Tropical Cyclone Intensity Forecasting: Still a Challenging Proposition

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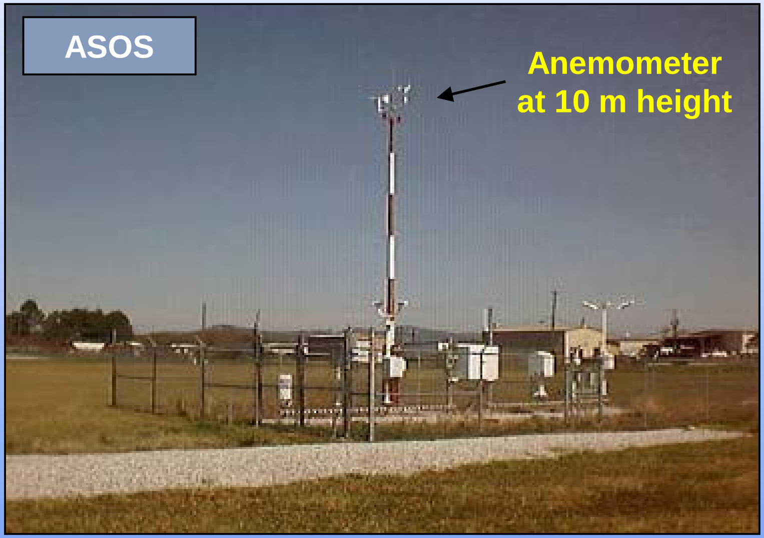
National Hurricane Center

April 20, 2017

What do we mean by Intensity?

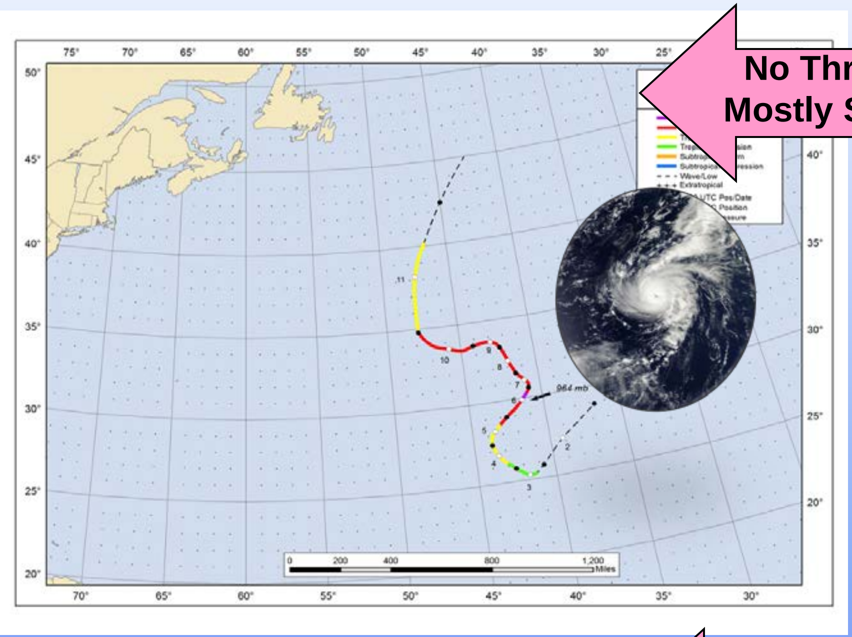


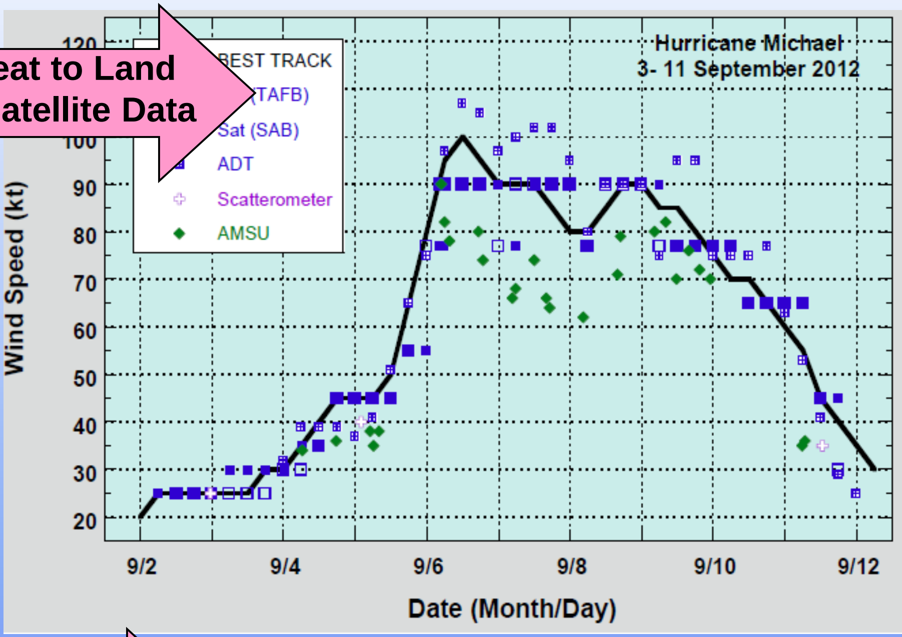
Maximum sustained winds:

Strongest **wind speed *averaged during a 1-minute period* at an altitude of *10 m (33 ft)*, associated with the circulation of the tropical cyclone at a given point in time**

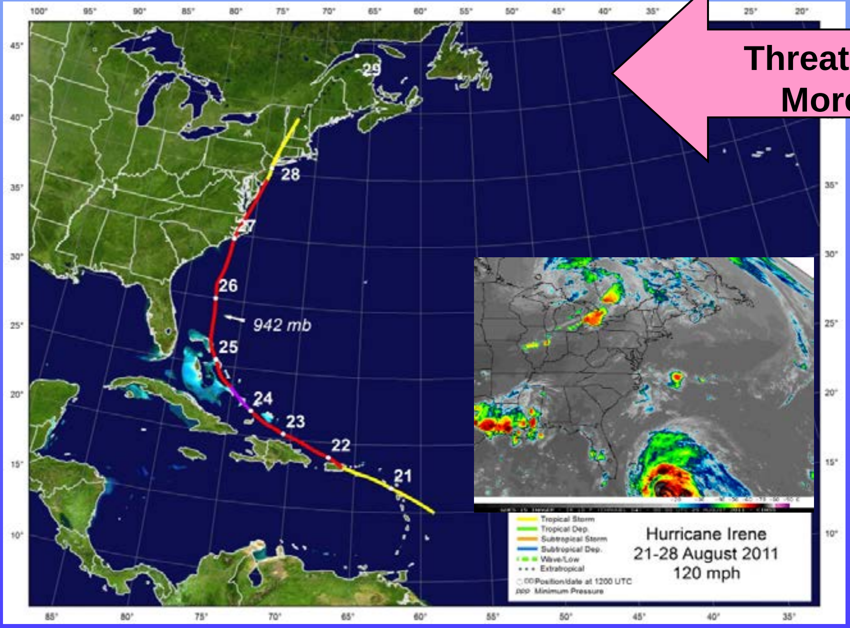
- **Central pressure is correlated with intensity, but pressure-wind relationship has variability**
- **Max wind speed usually estimated, rarely directly measured**

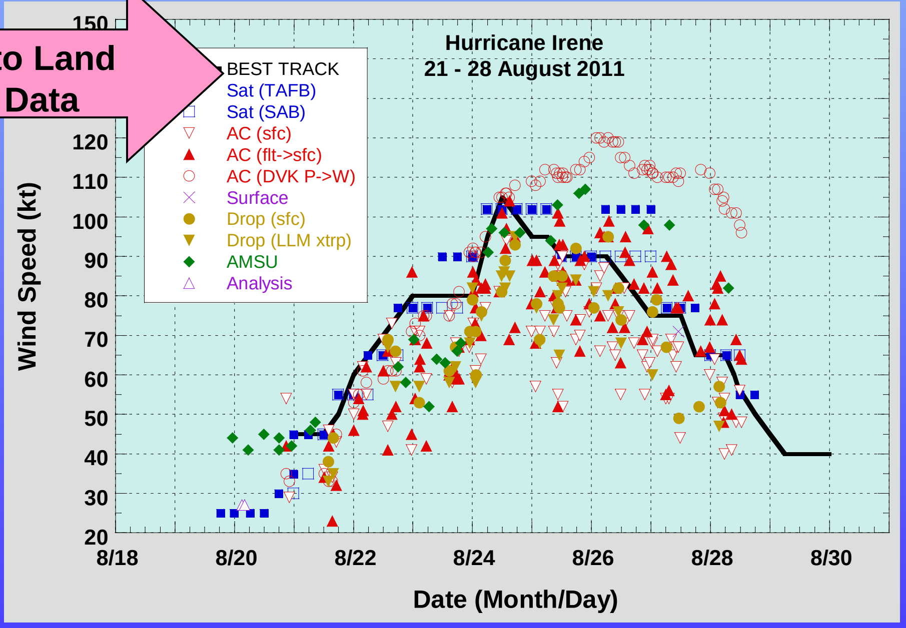
More Data for Land-Threatening TCs





No Threat to Land
Mostly Satellite Data





Threat to Land
More Data

Determine the Official Intensity

- Subjective Dvorak: **115 / 102 kt**
- Objective ADT: **130 kt**
- SFMR surface wind **103 kt**
- Recon sfc-adjusted flight-level wind: **119 kt**
- Dropsonde surface value: **111 kt**
- Drop sfc-adjusted WL150: **118 kt**
- Drop sfc-adjusted MBL: **111 kt**

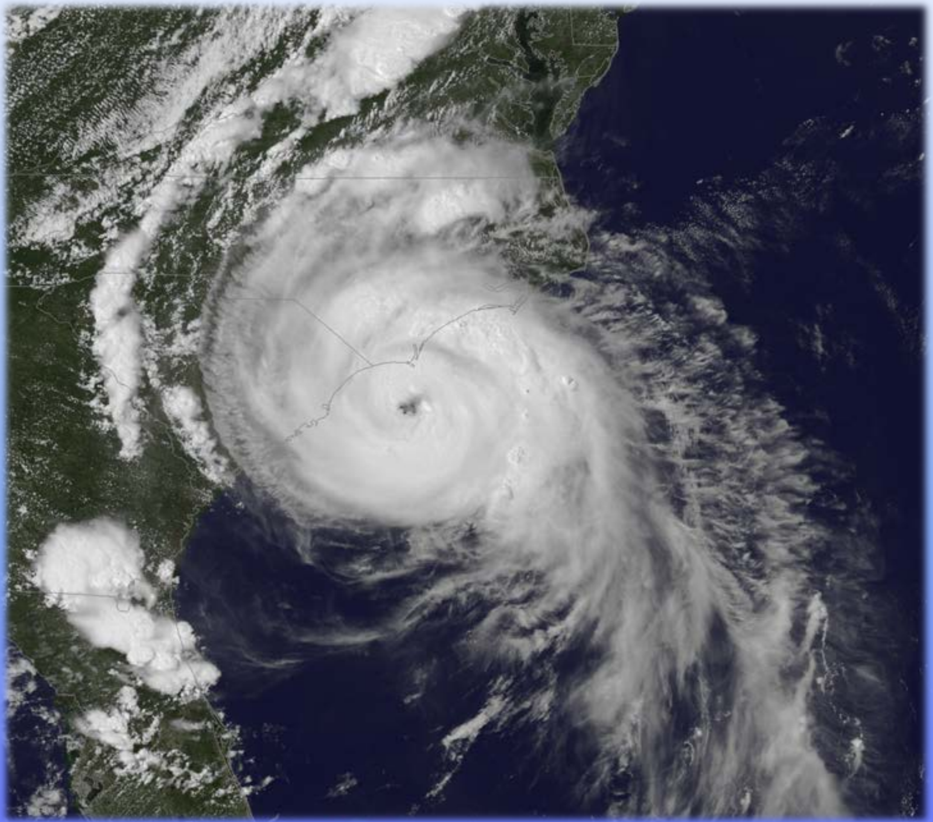
- OFCL at 0600 UTC: **110 kt**

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**

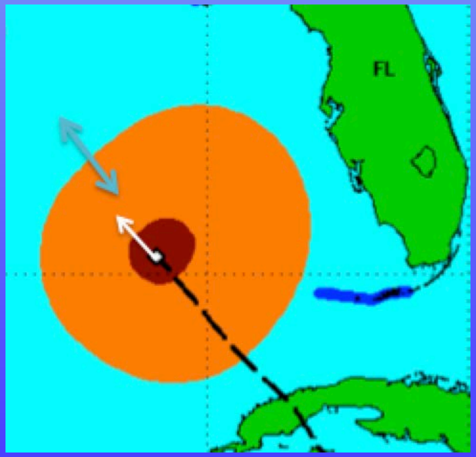
Typical Intensity & Size Uncertainty

Since there are insufficient observations of surface wind in tropical cyclones:

- **Intensity estimates are believed to be good to within 10%**
- **Tropical storm wind radii (size estimate) are believed to be good to within 25% and hurricane wind radii to within 40%**



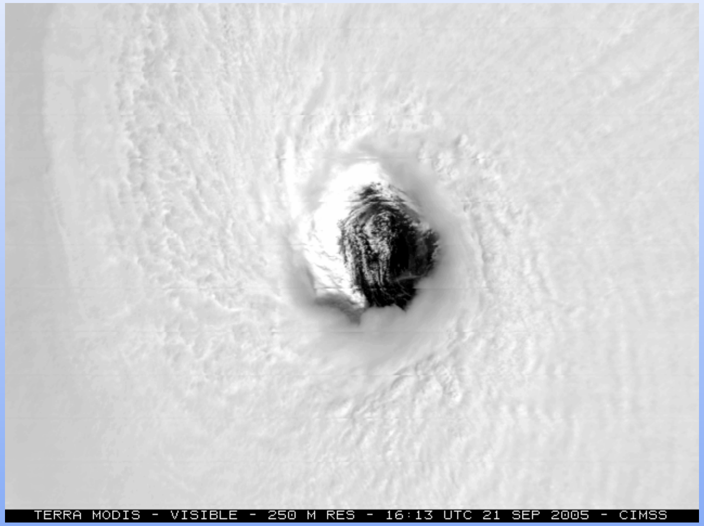
Hurricane Arthur (2014) near its estimated peak intensity of 100 mph

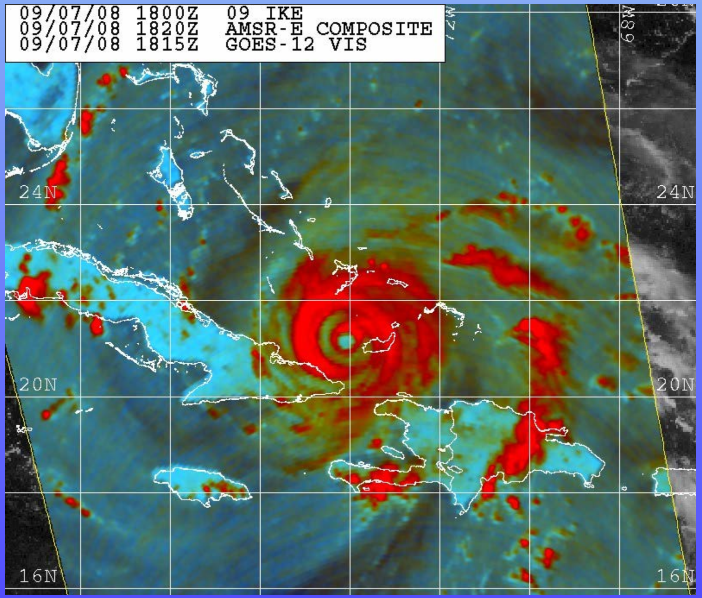


A 100 mph hurricane could have maximum winds of 90 mph or 110 mph.

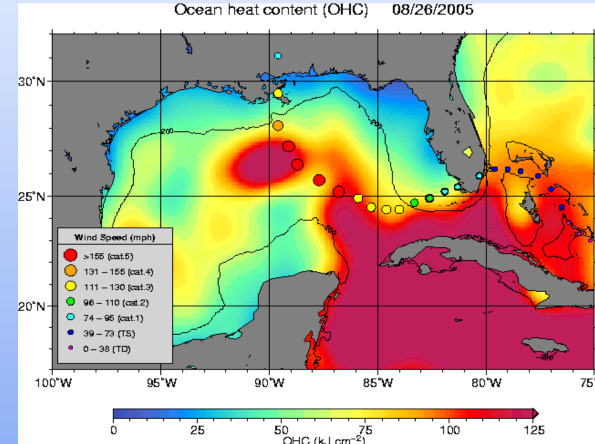
Intensity Forecast Considerations

- Much more complex forecast problem than track
  - Involves interactions between thunderstorms in the core, the environment, and atmosphere-ocean interactions
- Important factors
  - Track
  - Wind, temperature, and moisture patterns in the core and the near environment
  - Internal processes, such as eyewall replacement cycles, that are poorly understood

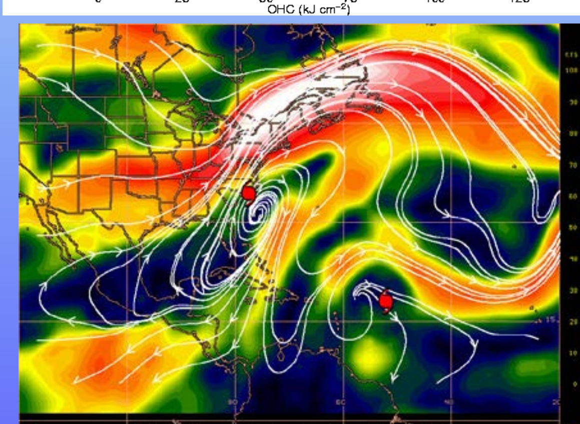




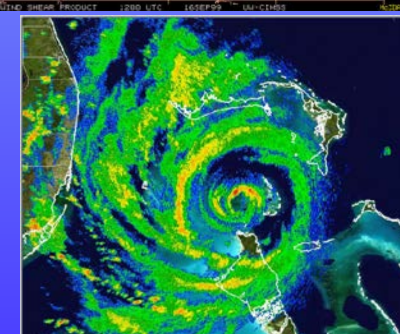
Factors Affecting Tropical Cyclone Intensity



- **Upper Ocean Temperatures**
  More heat favors a stronger storm
- **Interaction with Land/Topography**
  More land increases weakening



- **Vertical Wind Shear**
  Shear limits strengthening
- **Moisture in Storm Environment**
  Dry air can limit strengthening
- **Structural Changes, Eyewall Replacement**
  Difficult to forecast and not straightforward



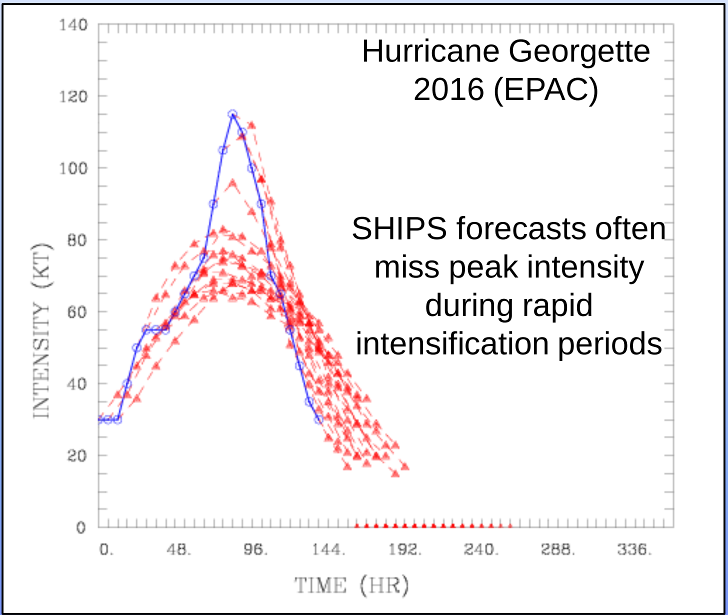
- **Interactions with other weather systems**

Tropical Cyclone Intensity Statistical Models

- **Decay SHIFOR**
  - **S**tatistical **H**urricane **I**ntensity **FOR**ecast with inland decay.
    - Based on historical information - climatology and persistence (uses CLIPER track).
    - Baseline for skill of intensity forecasts

Tropical Cyclone Intensity Statistical-Dynamical Models

- **SHIPS and DSHIPS:**
  - **S**tatistical **H**urricane **I**ntensity **P**rediction **S**cheme:
    - Based on climatology, persistence, and statistical relationships to current and forecast environmental conditions (with inland decay applied in DSHIPS)
- **LGEM**
  - Logistic **G**rowth **E**quation **M**odel:
    - 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 at the end of the forecast, but also more sensitive to track forecast errors.



* ATLANTIC SHIPS INTENSITY FORECAST *
* GOES AVAILABLE, OHC AVAILABLE *
* ALBERTO AL012012 05/21/12 12 UTC *

TIME (HR)	0	6	12	18	24	36	48	60	72	84	96	108	120
V (KT) NO LAND	35	36	37	39	39	39	36	29	25	22	19	16	DIS
V (KT) LAND	35	36	37	39	39	39	36	29	25	22	19	16	DIS
V (KT) LGE mod	35	35	35	35	35	34	33	31	30	32	35	38	DIS
Storm Type	EXTP	EXTP	EXTP	EXTP	EXTP	EXTP	EXTP	EXTP	EXTP	EXTP	EXTP	SUBT	N/A
SHEAR (KT)	39	40	42	45	46	60	57	51	23	7	10	6	N/A
SHEAR ADJ (KT)	-6	0	-1	-2	-7	-11	-17	-7	-4	1	-2	2	N/A
SHEAR DIR	259	261	252	247	243	250	251	261	262	301	105	12	N/A
SST (C)	25.3	25.3	25.2	24.8	24.0	22.7	22.6	19.9	19.5	15.0	11.5	8.3	N/A
POT. INT. (KT)	106	107	107	104	99	92	92	80	79	70	67	65	N/A
ADJ. POT. INT.	90	92	93	92	88	83	82	74	72	67	65	64	N/A
200 MB T (C)	-54.1	-53.5	-54.6	-55.0	-55.4	-56.2	-56.7	-56.7	-57.9	-59.0	-60.2	-60.6	N/A
TH_E DEV (C)	4	6	7	5	4	4	2	2	0	0	0	0	N/A
700-500 MB RH	44	44	47	54	59	60	61	49	43	43	42	43	N/A
GFS VTEX (KT)	7	7	6	7	6	5	3	2	LOST	LOST	LOST	LOST	LOST
850 MB ENV VOR	68	73	58	57	41	40	35	0	-31	-85	-73	-91	N/A
200 MB DIV	19	-2	18	27	38	62	60	34	0	-69	-52	-61	N/A
700-850 TADV	-7	-5	0	-8	-5	17	-1	6	-5	3	0	16	N/A
LAND (KM)	215	273	282	281	268	325	512	483	412	404	428	235	N/A
LAT (DEG N)	30.4	30.8	31.1	31.9	32.6	34.4	36.6	38.4	40.1	41.6	43.0	44.6	N/A
LONG(DEG W)	79.1	78.3	77.5	76.4	75.3	72.6	69.7	66.7	63.5	60.2	56.5	52.7	N/A
STM SPEED (KT)	6	8	10	12	13	15	16	15	15	15	16	16	N/A
HEAT CONTENT	6	0	0	0	0	0	0	0	0	0	0	0	9999

Example of SHIPS Model Output

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

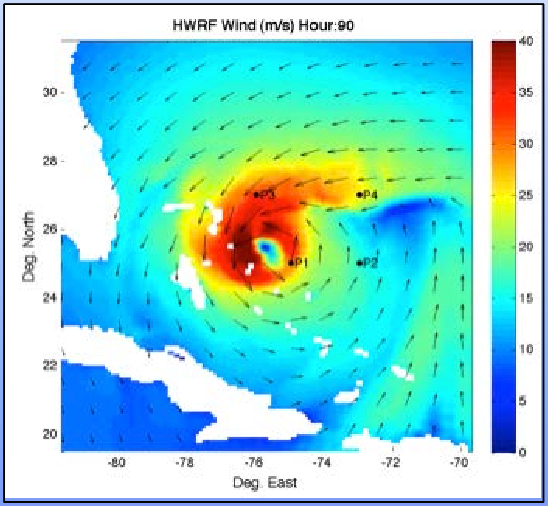
FORECAST TRACK FROM OFCI   INITIAL HEADING/SPEED (DEG/KT): 25/ 8   CX,CY: 3/ 7
T-12 MAX WIND: 40   PRESSURE OF STEERING LEVEL (MB): 594 (MEAN=618)
GOES IR BRIGHTNESS TEMP. STD DEV. 50-200 KM RAD: 23.8 (MEAN=14.5)
% GOES IR PIXELS WITH T < -20 C 50-200 KM RAD: 67.0 (MEAN=65.0)
PRELIM RI PROB (DV .GE.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

Tropical Cyclone Intensity Dynamical Models

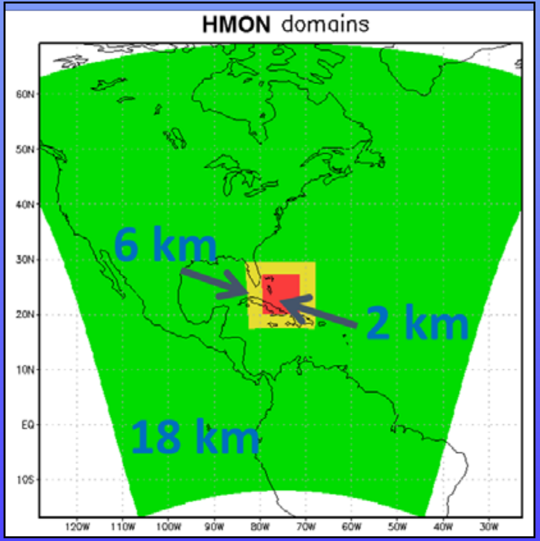
- **Dynamical Models:**
  - **HWRF, HMON, CTCI, GFS, ECMWF, UKMET**
  - Based on the present and the future by solving the governing equations for the atmosphere (and ocean).
  - These models are of limited use, because of…
    - Sparse observations
    - Inadequate resolution; the HWRF and HMON our highest-resolution operational hurricane models
    - Incomplete understanding and simulation of basic physics of intensity change
    - Problems with representation of shear

Tropical Cyclone Intensity Dynamical Hurricane Models

- **HWRF**
  - **H**urricane **W**eather **R**esearch and **F**orecast System
  - Moving nests of 18, 6, and 2 km
  - Coupled with the Princeton Ocean Model
  - Uses GSI 3D VAR data assimilation

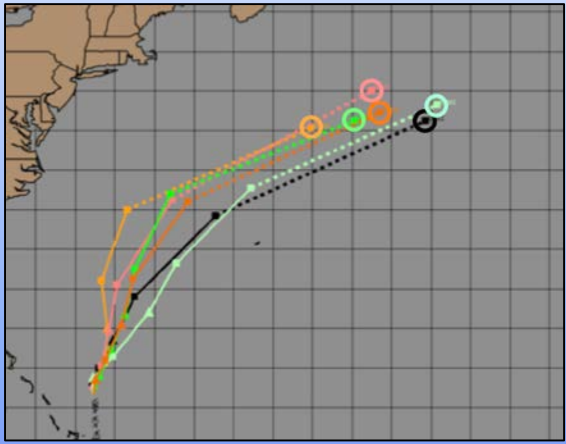


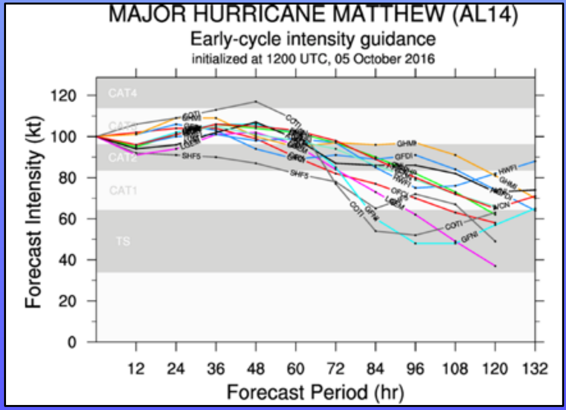
- **HMON** - New for 2017 (Replaces GFDL)
  - **H**urricanes in a **M**ulti-scale **O**cean coupled **N**on-hydrostatic model
  - Moving nests (same resolution as HWRF)
  - Will be coupled to other (ocean, waves, surge, inundation, etc.) models, but not in 2017
  - No data assimilation for 2017



Tropical Cyclone Intensity Consensus and Ensemble Models

- **ICON**
  - Consensus by averaging Decay-SHIPS, LGEM, and HWRF – All must be available
- **IVCN**
  - Consensus that requires at least 2 of the following: Decay-SHIPS, LGEM, HWRF, and CTCI
- **Florida State Superensemble (FSSE)**
  - Consensus that uses dynamical models and the previous NHC forecast. FSSE learns from past performances of its members in a “training phase”, then accounts for the model biases.
- **HFIP Corrected Consensus Approach (HCCA)**
  - FSSE approach adapted to NHC operations using a slightly different set of input models than FSSE.





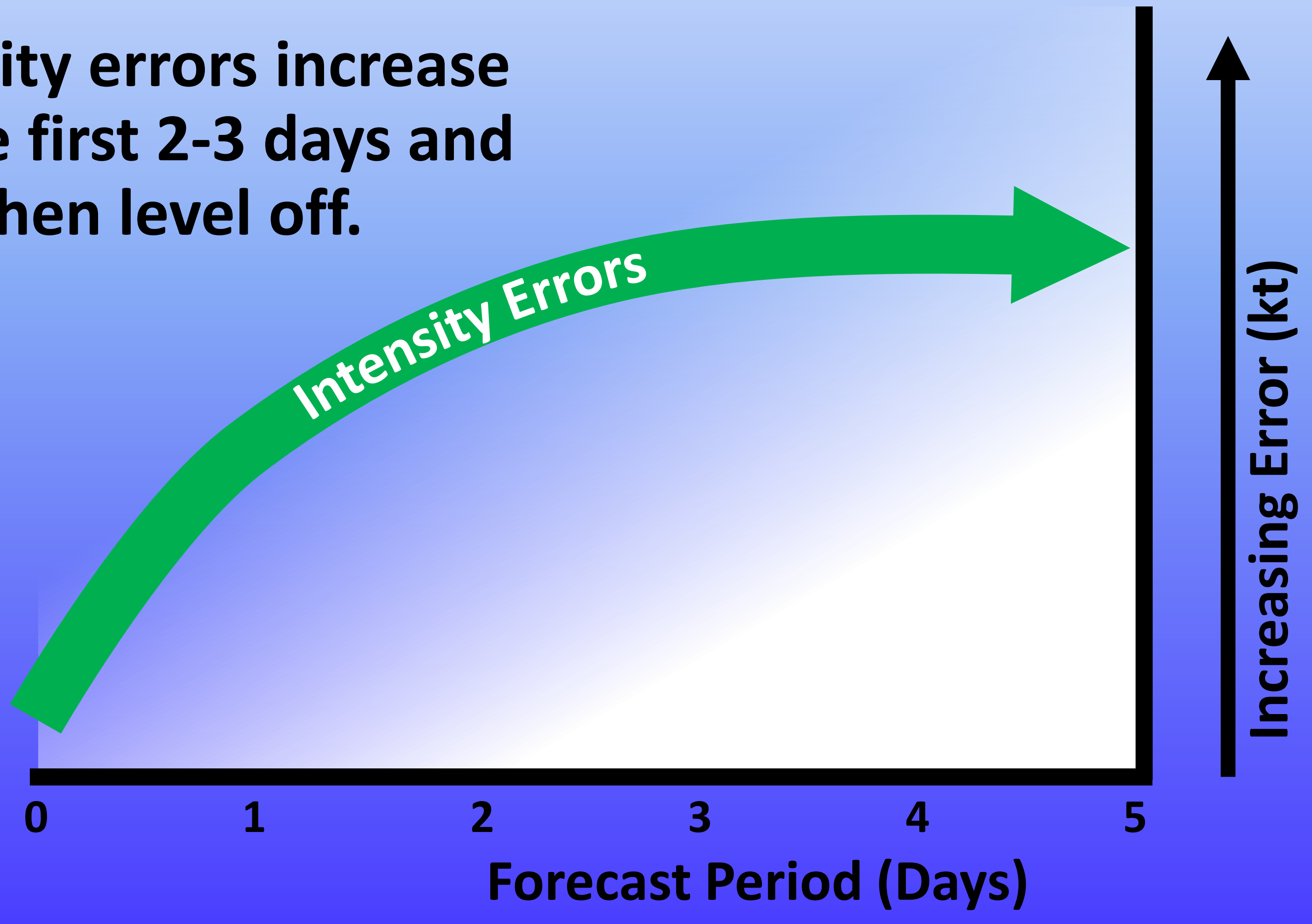
NHC Official Intensity Forecast

- **Persistence is used quite a bit, especially for short-term forecasts.**
- **Obvious signs in the environment, i.e. cooler waters, increasing upper-level winds, are taken into account.**
- **Tends to be conservative; *extreme events are almost never forecast*.**
- **For forecasts 24 h and beyond, the average error is roughly 1 SSHWS Category (about 15 kt)**

Forecast Intensity Errors

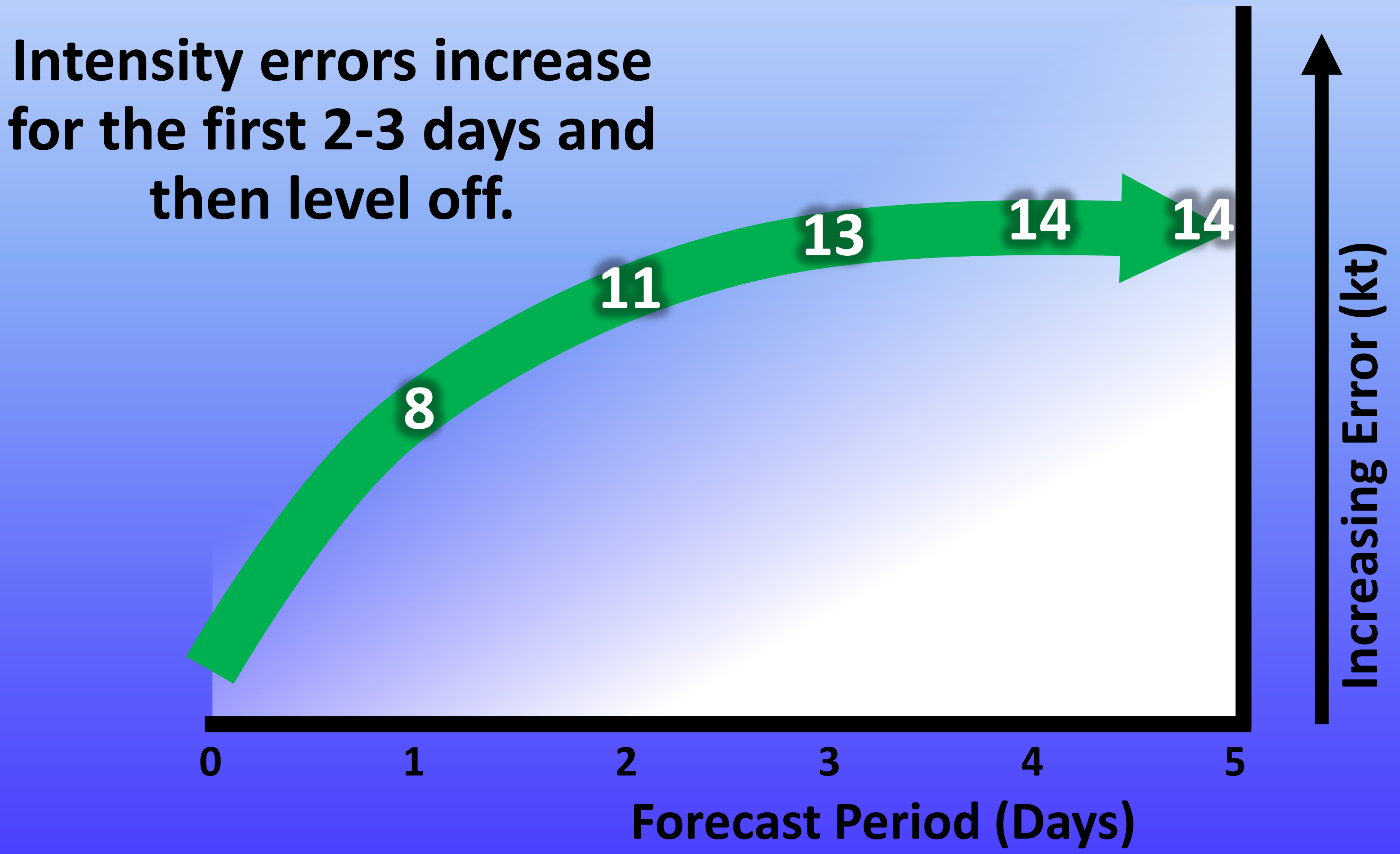
NHC 5-Year Averages

Intensity errors increase for the first 2-3 days and then level off.

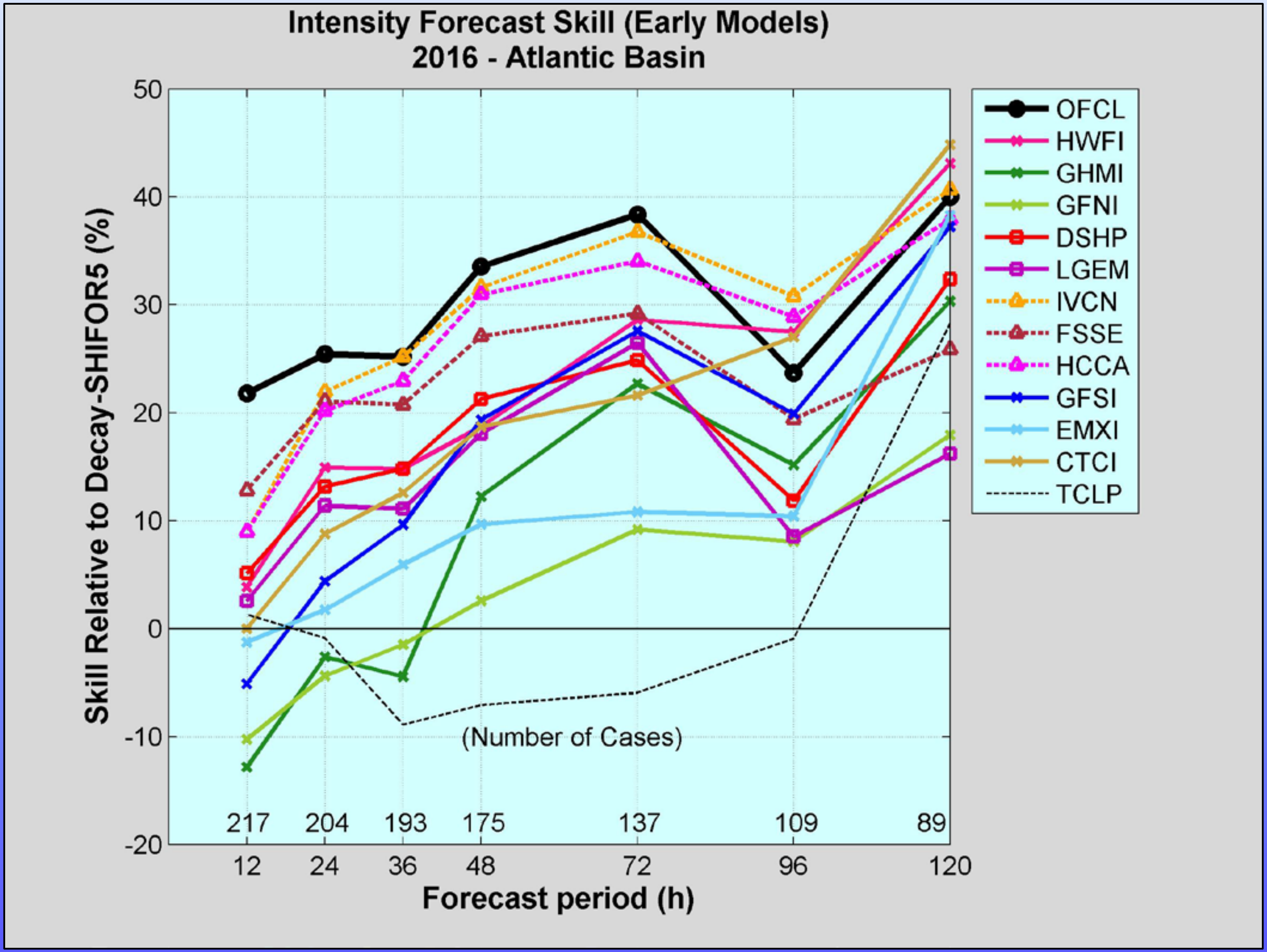


Forecast Intensity Errors

NHC 5-Year Averages



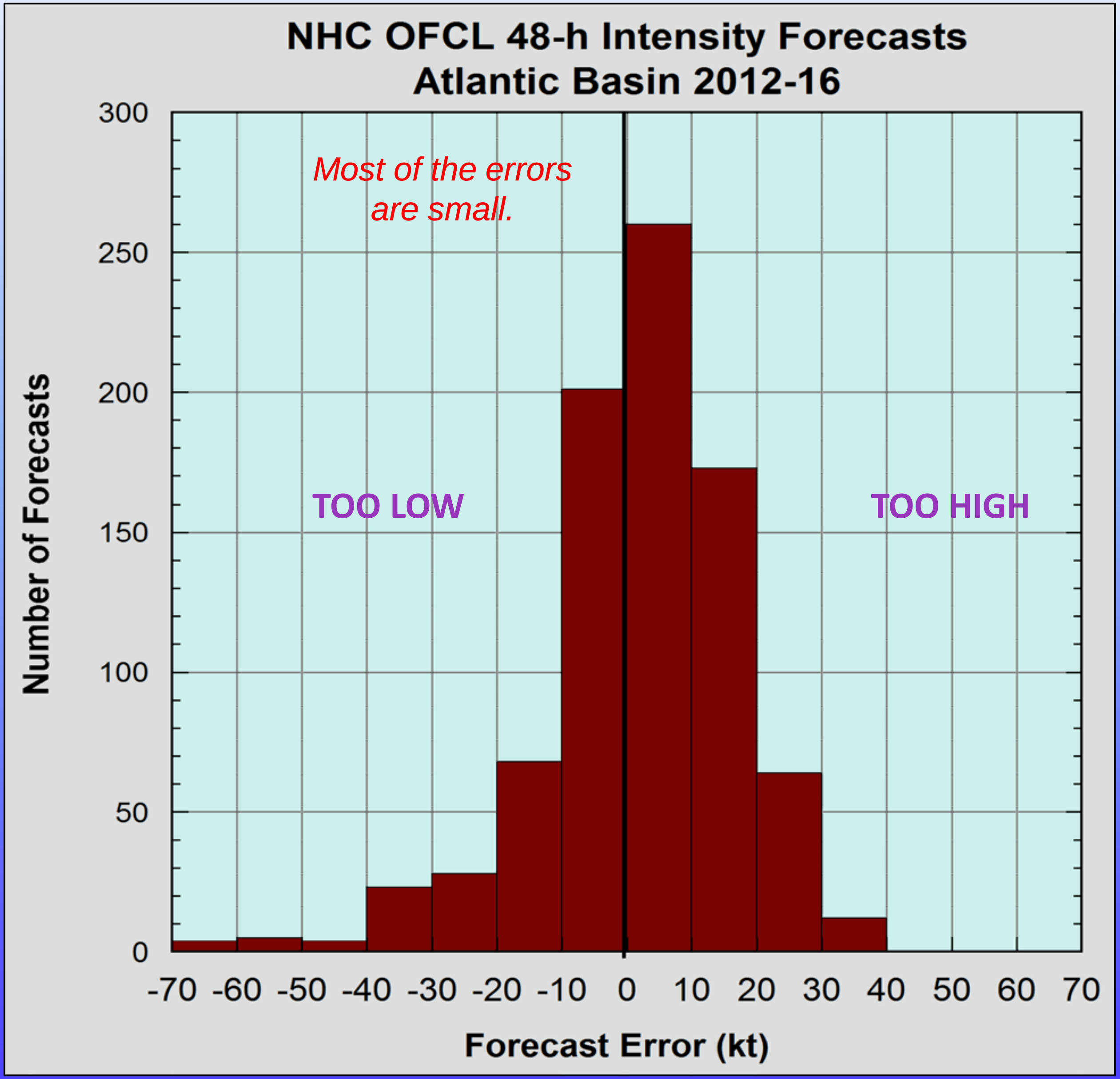
2016 Intensity Guidance



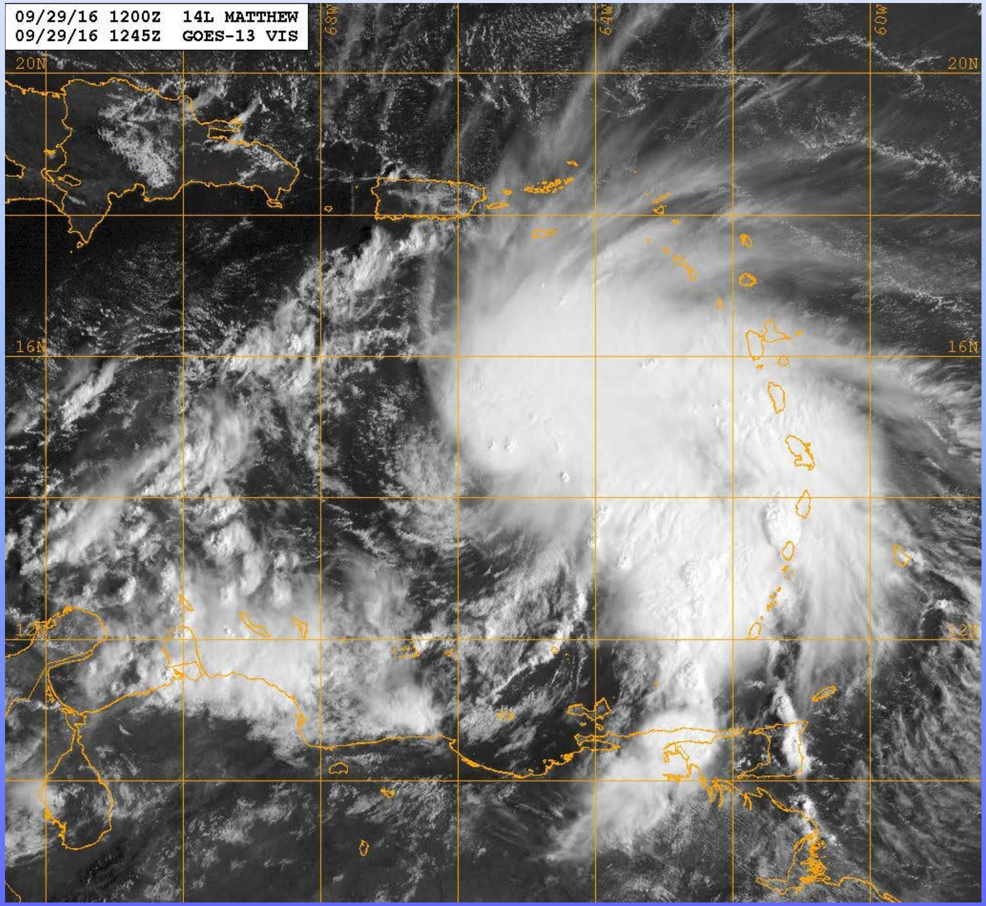
- *Among the consensus aids, IVCN was a little better than HCCA and FSSE.*
- *DSHP and LGEM were skillful but not as good as consensus aids or HWFI, CTCI.*
- *GFSI was competitive at 48 h and beyond.*
- *GFNI, GHMI, and EMXI trailed.*

Official forecasts skillful at all times, near or better than the top models.

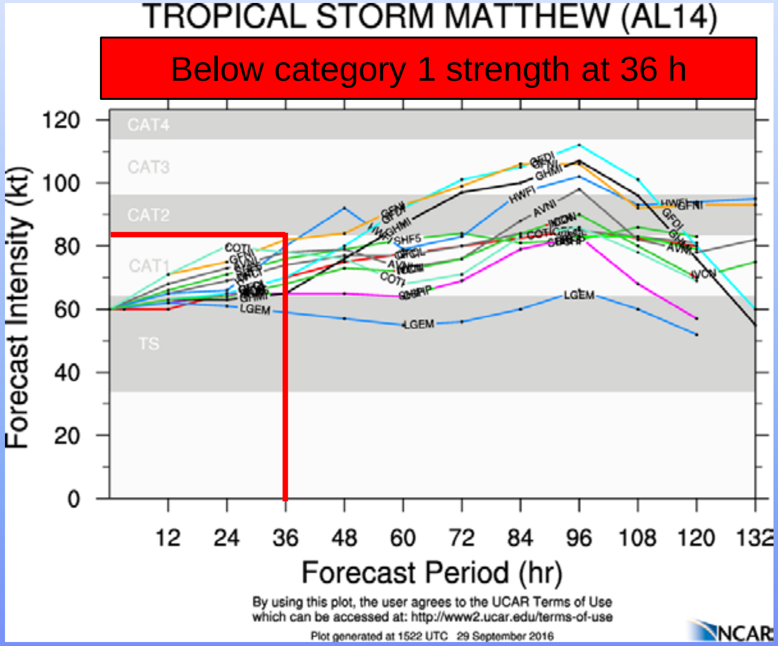
NHC Intensity Error Distribution



Difficulty Predicting Rapid Changes in Intensity



Tropical Storm Matthew – 70 mph
8:00 am September 29

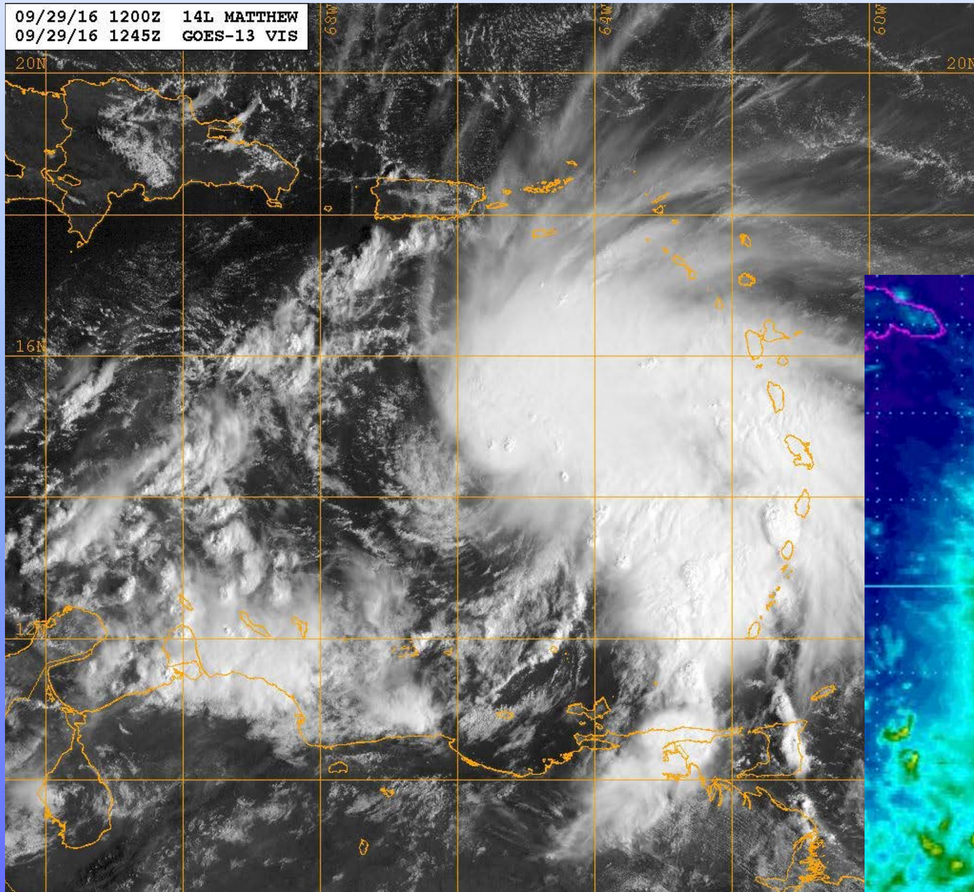


NHC Discussion 11 am Thursday, September 29, 2016

The center of Matthew is exposed to the southwest of the deep convection due to moderate southwesterly shear. Given the current shear and structure of Matthew, only slight strengthening is predicted during the next 24 hours.

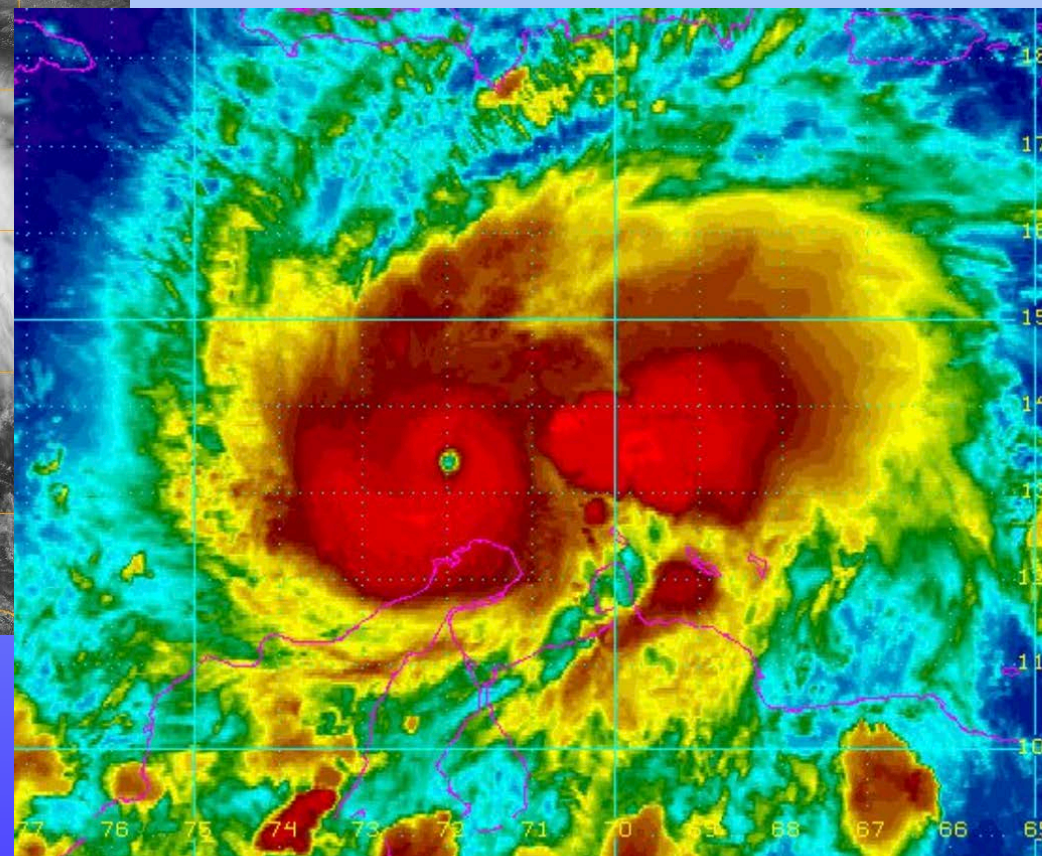
Forecaster Brown

Difficulty Predicting Rapid Changes in Intensity

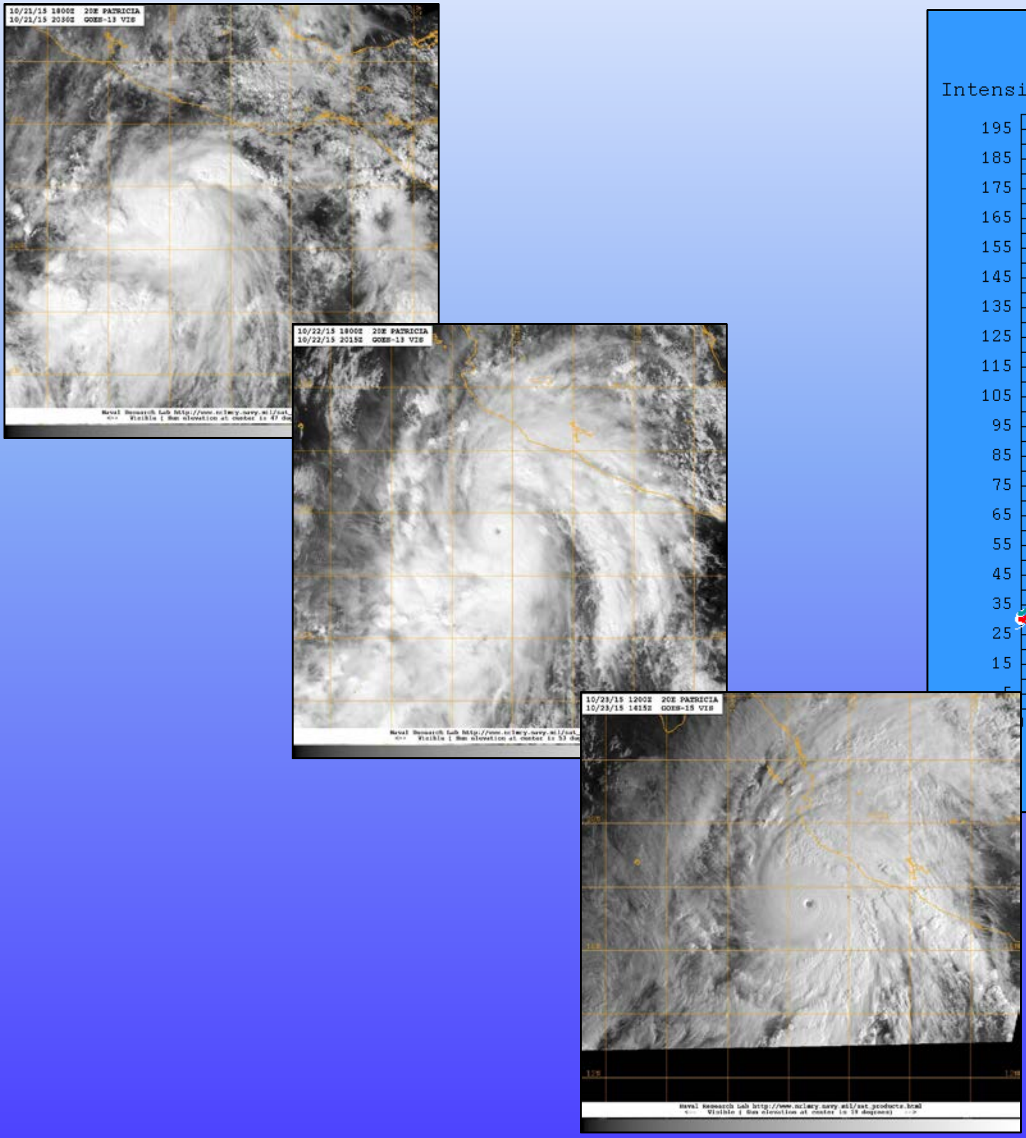


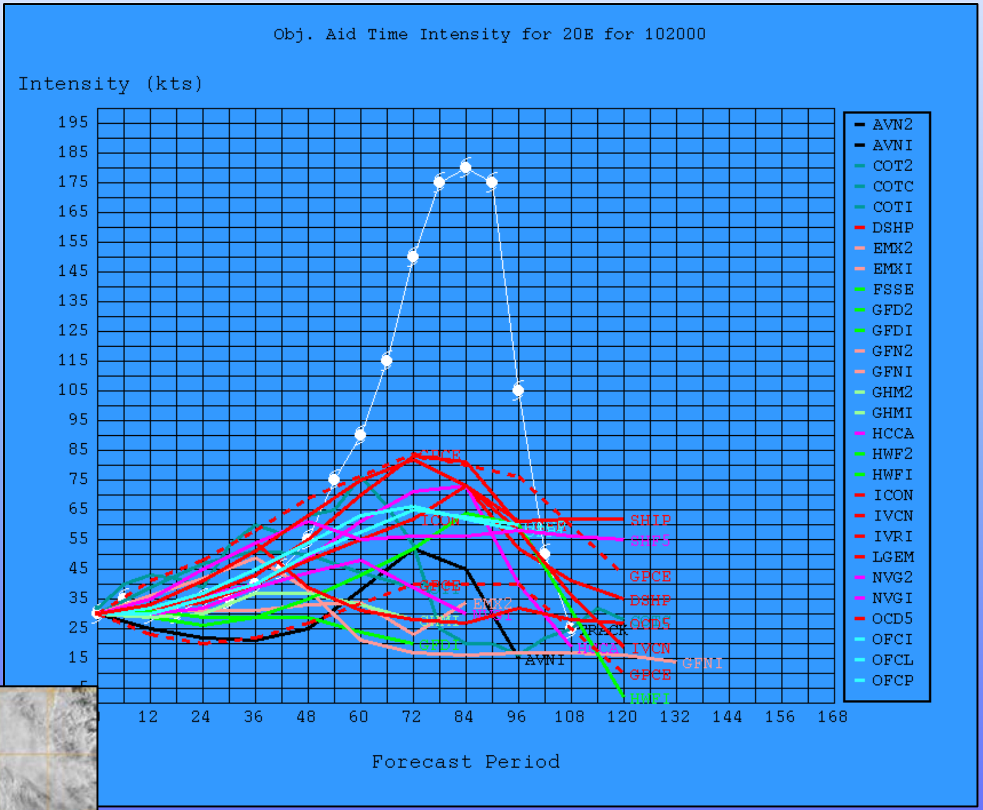
Tropical Storm Matthew – 70 mph
8:00 am September 29

36 hours later
Hurricane Matthew
Category 5 – 165 mph



Patricia’s Rapid Intensification Eastern Pacific - 2015



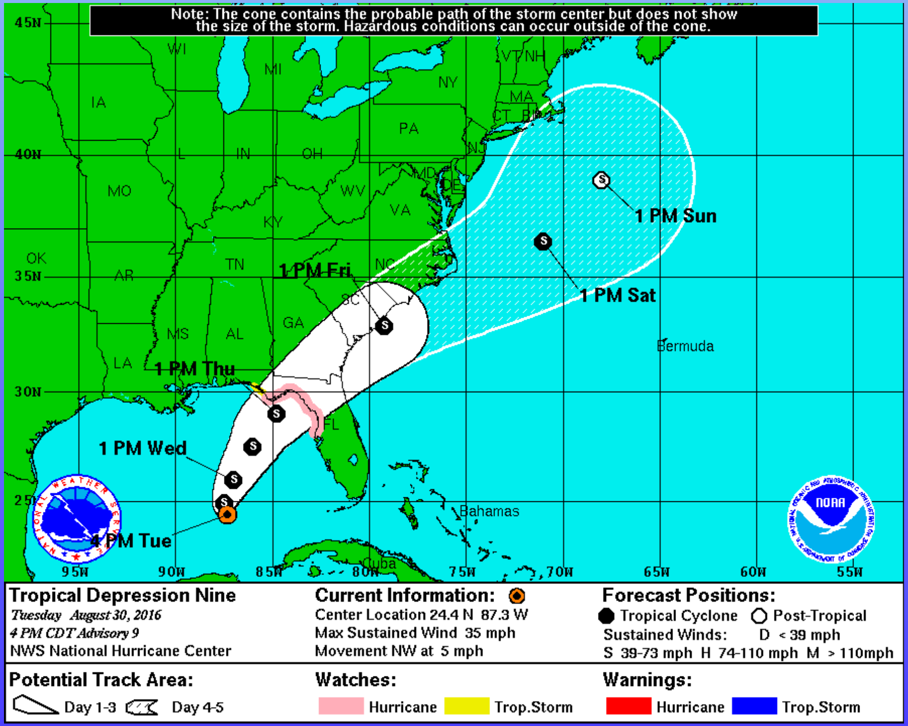


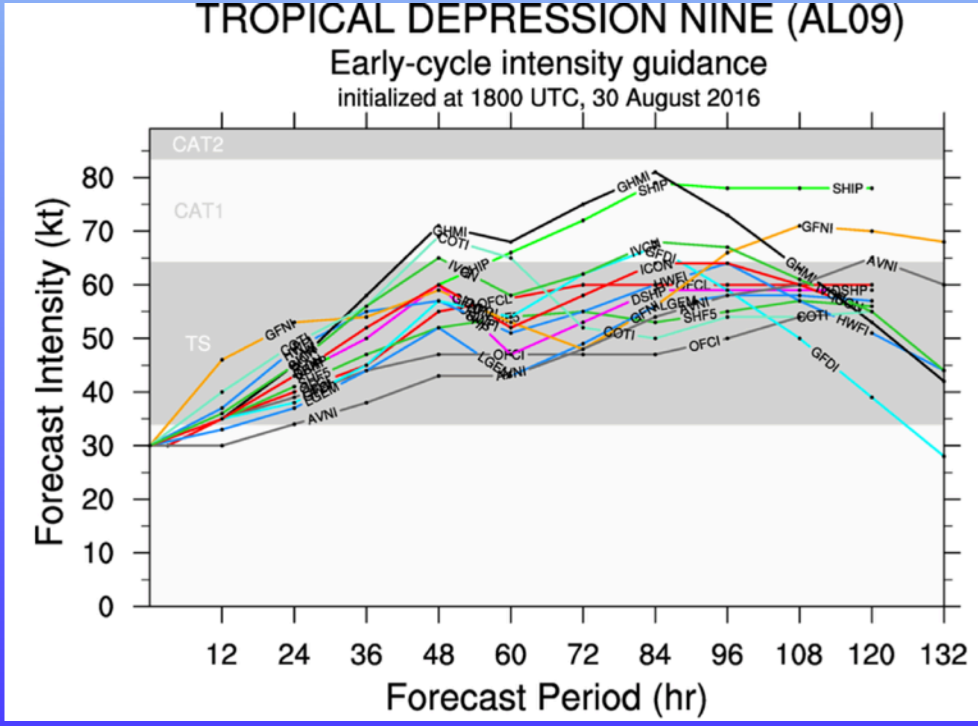
First NHC forecast and models predicted intensification but not to the rate that was observed.

Hermine's Intensification

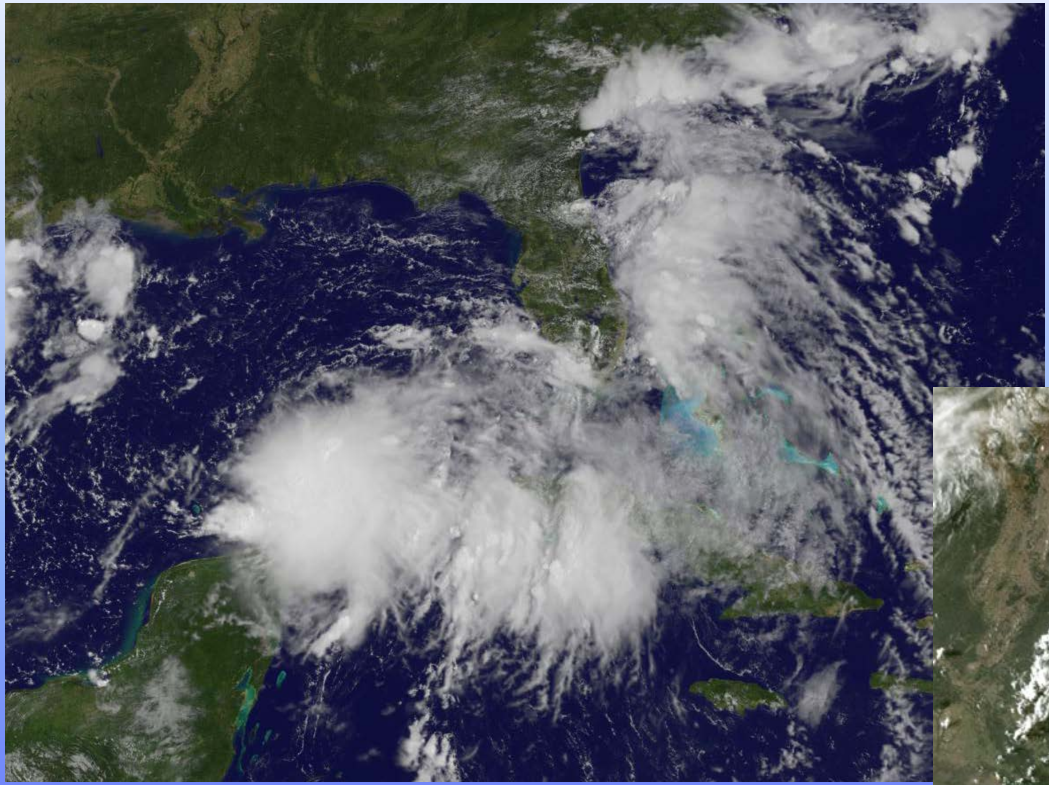
- NHC intensity forecasts were conservative during the first couple of days of the depression's existence.

- Hurricane Watch issued a little more than 48 h before the arrival of TS-force winds along the coast.
  - System was a 35-mph tropical depression at the time

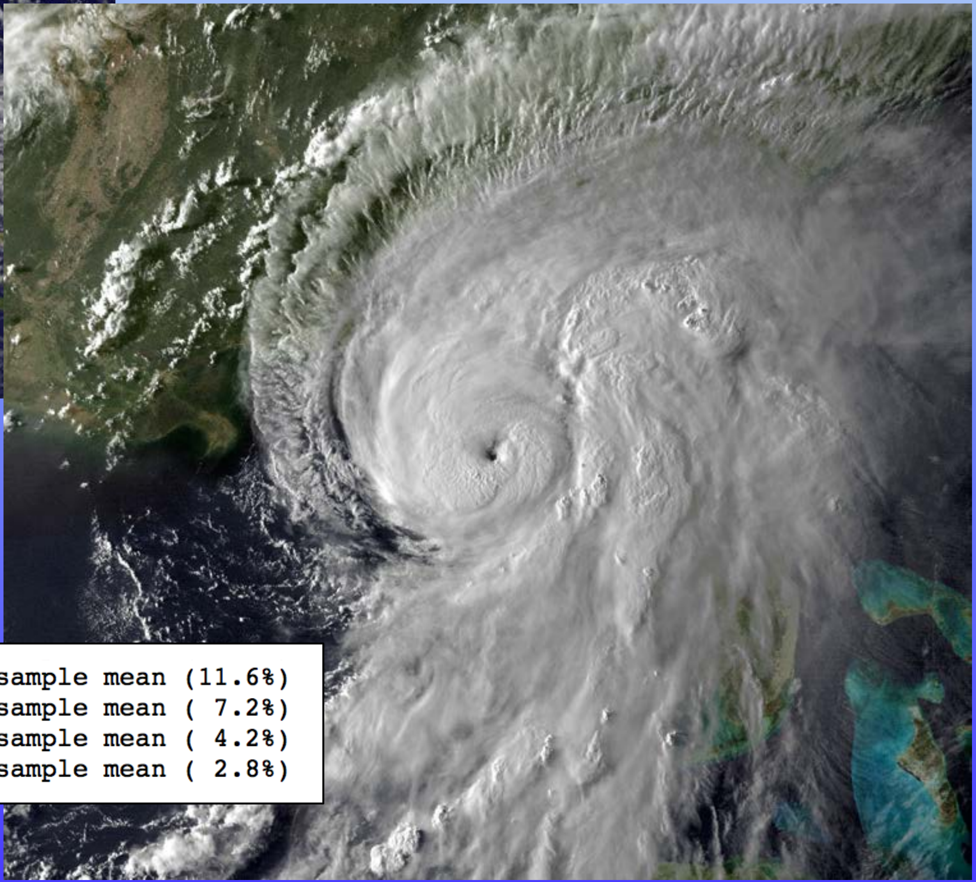




Hermine's Intensification



Hermine strengthened from a 35-mph tropical depression to a 80 mph hurricane in a little more than 48 hours.



SHIPS Rapid Intensification Index a helpful tool?

```
Prob RI for 25kt/ 24hr RI threshold=  35% is   3.0 times sample mean (11.6%)
Prob RI for 30kt/ 24hr RI threshold=  21% is   3.0 times sample mean ( 7.2%)
Prob RI for 35kt/ 24hr RI threshold=  12% is   2.9 times sample mean ( 4.2%)
Prob RI for 40kt/ 24hr RI threshold=   9% is   3.3 times sample mean ( 2.8%)
```

RI Guidance

Hurricane Patricia (2015 - East Pacific)

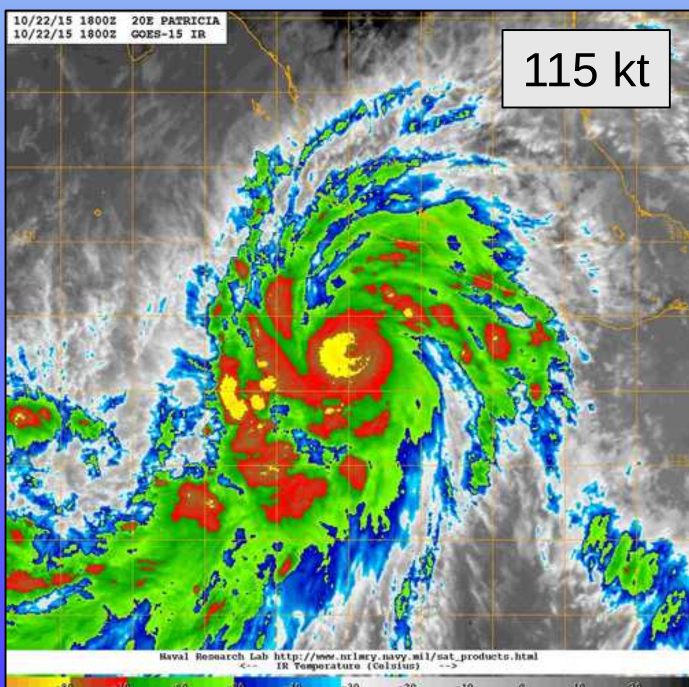
```
                 * EAST PACIFIC SHIPS INTENSITY FORECAST          *
                 * IR SAT DATA AVAILABLE,       OHC AVAILABLE     *
                 *  PATRICIA    EP202015  10/22/15  18 UTC        *

TIME (HR)         0     6    12    18    24    36    48    60    72    84    96   108   120
V (KT) NO LAND  115   129   139   140   140   118    85    73    62    53    44    38    35
V (KT) LAND     115   129   139   140   140    88    47    33    29    27    27    27    27
V (KT) LGE mod  115   131   140   143   138    88    45   DIS   DIS   DIS   DIS   DIS   DIS
Storm Type     TROP  TROP  TROP  TROP  TROP  TROP  TROP   N/A   N/A   N/A   N/A   N/A   N/A
```

```
 ** 2013 E. Pacific RI INDEX EP202015 PATRICIA    10/22/15   18 UTC **
         ( 30 KT OR MORE MAX WIND INCREASE IN NEXT 24 HR)

12 HR PERSISTENCE (KT):   40.0 Range:-22.0 to   38.5 Scaled/Wgted Val:  1.0/  2.2
850-200 MB SHEAR (KT) :    6.4 Range: 18.7 to    1.4 Scaled/Wgted Val:  0.7/  1.0
POT = MPI-VMAX (KT)   :   54.3 Range: 40.3 to  141.7 Scaled/Wgted Val:  0.1/  0.1
STD DEV OF IR BR TEMP :    4.4 Range: 38.9 to    2.4 Scaled/Wgted Val:  0.9/  1.0
Heat content (KJ/cm2) :   61.6 Range:  3.6 to   75.9 Scaled/Wgted Val:  0.8/  0.7
D200 (10**7s-1)       :  104.2 Range:-11.0 to  135.3 Scaled/Wgted Val:  0.8/  0.6
% area w/pixels <-30 C:  100.0 Range: 41.4 to  100.0 Scaled/Wgted Val:  1.0/  0.5
850-700 MB REL HUM (%):   71.2 Range: 57.6 to   96.8 Scaled/Wgted Val:  0.3/  0.0

Prob of RI for 25 kt RI threshold=    87% is   6.3 times the sample mean(13.1%)
Prob of RI for 30 kt RI threshold=    87% is  11.5 times the sample mean( 8.7%)
Prob of RI for 35 kt RI threshold=    87% is  16.7 times the sample mean( 6.0%)
Prob of RI for 40 kt RI threshold=    87% is  23.3 times the sample mean( 4.3%)
```

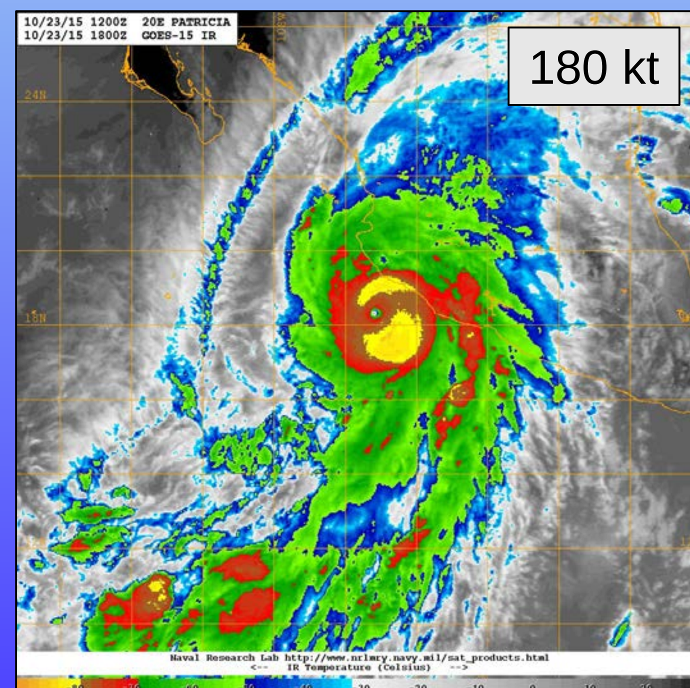
Rapid Intensification

Hurricane Patricia (2015 - East Pacific)

```
FORECAST POSITIONS AND MAX WINDS

INIT  22/2100Z 15.4N 104.6W  115 KT 130 MPH
 12H  23/0600Z 16.5N 105.6W  135 KT 155 MPH
 24H  23/1800Z 18.1N 105.9W  130 KT 150 MPH
 36H  24/0600Z 20.6N 104.9W  100 KT 115 MPH...INLAND
 48H  24/1800Z 23.3N 102.8W   50 KT  60 MPH...INLAND
 72H  25/1800Z...DISSIPATED
```



24 h



Intensity Guidance for Invests

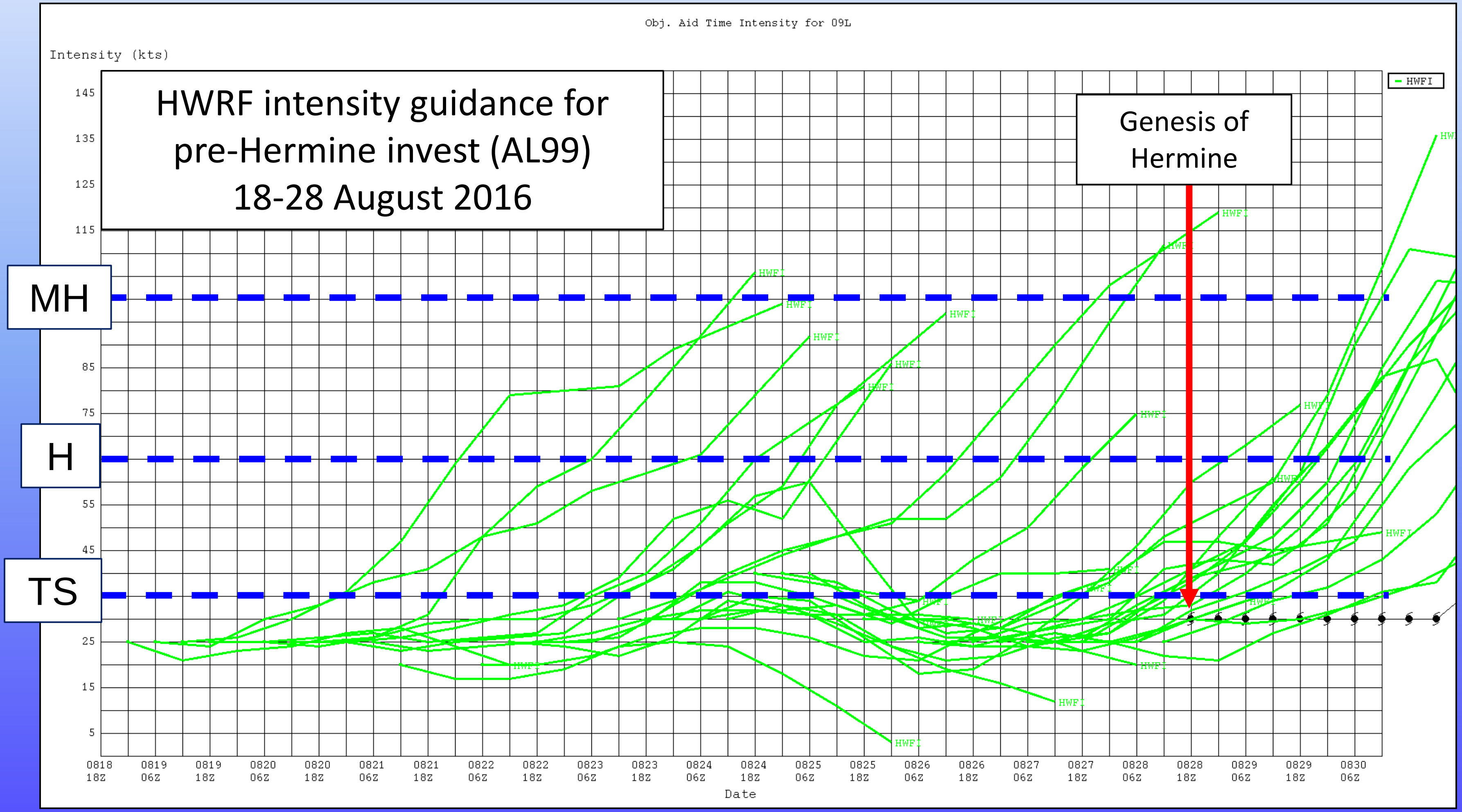
- **Nearly all of the guidance models (SHIPS, LGEM, HWRF) assume that the system already has the structure of a tropical cyclone, which often leads to a high bias in the intensity guidance.**

- **Guidance can have lots of run to run variability**

- **SHIPS diagnostic information can be useful to determine large-scale environment, but forecast environmental conditions highly dependent on the forecast track which is often very uncertain before formation**

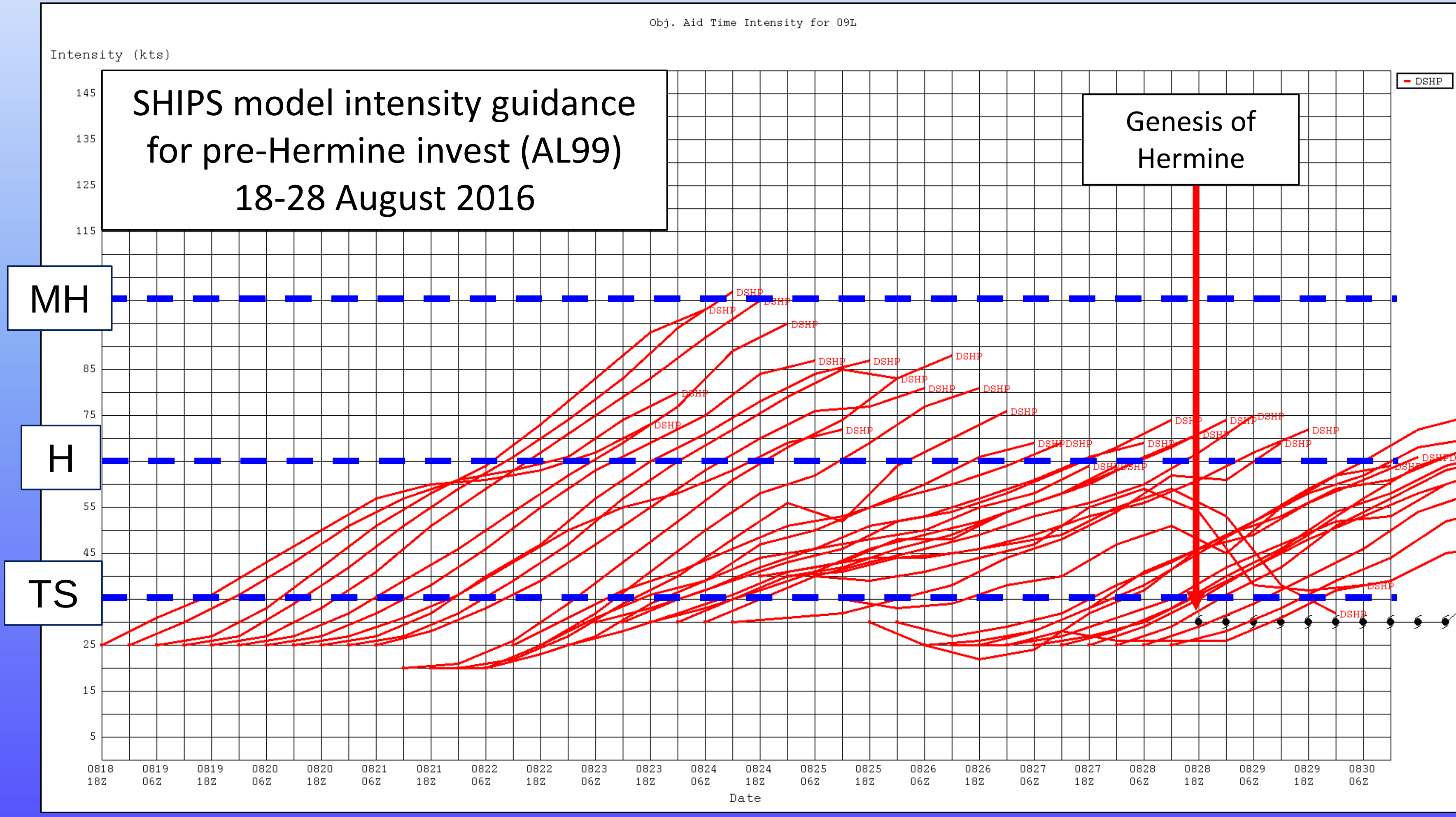
Intensity Guidance for Invests

Intensity guidance for invests can also be unreliable!



Intensity Guidance for Invests

Intensity guidance for invests can also be unreliable!



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 DSHIPS, LGEM, HWRF, IVCN and more recently, FSSE, HCCA, and in 2017 HMON
- 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. (HFIP)
- GOES-16 will provide new imagery and lightning data for dynamical and statistical-dynamical intensity models