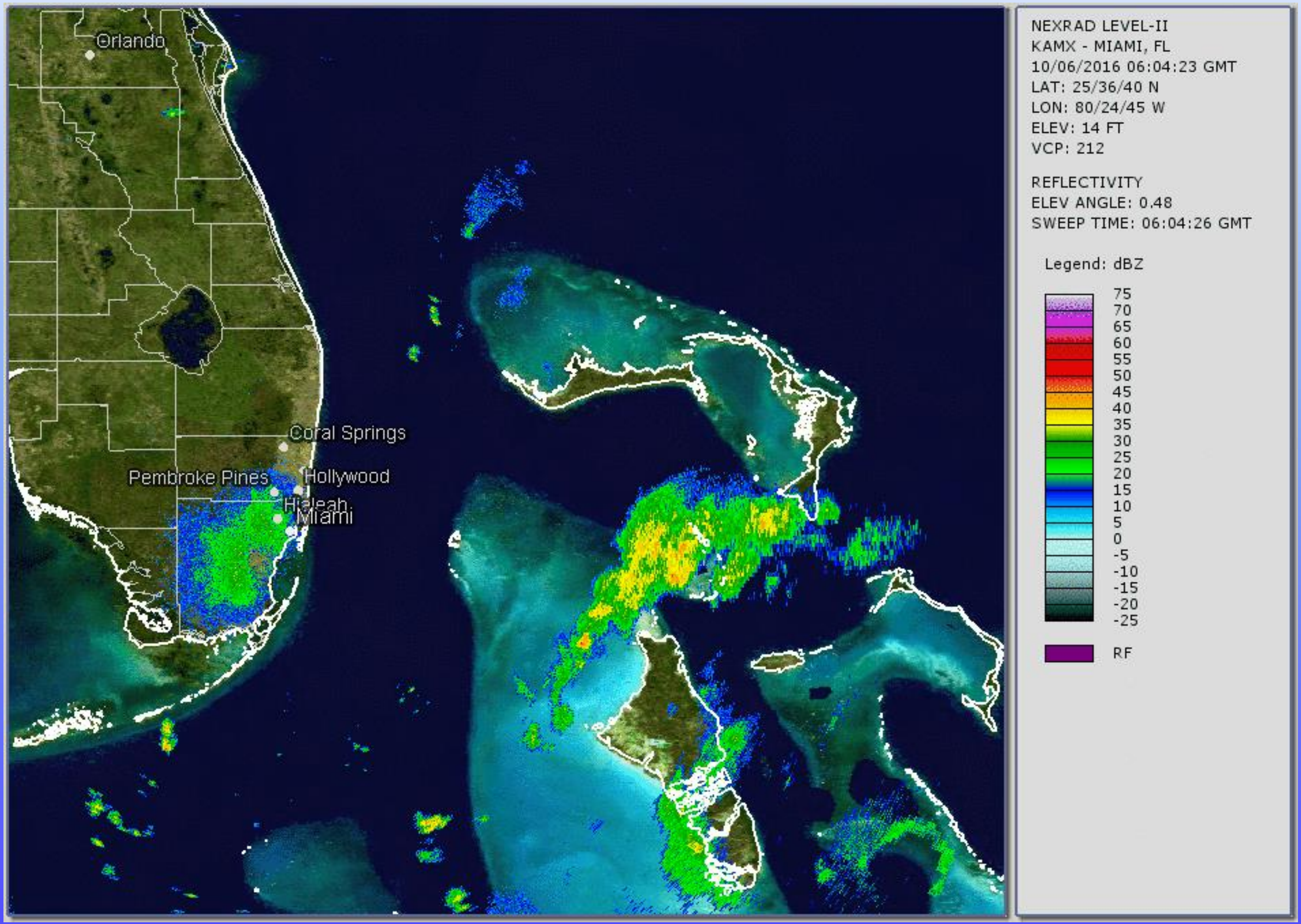
In addition to large-scale environmental influences, tropical cyclone intensity change can be caused by inner-core processes, such as eyewall replacement cycles:

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

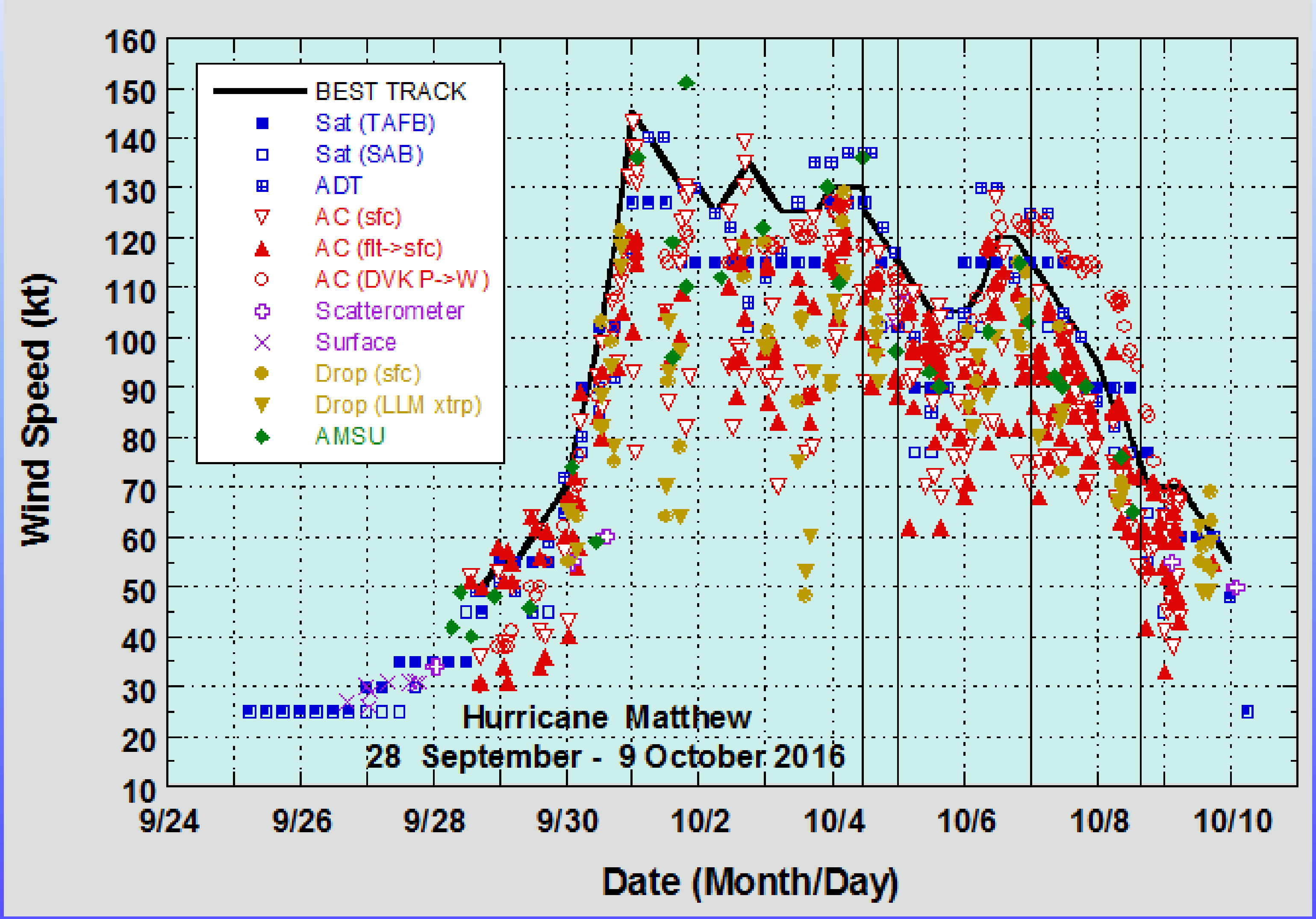
When this outer eyewall becomes dominant, some weakening usually occurs.

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

Hurricane Matthew Radar Loop

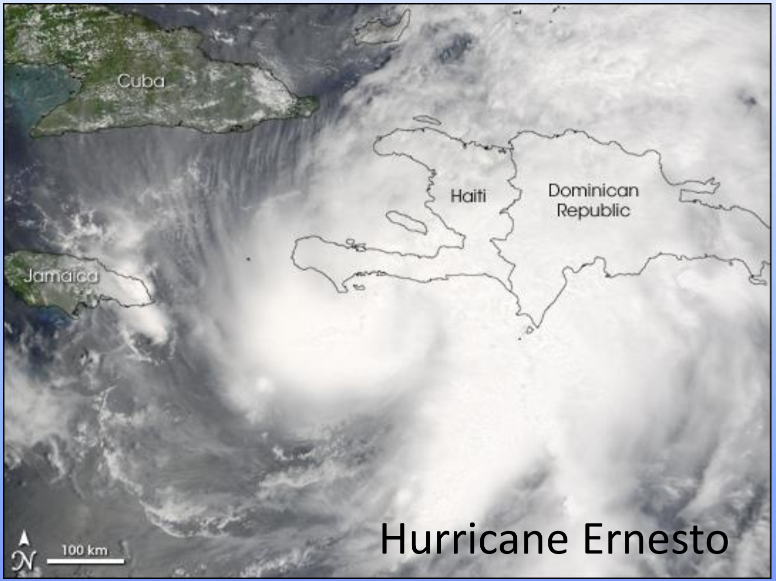


Hurricane Matthew Maximum Wind



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



Hurricane Ernesto

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**

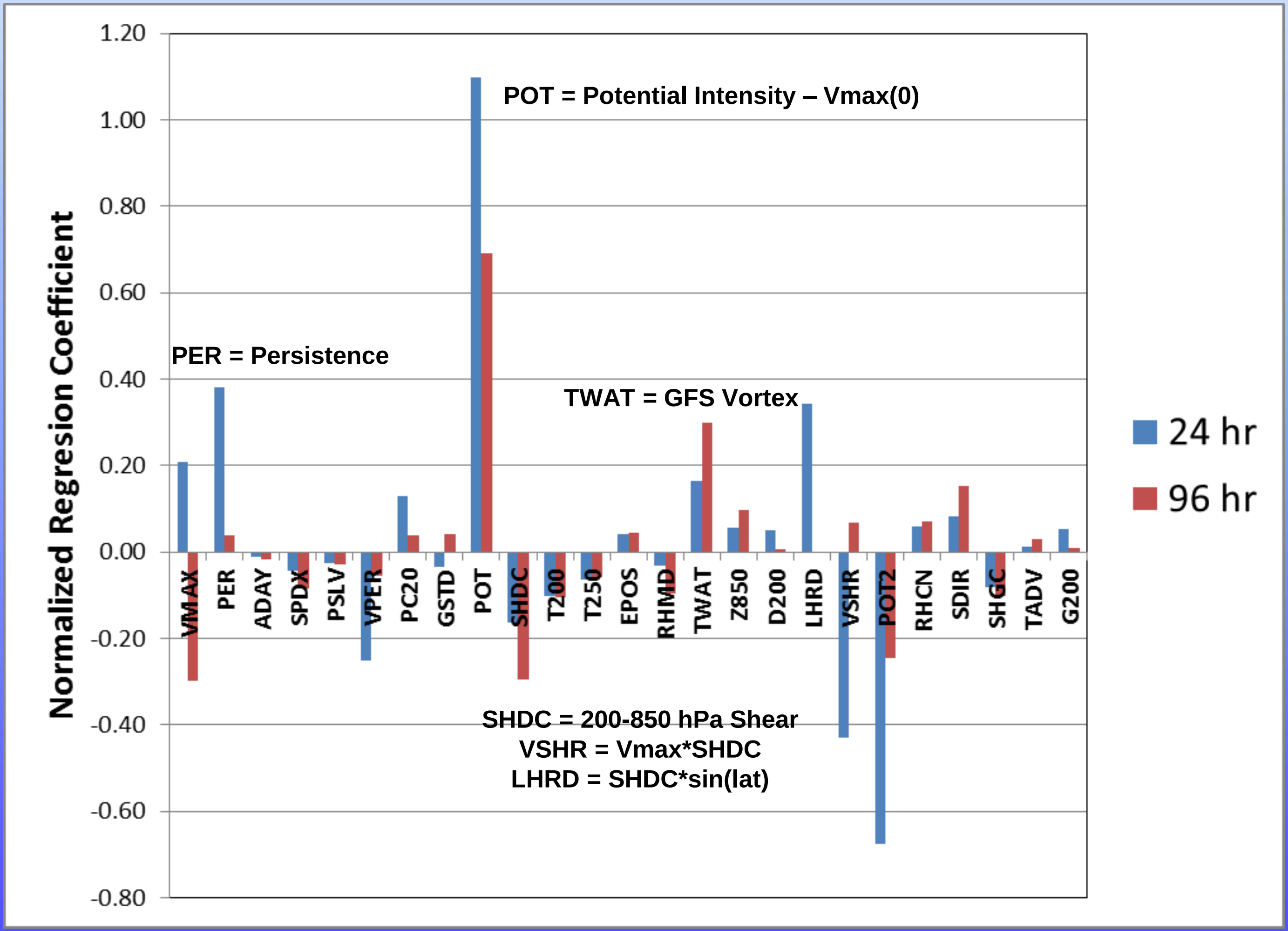
Overview of the SHIPS Model

- 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

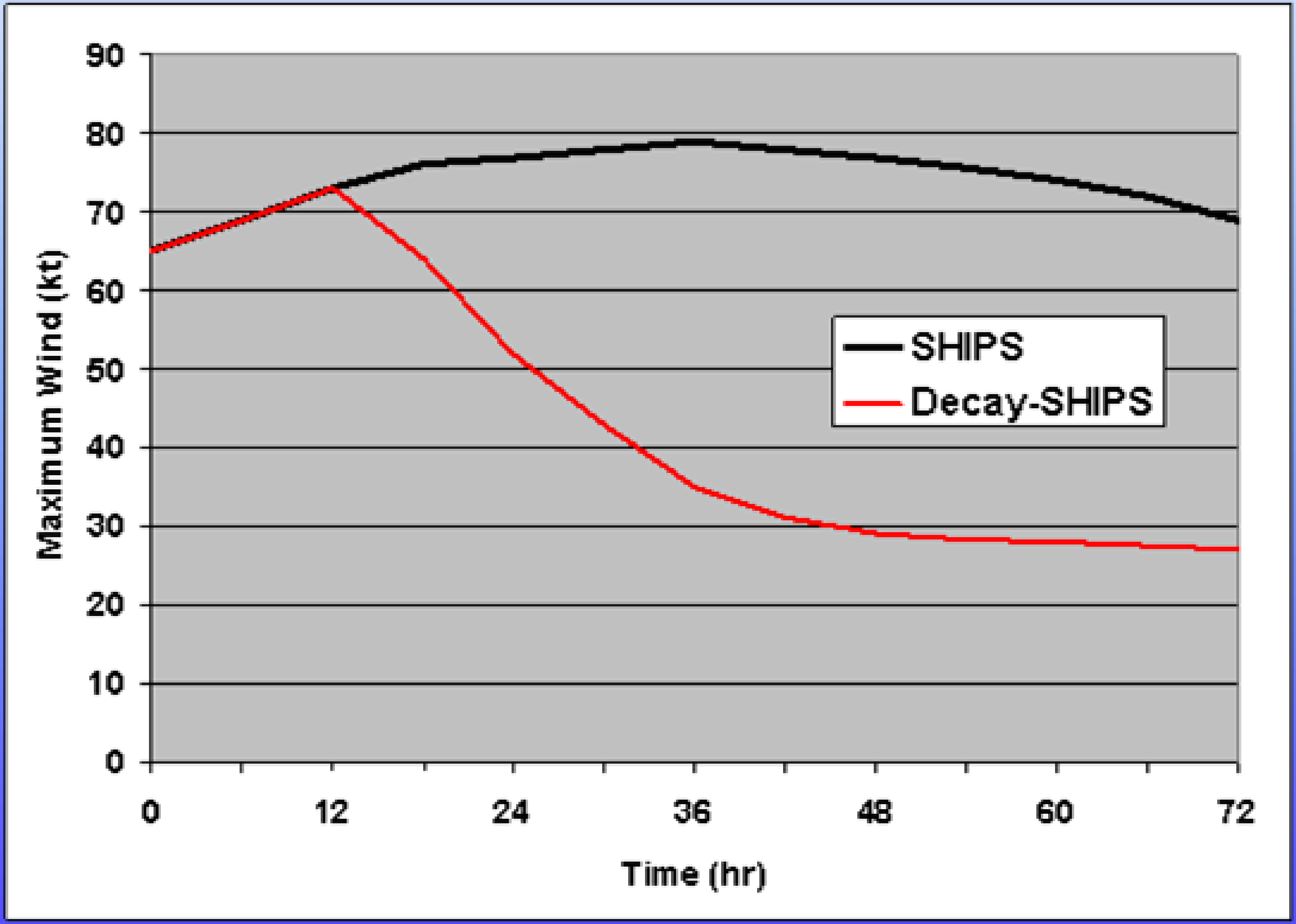
$$dV/dt = -\mu(V-V_b)$$

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

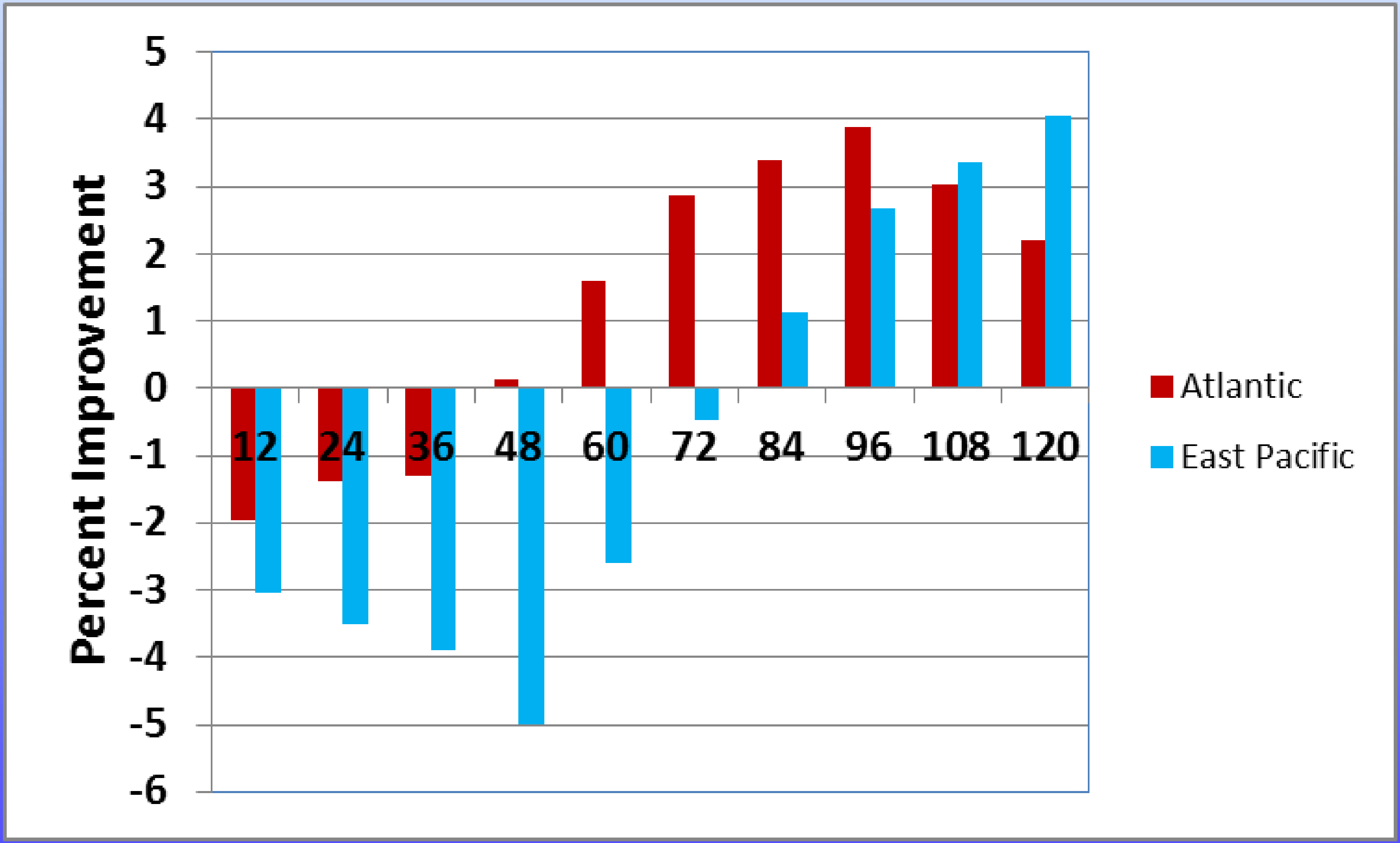
Steady State Solution: $V_s = V_{mpi}(\beta/\kappa)^{1/n}$

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

LGEM Improvement over SHIPS

AL and EP/CP Operational Runs 2006-2016



SHIPS Diagnostic File

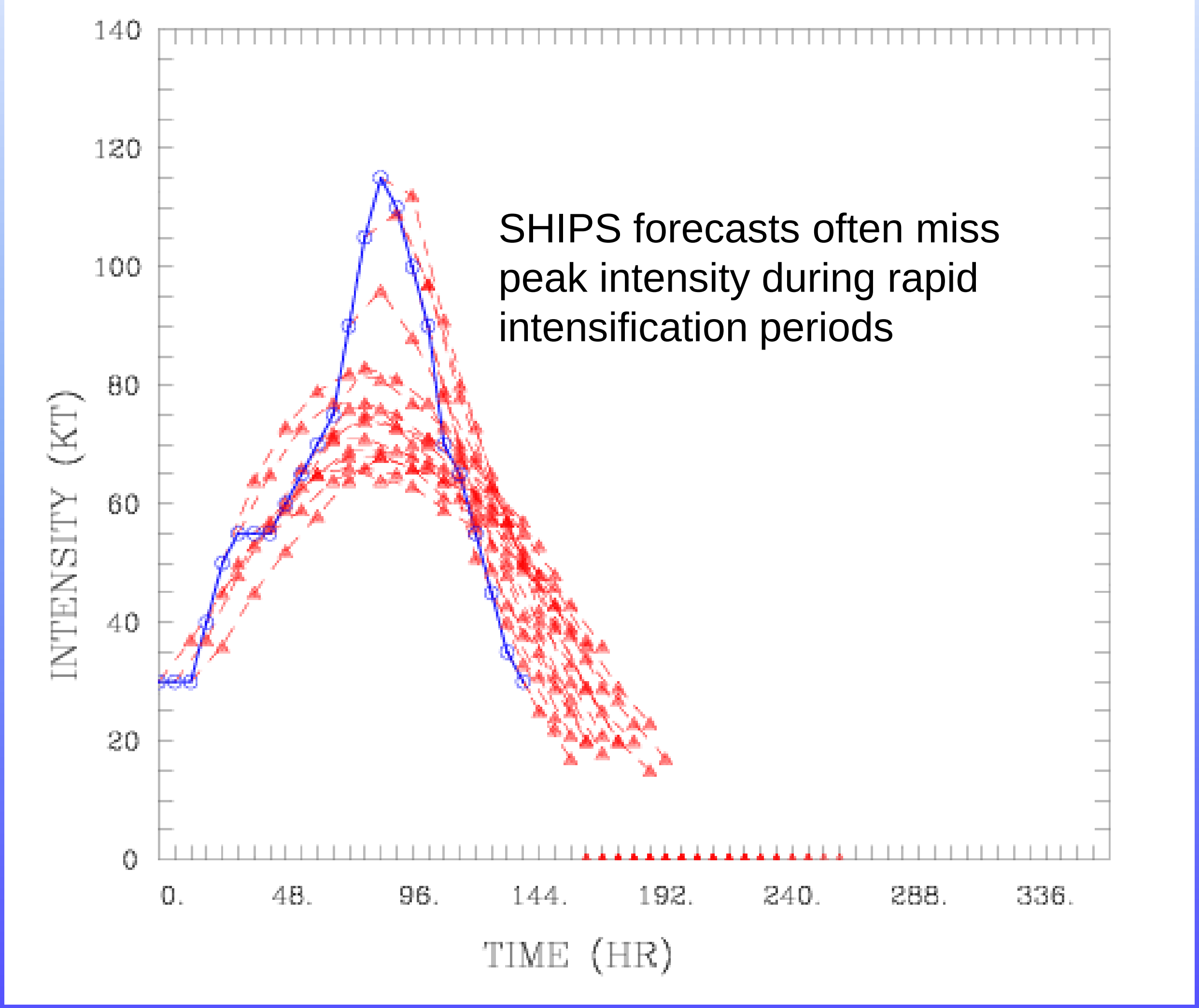
* ATLANTIC SHIPS INTENSITY FORECAST *
* IR SAT DATA AVAILABLE, OHC AVAILABLE *
* HERMINE AL092016 09/01/16 00 UTC *

TIME (HR)	0	6	12	18	24	36	48	60	72	84	96	108	120
V (KT) NO LAND	50	54	58	63	67	75	82	82	80	76	61	52	44
V (KT) LAND	50	54	58	63	67	56	37	30	31	28	DIS	DIS	DIS
V (KT) LGEM	50	55	60	65	70	60	38	31	28	30	26	24	25
Storm Type	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP	TROP
SHEAR (KT)	13	13	10	10	13	15	26	39	49	39	28	22	19
SHEAR ADJ (KT)	-2	1	5	1	0	-2	2	0	0	-6	-4	-3	-4
SHEAR DIR	301	303	285	258	236	257	238	241	229	216	247	251	240
SST (C)	30.4	30.3	30.2	30.2	30.2	29.9	29.2	28.7	27.5	26.8	26.5	26.1	26.1
POT. INT. (KT)	170	170	171	172	172	169	157	149	131	120	116	113	114
ADJ. POT. INT.	157	153	153	154	153	150	139	129	109	97	93	92	93
200 MB T (C)	-51.3	-51.7	-52.0	-51.5	-51.3	-51.6	-50.9	-51.4	-51.9	-53.1	-53.1	-53.1	-53.1
200 MB VXT (C)	1.0	1.2	0.8	0.3	0.4	0.7	0.9	1.1	1.0	0.5	1.2	1.7	1.4
TH_E DEV (C)	10	9	9	10	10	5	6	2	3	0	1	1	4
700-500 MB RH	64	62	64	64	66	65	56	46	49	53	52	52	46
MODEL VTX (KT)	17	18	20	22	23	25	28	27	28	30	22	20	17
850 MB ENV VOR	44	28	33	45	53	41	44	9	-3	2	9	17	16
200 MB DIV	30	24	48	56	78	71	90	58	62	43	46	6	14
700-850 TADV	7	15	16	14	12	20	21	42	9	-5	3	-2	-2
LAND (KM)	440	414	334	219	112	-62	-50	-96	7	61	96	179	246
LAT (DEG N)	25.5	26.2	26.8	27.8	28.7	30.5	32.7	35.0	37.1	38.4	38.7	39.0	39.1
LONG(DEG W)	87.1	86.7	86.3	85.7	85.2	83.6	81.0	78.3	75.8	74.3	73.7	72.4	70.5
STM SPEED (KT)	8	7	9	11	11	13	16	15	12	6	4	6	8
HEAT CONTENT	38	35	37	41	37	43	37	47	1	41	1	2	1

FORECAST TRACK FROM OFCI   INITIAL HEADING/SPEED (DEG/KT): 25/ 8   CX,CY: 3/ 7
T-12 MAX WIND: 40   PRESSURE OF STEERING LEVEL (MB): 594 (MEAN=618)
GOES IR BRIGHTNESS TEMP. STD DEV. 50-200 KM RAD: 23.8 (MEAN=14.5)
% GOES IR PIXELS WITH T < -20 C 50-200 KM RAD: 67.0 (MEAN=65.0)
PRELIM RI PROB (DV .GE. 30 KT IN 24 HR): 14.8

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

SHIPS Forecasts For East Pacific Hurricane Georgette (2016)



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)

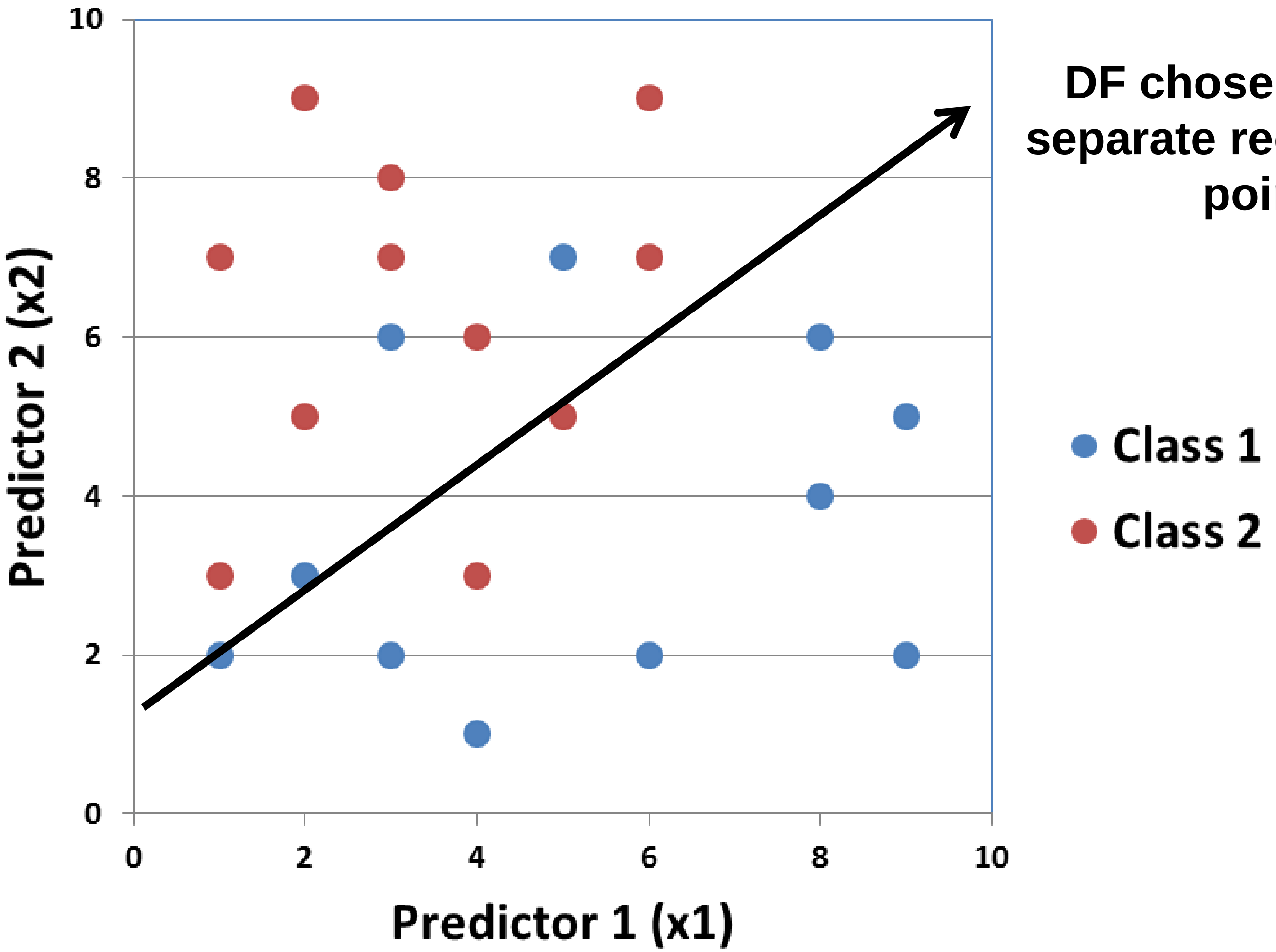
Linear Discriminant Analysis

- 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

$$DF = a_0 + a_1 x_1 + \dots a_N x_N$$

- 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

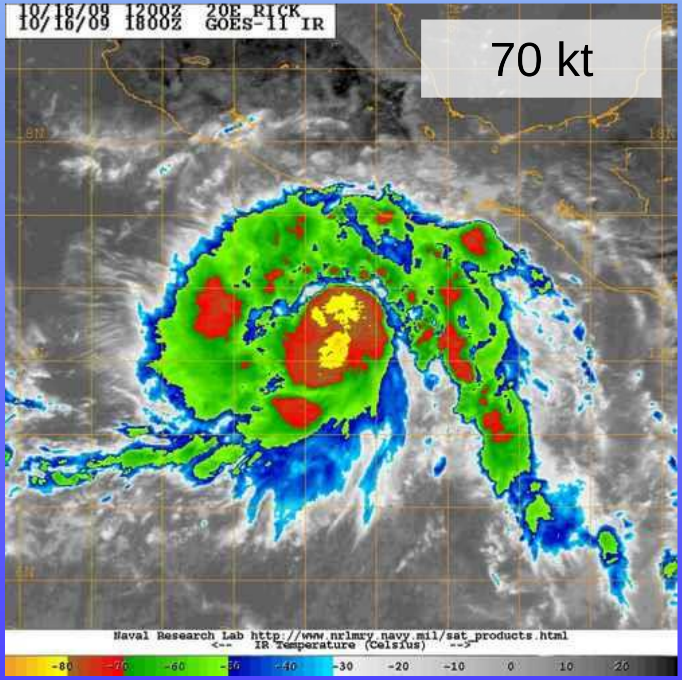
1. Previous 12 h max wind change (persistence)
2. Maximum Potential Intensity – Current intensity
3. Oceanic Heat Content
4. 200-850 hP shear magnitude (0-500 km)
5. 200 hPa divergence (0-1000 km)
6. 850-700 hPa relative humidity (200-800 km)
7. 850 hPa tangential wind (0-500 km)
8. IR pixels colder than -30^{o}C
9. Azimuthal standard deviation of IR brightness temperature

Rapid Intensification

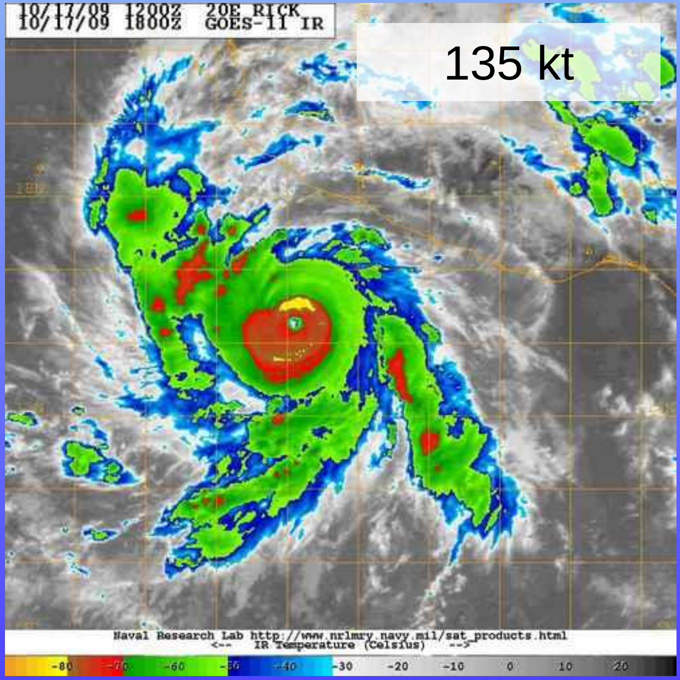
Hurricane Rick (2009 - East Pacific)

FORECAST POSITIONS AND MAX WINDS

INITIAL	16/2100Z	13.0N	100.0W	75 KT
12HR VT	17/0600Z	13.2N	101.3W	90 KT
24HR VT	17/1800Z	13.7N	103.3W	105 KT
36HR VT	18/0600Z	14.3N	105.8W	115 KT
48HR VT	18/1800Z	15.0N	108.1W	125 KT
72HR VT	19/1800Z	16.5N	111.5W	120 KT
96HR VT	20/1800Z	18.5N	113.0W	105 KT
120HR VT	21/1800Z	20.5N	113.0W	85 KT



24 hrs



RI Guidance

Hurricane Rick (2009 - East Pacific)

```
          *   EAST PACIFIC SHIPS INTENSITY FORECAST    *
          *      GOES DATA AVAILABLE                   *
          *       OHC  DATA AVAILABLE                   *
          *  RICK        EP202009  10/16/09  18 UTC    *
```

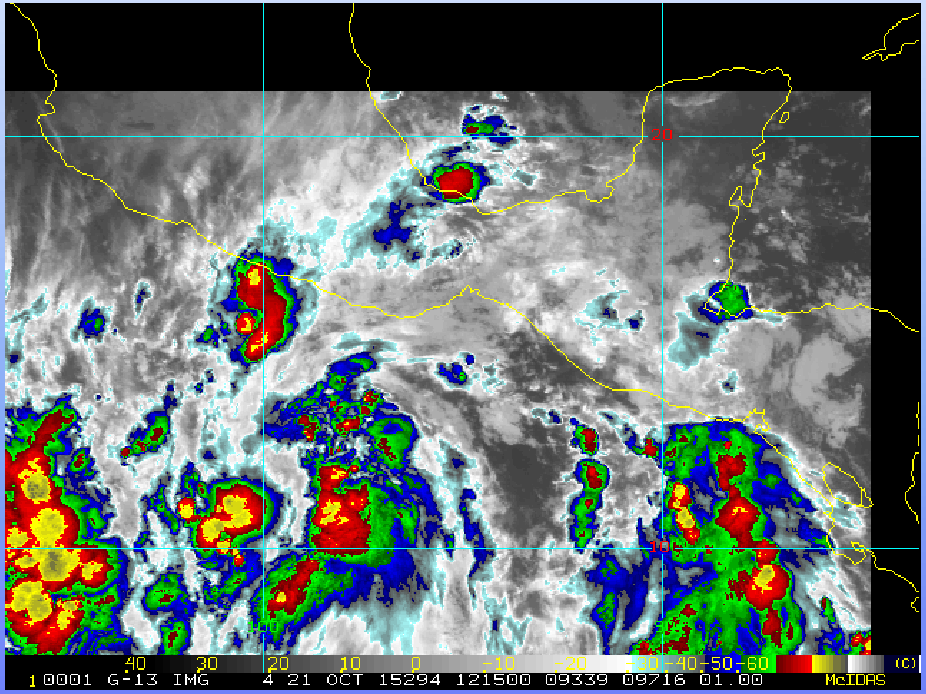
TIME (HR)	0	6	12	18	24	36	48	60	72	84	96	108	120
V (KT) NO LAND	70	79	86	92	97	104	108	111	111	107	107	101	93
V (KT) LAND	70	79	86	92	97	104	108	111	111	107	107	101	93
V (KT) LGE mod	70	79	86	92	96	99	95	91	87	85	83	80	76

```
 ** 2009 E. Pacific RI INDEX EP202009 RICK       10/16/09  18 UTC **
            ( 30 KT OR MORE MAX WIND INCREASE IN NEXT 24 HR)

 12 HR PERSISTENCE (KT):   20.0 Range:-20.0 to   35.0 Scaled/Wgted Val:  0.7/   1.6
 850-200 MB SHEAR (KT) :    6.0 Range: 15.2 to    1.6 Scaled/Wgted Val:  0.7/   0.8
 D200 (10**7s-1)       :   70.0 Range:-10.0 to 129.0 Scaled/Wgted Val:  0.6/   0.4
 POT = MPI-VMAX (KT)   :   96.7 Range: 46.6 to 134.3 Scaled/Wgted Val:  0.6/   0.6
 850-700 MB REL HUM (%):   79.4 Range: 64.0 to   88.0 Scaled/Wgted Val:  0.6/   0.2
 % area w/pixels <-30 C:   98.0 Range: 26.0 to 100.0 Scaled/Wgted Val:  1.0/   0.5
 STD DEV OF IR BR TEMP :    8.3 Range: 35.4 to    2.7 Scaled/Wgted Val:  0.8/   1.3
 Heat content (KJ/cm2) :   46.8 Range:   4.0 to   67.0 Scaled/Wgted Val:  0.7/   0.4

 Prob of RI for 25 kt RI threshold=    78% is   6.8 times the sample mean(11.5%)
 Prob of RI for 30 kt RI threshold=    71% is   9.3 times the sample mean( 7.7%)
 Prob of RI for 35 kt RI threshold=    66% is  12.6 times the sample mean( 5.2%)
```

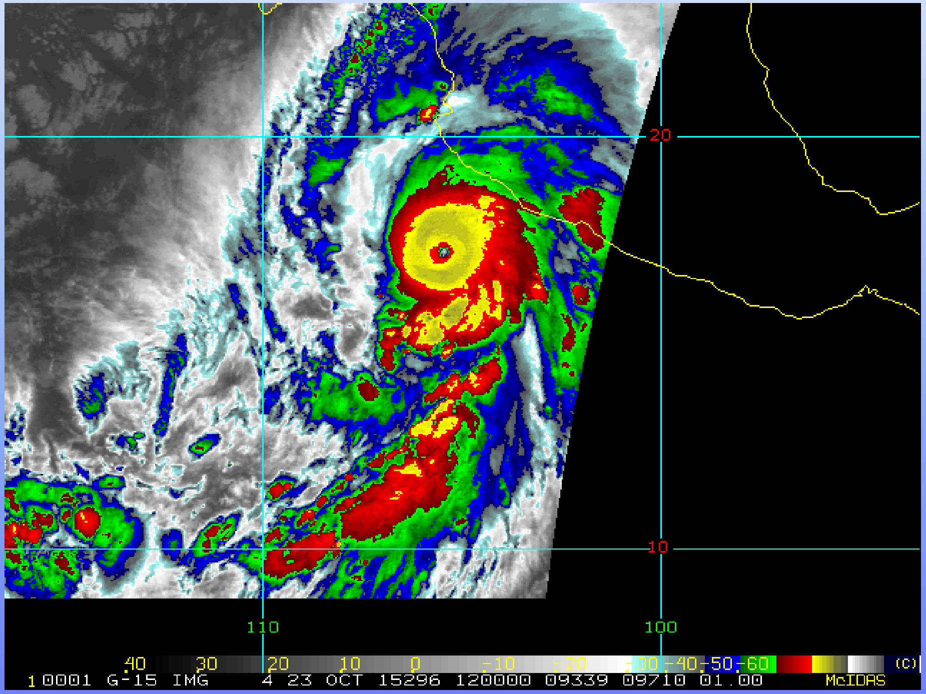
RII Guidance Output
Part of SHIPS diagnostic file

```
                   CURRENT MAX WIND (KT):    50. LAT, LON:    25.5    87.1

     ** 2015 ATLANTIC RI INDEX AL092016 HERMINE     09/01/16  00 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
12 HR PERSISTENCE (KT):     10.0     -49.5  to   33.0       0.72           4.6
850-200 MB SHEAR (KT) :     11.9      28.8  to    2.9       0.65           1.9
HEAT CONTENT (KJ/cm2) :     37.6       0.0  to  155.1       0.24           0.5
STD DEV OF IR BR TEMP :     23.8      37.5  to    2.9       0.40           1.1
2nd PC OF IR BR TEMP  :      0.4       2.8  to   -3.1       0.41           1.1
MAXIMUM WIND (kt)     :     50.0      22.5  to  121.0       0.78           0.8
D200 (10**7s-1)       :     47.2     -23.1  to  181.5       0.34           0.4
POT = MPI-VMAX (KT)   :    104.0      28.4  to  139.1       0.68           1.1
% AREA WITH TPW <45 mm:      0.0     100.0  to    0.0       1.00           0.7
BL DRY-AIR FLUX (w/m2):    143.4     960.3  to  -67.1       0.80           0.0

SHIPS Prob RI for 20kt/ 12hr RI threshold=   7% is   1.3 times sample mean ( 5.5%)
SHIPS Prob RI for 25kt/ 24hr RI threshold=  24% is   2.1 times sample mean (11.6%)
SHIPS Prob RI for 30kt/ 24hr RI threshold=  12% is   1.7 times sample mean ( 7.2%)
SHIPS Prob RI for 35kt/ 24hr RI threshold=  11% is   2.7 times sample mean ( 4.2%)
SHIPS Prob RI for 40kt/ 24hr RI threshold=   8% is   2.9 times sample mean ( 2.8%)
SHIPS Prob RI for 45kt/ 36hr RI threshold=  10% is   2.1 times sample mean ( 4.9%)
SHIPS Prob RI for 55kt/ 48hr RI threshold=  19% is   3.7 times sample mean ( 5.1%)

Matrix of RI probabilities
---------------------------------------------------------------------
 RI (kt / h)   | 20/12 | 25/24 | 30/24 | 35/24 | 40/24 | 45/36 | 55/48
---------------------------------------------------------------------
  SHIPS-RII:      7.3%   24.1%   12.2%   11.4%    8.2%   10.4%   18.8%
   Logistic:      6.9%   28.6%   16.2%    8.6%    0.0%    8.5%    6.9%
   Bayesian:      3.1%    2.1%    0.4%    0.3%    0.1%    0.6%    0.5%
  Consensus:      5.8%   18.3%    9.6%    6.8%    2.8%    6.5%    8.8%
```

PATRICIA INTENSIFIED FROM 40 KT TO 185 KT IN 48 HOURS!



21 OCT 2015 12 UTC



23 OCT 2015 12 UTC

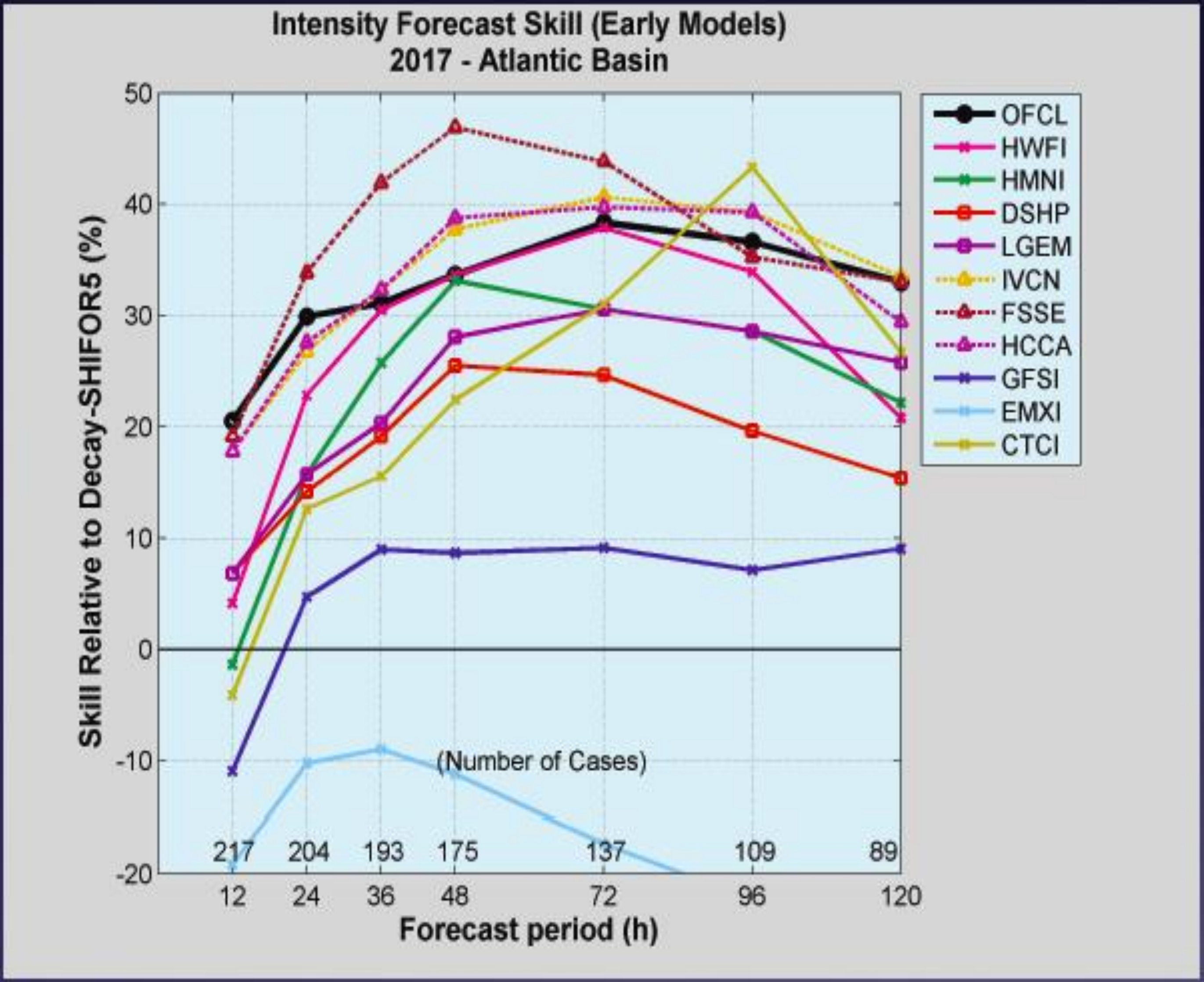
Tropical Cyclone Intensity Dynamical Forecast Models

- HWRF, HMON, NCEP Global Model (GFS), UKMET (U.K. Met Office), NOGAPS (U.S. Navy), ECMWF (European)
- 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 about 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

Consensus and Ensemble Forecasts

- ICON – Consensus that is computed by averaging the forecast intensities from Decay-SHIPS, LGEM, HWRF, and GFDL. All must be available.
- IVCN – Consensus that requires at least 2 of Decay-SHIPS, LGEM, HWRF, 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

2017 Intensity Guidance



Official forecasts skillful at all times, but were beat by the consensus models at most time periods.

FSSE best model from 24 to 72 h.

HWFI was a strong performer, best individual model.

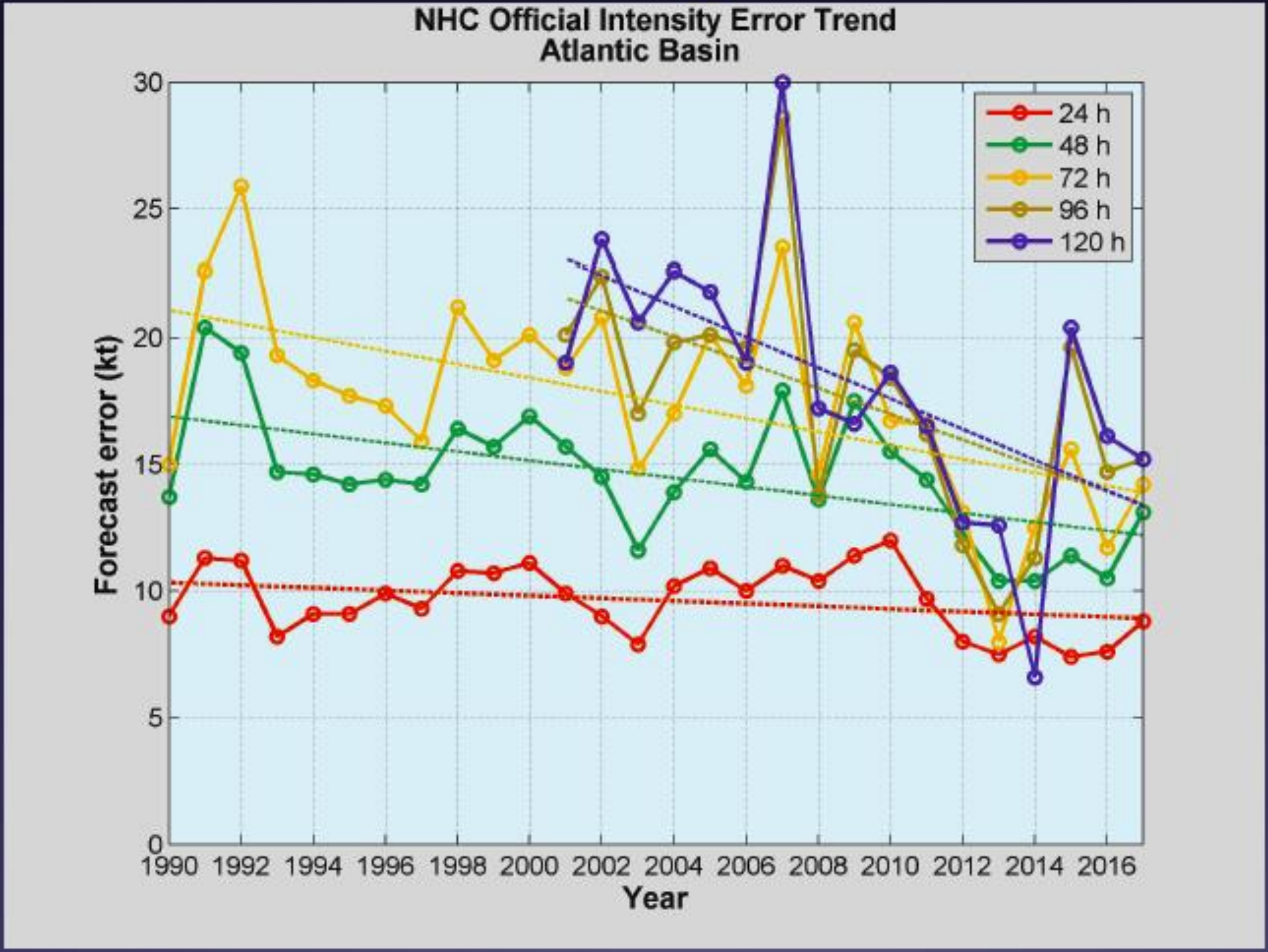
HMNI not as good as HWFI, but beat statistical aids.

DSHP and [illegible] were fair performers, but not as good as HWFI, HMNI, and consensus models.

CTCI showed increased skill with time. Strong performer from days 3 to 5.

[illegible] had some skill, but not competitive. EMXI not skillful.

Atlantic Intensity Error Trends

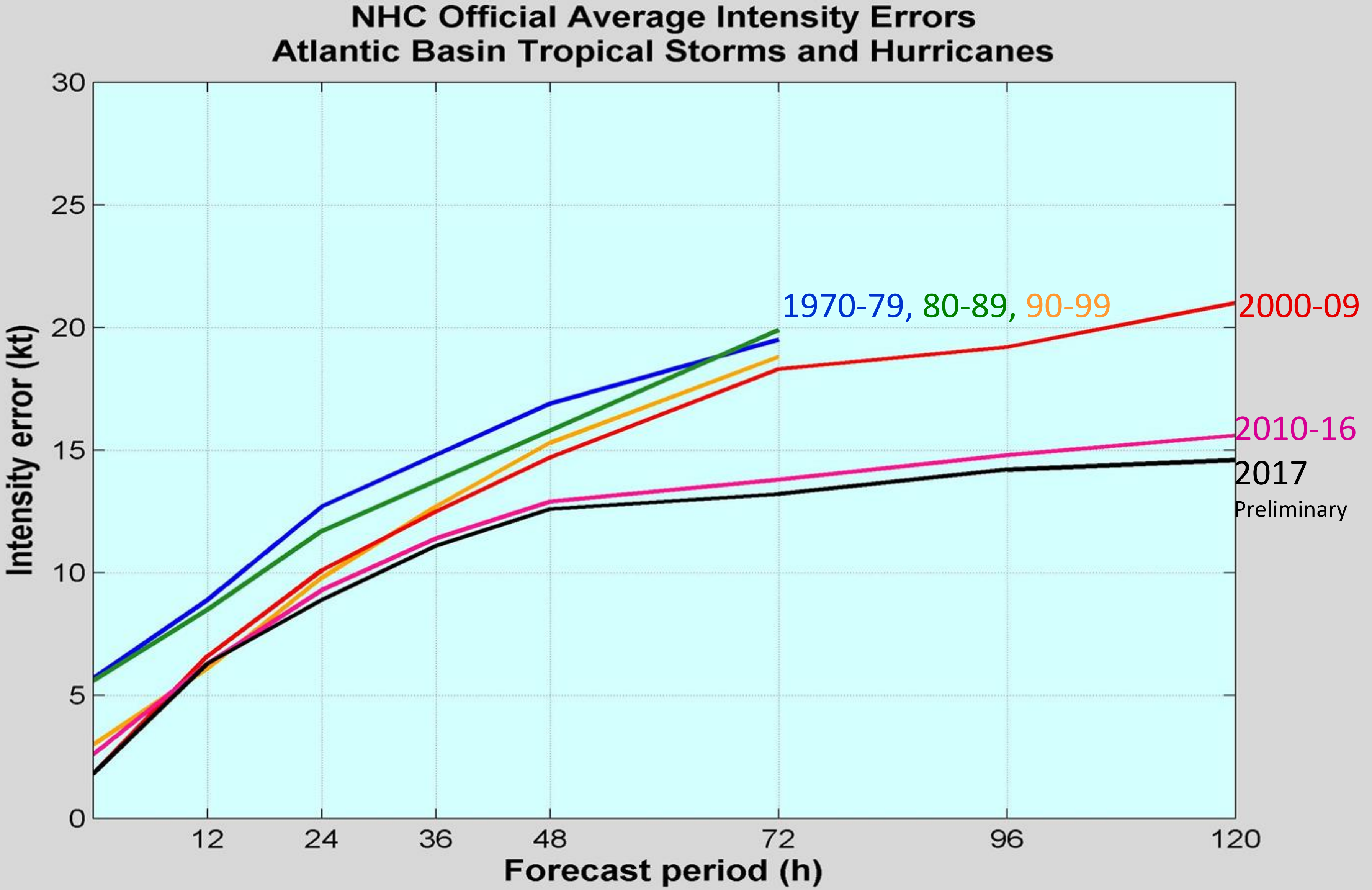


Errors increased at most time periods in 2017. Long term trends show slow improvement in intensity forecasts.

NHC Official Intensity Forecast

- Based on statistical guidance from SHIPS and D-SHIFOR, qualitative guidance from dynamical models and consensus.
- Dynamical models (HWRF and COTC) 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 24 h and beyond, the average error is roughly 1 SSHWS Category (15-20 knots).

NHC Official Intensity Forecast Trends

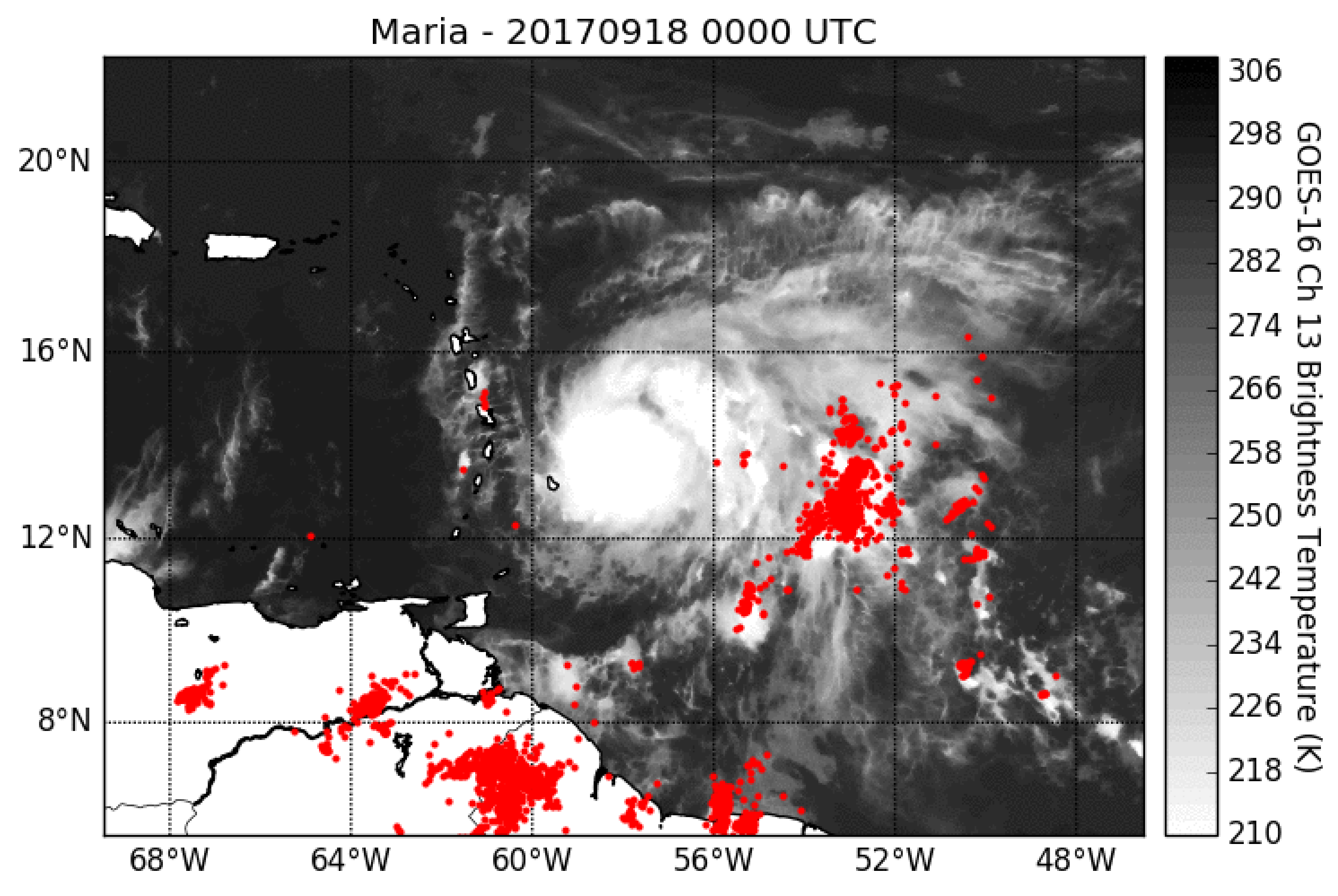


Concluding Remarks

- Intensity forecasting is not as advanced as track forecasting.
- There is less skill for intensity forecasting than there is for track forecasting.
- Current guidance is provided mainly by HWRF, DSHIPS, LGEM, IVCN and more recently, COAMPS-TC, HMON, FSSE and HCCA
- 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)
- GOES-16 is providing new imagery and lightning data for dynamical and statistical-dynamical intensity models

GOES-16 Imagery and Lightning Locations



EXERCISE 2
Intensity Forecast