Evaluation of CFAN's 2020 hurricane forecasts

January 12, 2021

SUMMARY

Seasonal statistics. The 2020 Atlantic hurricane season saw 30 named storms, 13 hurricanes and 6 major hurricanes. The seasonal Accumulated Cyclone Energy (ACE) was 180. The 2020 season broke the previous record in 2005 for number of named storms. A record 12 named storms made landfall in the continental U.S. 10 tropical cyclones underwent rapid intensification.

Track verification. Track verification focused on forecasts for landfalling hurricanes out to 60 and 96 hours. CFAN's calibrated ECMWF forecasts continue to perform best overall. For the cases considered, 72 hour track error in 2020 was lower (61 nm) than for 2017 (68 nm), albeit with large variability (25 to 100 knots). Many of the track forecasts were dominated by track speed error, with smaller error in the overall track trajectory.

Long-range tracks. For the 9 storms identified as long-track hurricanes, CFAN's synthetic track forecasts provided a reliable indication of the general track trajectory (including general region of landfall) at the time of genesis or earlier. CFAN's GEFS and ECMWF synthetic tracks each provided the best early indication of track trajectory for a different group of four storms.

Genesis (formation). NHC did well in predicting genesis, with no misses. CFAN's synthetic tracks provided advanced lead time (up to 7 days) relative to NHC on long track storms developing from African easterly waves. ECMWF had no false alarms but several misses relative to the NHC. GEFS had fewer misses, but many more false alarms.

Intensity verification. Intensity verification focused on the 60 hours prior to landfall, particularly the 48 hour forecasts. Forecast errors prior to landfall were larger than usual in 2020. At 48 hours, the NHC, CFAN's calibrated ECMWF HRES and HWRF most frequently had the best forecast close to landfall; however ECMWF HRES and HWRF also frequently had the worst forecast. Overall the NHC shows the best intensity forecast performance.

Rapid intensification. CFAN introduced rapid intensification forecasts, displaying the NHC forecasts as well as CFAN's new RI index. CFAN's RI index substantially outperformed the NHC indices, identifying several RI instances that were not identified by the NHC. The analysis for the 2020 storms suggests several improvements to CFAN's RI model.

Landfall winds. CFAN's calibration of landfall winds has provided a big improvement in forecast of landfall winds, with accuracy depending on the intensity forecasts. Evaluation of 2D wind forecasts 24 hour lead times shows: GFS and ECMWF raw winds are much improved relative to last year; GFS calibrated with NHC intensity forecasts were generally the best, provided that the NHC intensity forecast extends sufficiently inland.

Integrated Kinetic Energy. CFAN's calculations of IKE were compared at specific times with 16 values from RMS HWIND. CFAN's NHC-based calculations averaged ~10% lower, while CFAN's ECMWF HRES-based calculation averaged about 20% higher than HWIND. Given the large range of the IKE forecasts, this evaluation generally supports the accuracy of CFAN's IKE calculation, but forecast accuracy depends not only on intensity accuracy but also forecast of hurricane size.

SUMMARY OF ACTIVITY

The 2020 Atlantic hurricane season saw 30 named storms, 13 hurricanes and 6 major hurricanes. The seasonal Accumulated Cyclone Energy (ACE) was 179. The 2020 season broke the previous record in 2005 for number of named storms.

Name	Max (mph)	Form	Duration	ACE	Formation
Arthur	TS 60	5/17	2days	1.8	Carib
Bertha	TS 50	5/27	1 day	0.4	GoM
Cristobal	TS 60	6/2	6 days	3.5	GoM
Dolly	TS 45	6/23	1 day	0.6	frontal
Eduoard	TS 45	7/6	<1 day	0.6	frontal
Fay	TS 60	7/9	2 days	1.1	GoM
Gonzalo	TS 65	7/22	3 days	2.8	MDR
Hanna	HR 90	7/24	2 days	3.4	GoM
Isaias	HR 85	7/30	5 days	9.2	MDR
Josephine	TS 45	8/13	3 days	1.9	MDR
Kyle	TS 50	8/14	2 days	1.0	frontal
Marco	HR 75	8/22	3 days	3.4	MDR
Laura	MHR 150	8/21	7 days	12.8	MDR
Nana	HR 75	9/1	2 days	2.6	MDR
Omar	TS 40	9/2	<1 day	0.4	frontal
Paulette	HR 105	9/7	15 days	15.9	MDR
Rene	TS 50	9/7	5 days	2.2	MDR
Teddy	MHR 140	9/14	9 days	27.8	MDR
Sally	HR 105	9/12	5 days	7.4	Carib
Vicky	TS 50	9/14	3 days	2.1	MDR
Wilfred	TS 60	9/18	2 days	0.9	MDR
Alpha	STS 50	9/18	<1 day	0.4	midlatitude
Beta	TS 60	9/18	4 days	3.3	GoM
Gamma	TS 70	10/3	2 days	2.5	Carib
Delta	MHR 145	10/5	5 days	15.7	Carib
Epsilon	MHR 100	10/19	5 days	13.1	nontropical
Zeta	HR 90	10/25	4 days	7.5	Carib
Eta	MHR 150	11/1	12 days	18.1	Carib
Theta	TS 70	11/10	5 days	5.3	nontropical
Iota	MHR 160	11/13	4 days	12.2	Carib

Apart from the high numbers, there were several additional aspects of the 2020 season that were unusual. Only ten of the named storms formed in the main development region (MDR). Of the 13 hurricanes, only 6 formed in the main development region, and less than half of the major hurricanes formed in the MDR. On average, 60% of hurricanes and 85% of major hurricanes form in the MDR. A total of 6 named storms had a non-tropical origin (subtropical, mid-latitude, frontal).

Another unusual feature of the 2020 season was the seasonal distribution of activity, which is indicated by the daily accumulation of ACE (plot from CSU), relative to the 1982-2010 climatology.

By the end of Aug, there had been 13 named storms and 2 hurricanes. On Sept 11, the climatological peak of the hurricane season, the 2020 accumulated ACE was 53.6. This value is close to the 1981-2010 climatological ACE average of 51.8 (relative to a seasonal total ACE of 105.6). The relatively large number of storms with small ACE was associated with a substantial number of storms having non-tropical origins, with relatively few forming in the Main Development Region.

In the second half of September, activity was high with the formation of 8 named storms (3 hurricanes). While adding to the ACE totals (reaching 104.6 by Sept 21), overall this was a weak showing for activity in the Main Development Region during the peak of climatological activity, for an otherwise extremely active season.

The most anomalous seasonal activity occurred during October and the first half of November, with 7 named storms, 5 hurricanes and 4 major hurricanes. La Nina strengthened substantially by early October. During La Nina years, the Madden-Julian Oscillation (MJO) is more active. Distinct active and break periods during October and November were associated with the subseasonal signals (MJO and related oscillations). The three week period ending in mid November was a perfect storm of conditions in the Caribbean: weak wind shear from La Nina and extremely favorable subseasonal conditions (e.g. MJO) that were associated with strong rising motion in the Caribbean.

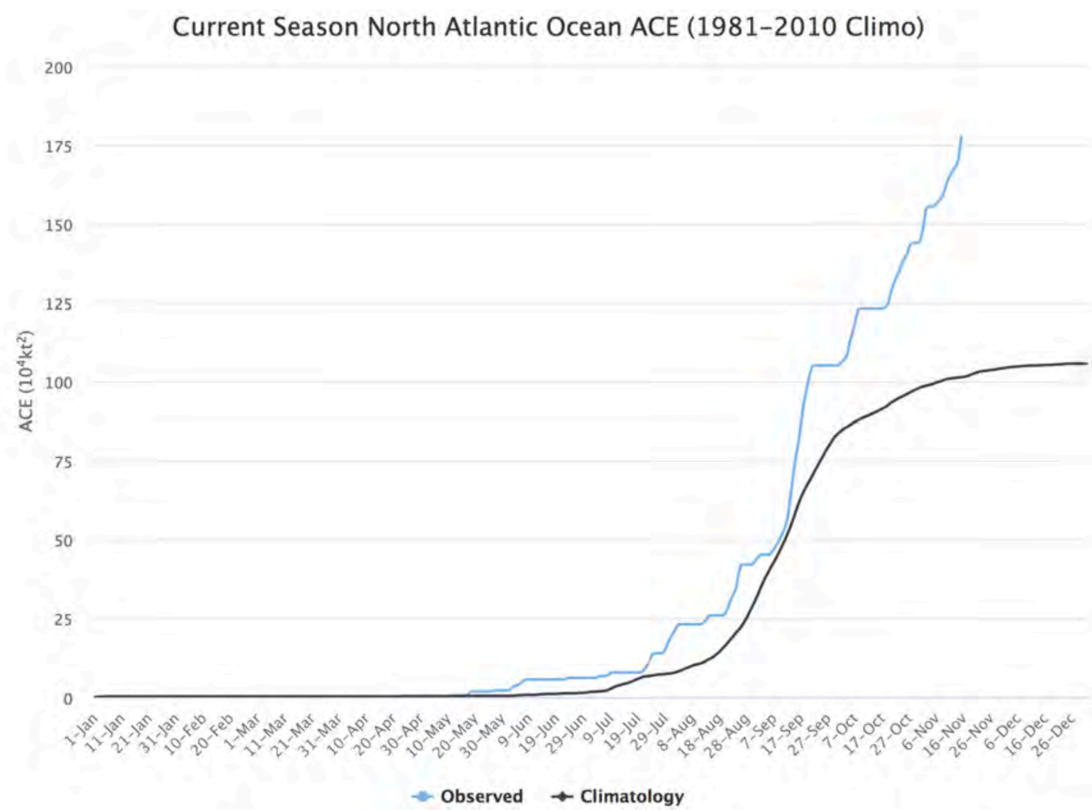


Figure from Colorado State

TRACK VERIFICATION

Summary. This analysis of track forecast performance for 2020 focuses on forecasts for hurricane landfalls out to 60 and 96 hours. Overall, CFAN's calibrated ECMWF forecasts continue to show the best performance. For the cases considered, 72 hour track error in 2020 was lower (61 nm) than for our 2017 analysis (68 nm), albeit with large variability from 25 to 100 knots. Many of the track forecasts were dominated by track speed error, with smaller error in the overall track trajectory. While ECMWF tracks performed best overall, there was large forecast error prior to landfall for Laura that was not anticipated by prior real-time track verification statistics.

During the 2017 Atlantic hurricane season, CFAN undertook a comprehensive evaluation of ECMWF track forecasts relative to the NOAA/NHC forecasts. At 72 hours (3 days) and 120 hours (5 days), the following overall track error statistics were obtained (nm):

Tracks	72hr	120hr
NOAA GFS (raw)	90	183
NHC Official	80	148
ECMWF HRES (raw)	73	127
CFAN HRES calibrated	69	120
ECMWF Ens Mean (raw)	73	120
CFAN Ens Mean calibrated	68	114

NHC annual track forecast evaluations (typically issued in April or May) show year-to-year variability in skill, largely arising from weather conditions associated with individual storms, but also associated with steady improvements in the forecast models. Relative to the 2017 evaluation, the biggest change has been to the GFS/GEFS – a new forecast model system with updated hindcasts. While the transition for GFS occurred in autumn 2019, the GEFS transition occurred in autumn 2020, in the middle of the hurricane season.

To evaluate track forecast skill for the 2020 season, 10 landfalling hurricanes plus one that passed close to Bermuda were selected for evaluation. We examined forecasts made within 60 and/or 96 hours prior to landfall and at other times that provide insight into the evolution of forecast skill over the course of the storm.

Summary counts of 'best' track forecasts (ECMWF and GEFS/GFS are CFAN calibrated):

ECMWF: 14
GEFS/GFS: 4
NHC: 3

We elected not to reproduce the season-wide track verification analysis that we conducted in 2020. The primary reason for this is that the verification statistics would be dominated by the large number of tropical storms and the long-track storms in the Atlantic. Instead, we focus on the most consequential forecasts associated with landfalling hurricanes. The Table below evaluates qualitatively the track forecasts for 11 storms from NHC, ECMWF HRES and Ens Mean, GFS and GEFS, using the real time verification tool on the Active System page. The best forecast over the second half of the verification period is indicated in the Table; a '+' indicates that the forecast was best by a substantial margin.

Hurricane	Impact	60 hrs	96 hrs	72 hr min error (kts)
Hanna	TX landfall	EC Mean	EC HRES	83
Isaias	NC/SC landfall	EC Mean	EC Mean	50
Laura	Cuba landfall	EC Mean		
	LA landfall		NHC/GFS +	25
Paulette	MDR track	EC HRES		
	Bermuda landfall		EC Mean	55
Teddy	MDR track	EC Mean		
	Bermuda landfall		GFS	80
Sally	AL landfall	EC HRES	NHC	95
Delta	Yucatan landfall	GFS		
	LA Landfall		EC Mean	25
Epsilon	SE of Bermuda		EC Mean+	25
	Passing Bermuda	EC Mean+		
Zeta	Yucatan landfall	EC Mean		
	MS landfall		NHC	80
Eta	Nicaragua landfall	NHC		
	FL landfall		EC HRES	100
Iota	Nicaragua landfall		EC Mean	55
Average				61

The 72 hour minimum error in the track forecasts shows substantial inter- and intra-storm variability, with an average value of 61 knots. For reference, from the 2017 analysis, the 72 hr track error was 68 knots for ECMWF Ens Mean and 80 knots for NHC.

The images for the real time verification statistics for each storm used in the Table are given in Appendix A.

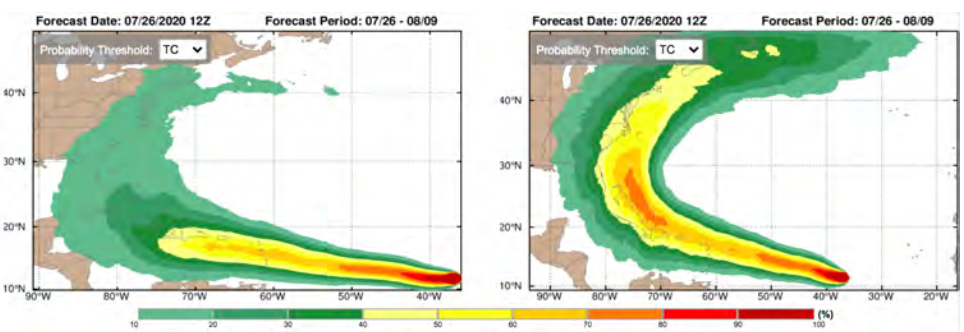
LONG-TRACK HURRICANES

Summary. For the 9 storms identified as long track hurricanes, 8 formed in the main development region from African easterly waves. For each of these storms, CFAN's synthetic tracks provided a reliable indication of the eventual track trajectory at the time of genesis or earlier. The GEFS and ECMWF synthetic tracks each provided the best early indication of track trajectory for a different group of four storms.

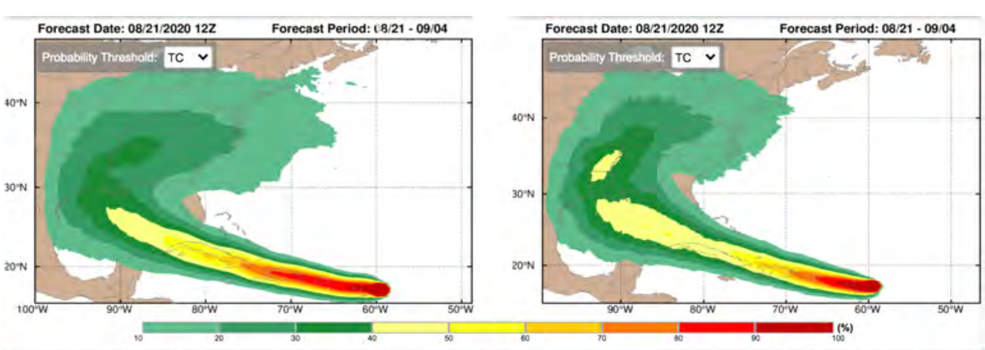
CFAN's most important innovation in hurricane track forecasts is the synthetic track probabilities, which are created from 1500 synthetic tracks for each forecast using a Monte-Carlo resampling technique. The synthetic tracks provide extended-range information for hurricane formation and also long range track outlooks, which are most relevant from the long track hurricanes that develop from African easterly waves. Below are examples of long-lead track forecasts, which predicted the correct overall track trajectory prior to, or at the time of, genesis.

In the images below, the ECMWF synthetic tracks are on the left, and GEFS on the right.

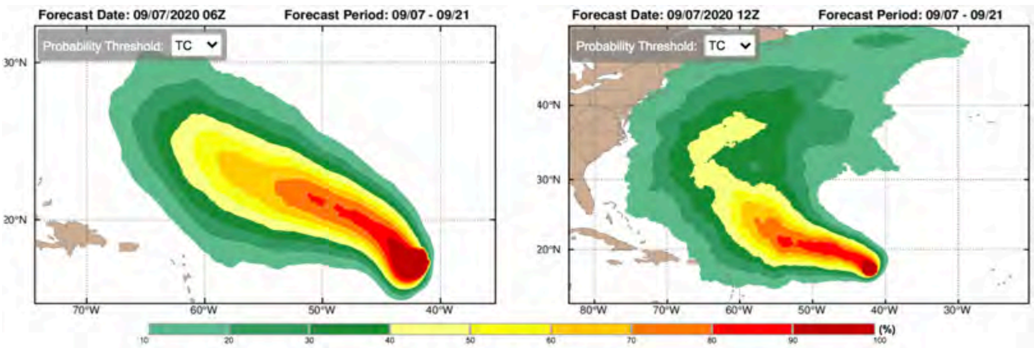
HR Isaias – formed 7/30 00Z; landfall 8/04 00Z. 3.5 days before genesis, the GEFS synthetic tracks targeted a NC landfall.



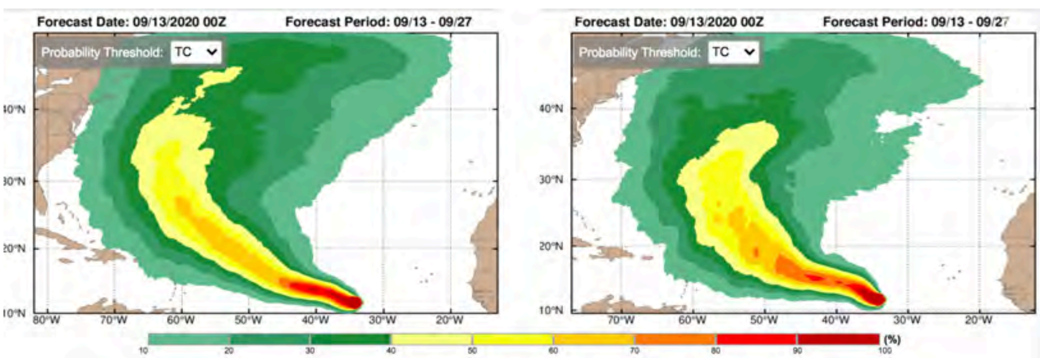
MHR Laura – formed 8/21 12Z; landfall 8/27 06Z. At the time of genesis, both models targeted a landfall on the central Gulf coast.



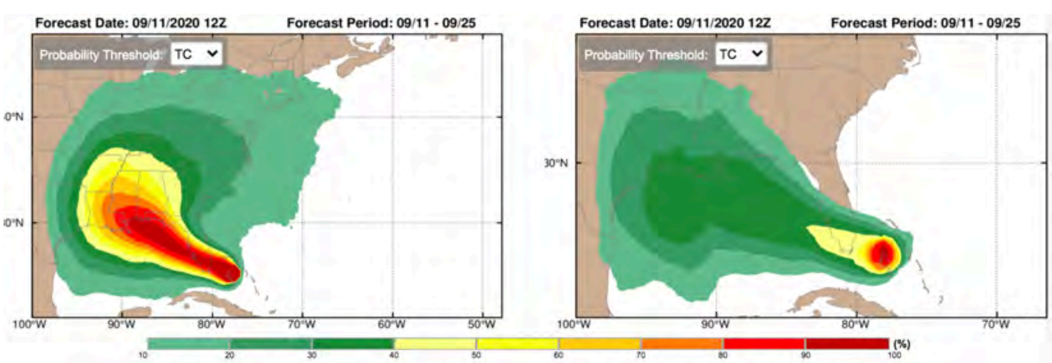
HR Paulette – formed 9/07 12Z; landfall 9/14 06Z. At the time of genesis, GEFS captured the general track. Note a glitch in the ECMWF processing showed only the shorter lead time (6 day) tracks.



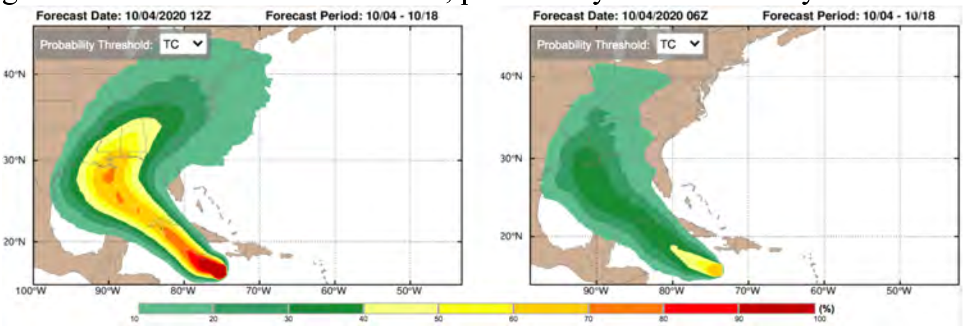
MHR Teddy – formed 9/14 06Z; passed Bermuda 9/21 18Z. 30 hours prior to genesis, both models generally captured the track, but GEFS showed a characteristic eastward bias.



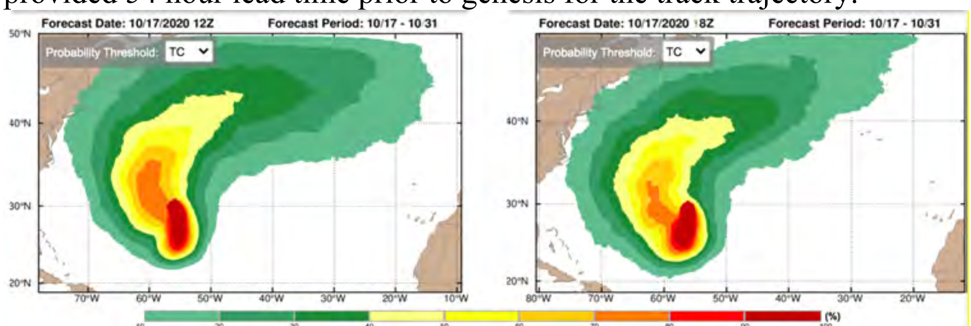
HR Sally – formed 9/12 18Z; landfall 9/16 12Z. 30 hours prior to genesis, both models generally captured the track, with a very clear signal from ECMWF.



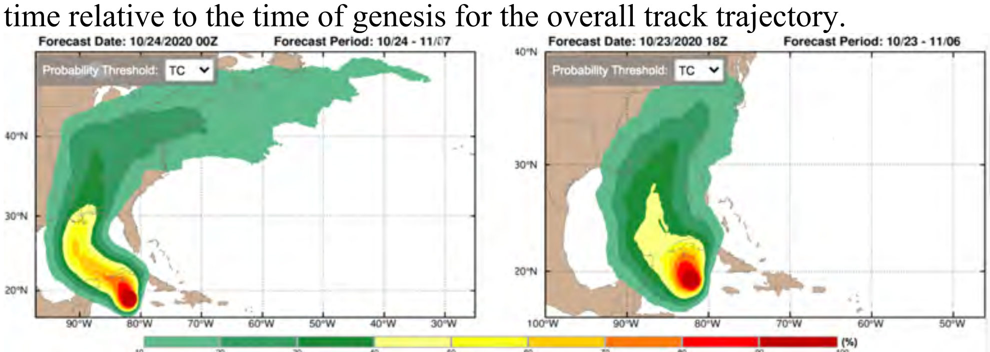
MHR Delta – formed 10/05 12Z ; landfall 10/10 00Z. 24 hours prior to genesis, models gave a clear indication of the track, particularly the ECMWF synthetic tracks



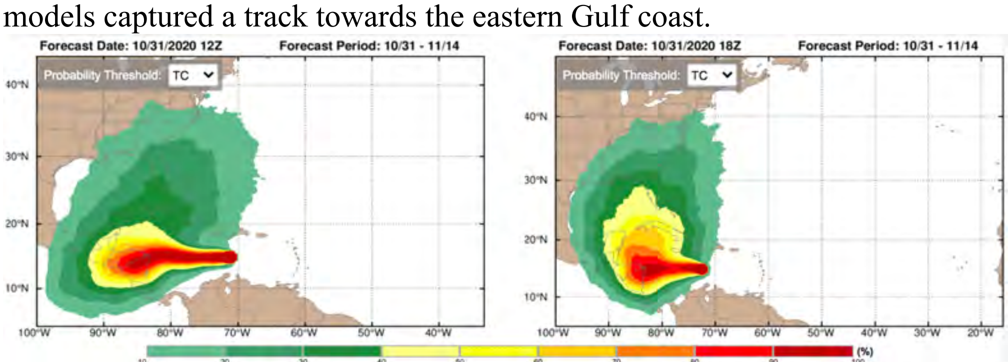
MHR Epsilon – formed 10/19 18Z; landfall (Bermuda pass) 10/23 00Z. Both models provided 54 hour lead time prior to genesis for the track trajectory.



MHR Zeta – formed 10/25 06Z; landfall 10/29 0Z. Both models provided 30 hours lead time relative to the time of genesis for the overall track trajectory.



MHR Eta – formed 11/01 00Z; (2nd) landfall 11/12 06Z. 12 hours before genesis, both models captured a track towards the eastern Gulf coast.



TROPICAL CYCLOGENESIS

Summary. NHC issued 40 invests for 30 named storms. NHC did well in predicting genesis, with no misses. CFAN's synthetic tracks provide advanced lead-time relative to NHC on the long track storms developing from African easterly waves. ECMWF had no false alarms but several misses relative to the NHC invest. GEFS had fewer misses, but many false alarms.

NHC appears to issue an invest when genesis probability exceeds 50%. CFAN's genesis forecast is tied to our synthetic track intensity probabilities. In evaluating genesis from CFAN's forecasts, this season was complicated by several storms in the same region at the same time, and also formations in the central Atlantic (outside of CFAN's genesis domain).

Evaluation of genesis for each invest/named storm is provided in the Table on the next page. For a named storm, a CFAN probability >60% at the time of invest is scored as a win (indicated by asterisk in the Table below); for an invest that doesn't get named, a CFAN probability <30% is scored as a win. A loss (indcated by -) is associated with a false alarm (red) on a storm that doesn't get named or a miss (yellow or green) on a storm that does get named. A summary table:

Genesis Hits (earliest genesis forecast):
- NHC: 4
- EC Syn: 8
- GEFS Syn: 12

Genesis Misses (relative to time of NHC invest; yellow or green from Syn):
- NHC: N/A
- EC Syn: 5
- GEFS Syn: 3

Genesis False Alarms (relative to invests that didn't form; red from Syn):
- NHC: (10)
- EC Syn: 0
- GEFS Syn: 2

Overall, NHC had a higher rate of named storms per # of invests in 2020 than in 2019 (in 2019, half on NHC's invests did not develop). In 2020, NHC invests were reliable estimates of tropical cyclone genesis, with >75% hit rate (no misses). For 15 of the named storms, CFAN's synthetic tracks (ECMWF and/or GEFS) spotted the formation of a named storm prior to the NHC invest (>60%); only 3 named storms had ECMWF/GEFS at yellow at the time of invest that actually developed. GEFS spotted more storms with greater lead-time; however the GEFS was associated with more false alarms (including systems for which NHC never issued an invest). For 8 of the named storms, CFAN's synthetic tracks provided greater than 1-day lead-time on genesis, relative to the NHC invest, particularly for long-track storms originating from African Easterly waves.

Green: 1-10% Yellow: 10-30% Orange: 30-60% Red: >60%

Name	Date	Location	ECMWF Syn Lead	GEFS Syn Lead
Arthur	5/14 18Z	FL straits	Y-	O
Bertha*	5/26 18Z	SE coast	Y-	Y-
92L	5/29 00Z	Cent ATL	out of domain	
Cristobal	6/01 00Z	BoC	R* 1 day	R* 1 day
94L	6/16 12Z	SE coast	Y*	G*
Dolly	6/21 12Z	Mid Atl coast	out of domain	
96L	6/28 12Z	MDR	Y*	Y*
Eduoard*	7/04 00Z	SE coast	Y-	O
Fay*	7/05 18Z	Gulf	Y-	G-
90L	7/20 12Z	Gulf	O	Y*
Gonzalo	7/20 12Z	MDR	O	O
Hanna	7/21 18Z	Gulf	O	O
Isaias	7/24 12Z	MDR	R* 2 days	R* 2 days
Ten	7/30 06Z	MDR	Y*	Y*
94L	8/01 18Z	MDR	O	Y*
Josephine	8/09 06Z	MDR	O	R* 2 days
Kyle	8/14 00Z	Mid Atl coast	O	O
Marco	8/16 18Z	MDR	O	Unavailable
Laura	8/17 12Z	MDR	R*	R*
Nana	8/30 06Z	MDR/Car	R*	R*
Omar	8/30 18Z	SE coast	R*	R*
91L	9/01 18Z	MDR	O	O
Paulette	9/04 12Z	MDR	R* 6 days	R* 7 days
Rene	9/06 06Z	MDR	R*	R*
94L	9/07 18Z	Cent Atl	out of domain	
Teddy	9/10 18Z	MDR	R*	R*
Sally*	9/11 00Z	FL	Y-	Y-
Vicky	9/12 06Z	MDR	Confused with Teddy	
Wilfred	9/15 00Z	MDR	O	R*
Alpha	9/15 12Z	Cent ATL	out of domain	
Beta	9/16 06Z	BoC	O	R* 12 hrs
Gamma	10/01 06Z	Carib	O	R* 1 day
Delta	10/03 12Z	Carib	R* 12 hrs	R* 4 days
96L	10/07 12Z	MDR?	G*	R-
93L	10/11 12Z	MDR/Carib	O	R-
Epsilon	10/16 06Z	Cent Atl	out of domain	
Zeta	10/23 00Z	Carib	O	Unavailable
Eta	10/30 00Z	Carib	R+12 hrs	R*+3
Theta	11/08 12Z	Cent Atl	out of domain	
Iota	11/10 12Z	Carib	O	R*4 days

INTENSITY

Summary. Intensity forecast errors prior to landfall were larger than usual in 2020, owing to a substantial number of rapid intensification events. Unless there was a rapid intensification situation, most of the 24 intensity forecast errors were close to or less than 10 knots. At 48 hours, the NHC, ECMWF HRES and HWRF most frequently had the best forecast close to landfall; however, ECMWF HRES and HWRF also frequently had the worst forecast, while NHC never ranked among the worst forecasts). Overall the NHC shows the best intensity forecast performance, but there is wide interstorm and intrastorm variability in intensity forecast performance. The global models perform poorly for storms with small horizontal extent.

To evaluate intensity forecast skill for the 2020 season, we evaluated the highest impact forecasts 60 hours prior to landfall for 9 landfalling hurricanes (including two storms with multiple landfalls). Forecasts evaluated included NHC Official, HWRF, HMON, ECMWF HRES, ECMWF Ens Mean, GFS and GEFS Ens Mean. The ECMWF and GFS/GEFS intensities are calibrated by CFAN. The Table below summarizes the forecast skill and error for the 48 hour forecasts (average of 3 forecasts within the 60 hour period).

Storm	Best forecast	Min error (kts)
Hanna	NHC	24
Isaias	EC HRES	5
Laura	HWRF	8
Paulette	GFS	2
Sally	EC HRES, NHC, GEFS	16
Delta	EC HRES, NHC, GEFS, HWRF	3
Eta	HWRF	28
	NHC	5
Zeta	HWRF, HMON	8
	EC HRES	10
Iota	HMON	10

Summary of 'best forecast model' frequency:

NHC:	4
EC HRES:	4
HWRF:	4
GEFS:	2
GFS:	1
HMON:	1

While ECMWF HRES and HWRF often scored as 'best model', they also frequently scored near the worst model (HWRF too high, ECMWF HRES too low.) NHC never scored near the worst models, making the NHC best overall.

The real time verification statistics used in the Table are shown in Appendix B.

RAPID INTENSIFICATION

Summary. CFAN has developed a new Rapid Intensification (RI) model, using different input variables than the NHC RI models. CFAN's new RI model outperformed the NHC indices, particularly in terms of detecting some events that were missed by NHC forecast models. False alarms from CFAN's RI model were mostly attributed to landfalls and unfavorable environmental conditions, which can be discerned independently using forecasts of landfall and the NHC SHIPS RI index.

In 2020, CFAN introduced rapid intensification (RI) forecasts on the Active System page. We provide 3 different RI models from the NHC: SHIPS RI, Consensus and DTOPS, plus a climatological RI probability (typically around 5%).

Starting with Josephine, CFAN began making operational forecasts using a new RI model that we are developing (for a total of 20 named storms). Our original idea was to develop the new index as a supplement to the NHC RI Index, using completely different inputs from the NHC indices. Our strategy was to rely more on storm history and structural characteristics, rather than the current or forecasted environmental conditions (e.g. wind shear, ocean heat content). We developed our RI index using data from 26 storms selected from the 2016-2019 seasons. Verification statistics showed substantially greater skill for CFAN's index relative to the NHC indices, especially with regards to probability of detection. We were somewhat surprised by the high stand-alone skill of CFAN's Index, without any consideration of environmental conditions/forecasts.

The 2020 hurricane season provided an excellent opportunity for verification of our new RI scheme, with 10 RI events. The RI forecasts for the 2020 storms are evaluated statistically, using a contingency table approach:

- Probability of detection (hit rate): What fraction of the observed "yes" events were correctly forecast? [POD=hits/(hits+misses)]
- Miss rate: What fraction of the predicted "no" events actually did occur (i.e., were missed)? [MSR=miss/(hits+misses)]
- False alarm rate: What fraction of the predicted "yes" events actually did not occur (i.e., were false alarms)? [FAR=FA/(hits+FA)]
- Success rate: What fraction of the forecast "yes" events were correctly observed? [SR = hits/(hits + FA)]
- Threat score (critical success index): How well did the forecast "yes" events correspond to the observed "yes" events? [TS=hits/(hits+miss+FA)]

In assessing the skill scores, the time series was filtered to eliminate any 24 hour forecast within 18 hours of landfall, and within 36 hours of landfall for the 48 hour forecast. For emergences following landfall, forecasts were eliminated for the period over which the storm was over land (e.g. Yucatan). The tables below summarize the RI forecasts for 5 different forecast probability ranges. 50% refers to all probability forecasts ≥50%, etc.

The tables show that overall, CFAN's RI index outperforms NHC SHIPS and DTOPS. CFAN's Probability of detection (POD; hit rate) is much higher than the NHC indices, with much lower Miss Rates (MSR). However, CFAN has a higher False Alarrm Rate (FAR). Overall, CFAN has a higher Threat Score (TS; critical success index) than NHC.

CFAN 0-24h RI forecast (>30kts)

	10%	25%	40%	60%.	70%
POD (p=1)	1.00	1.00	0.80	0.55	0.33
SR (p=1)	0.28	0.29	0.29	0.37	0.43
MSR (p=0)	0.00	0.00	0.20	0.45	0.67
FAR (p=0)	0.72	0.71	0.71	0.63	0.58
Ts (p=1)	0.28	0.29	0.27	0.29	0.23

SHIPS 0-24h RI forecast (>30kts)

	10%	25%	40%	60%.	70%
POD (p=1)	1.00	0.49	0.28	0.05	0.03
SR (p=1)	0.14	0.36	0.65	0.67	1.00
MSR (p=0)	0.00	0.51	0.72	0.95	0.97
FAR (p=0)	0.86	0.64	0.35	0.33	0.00
Ts (p=1)	0.14	0.26	0.24	0.05	0.03

DTOPS 0-24h RI forecast (>30kts)

	10%	25%	40%	60%.	70%
POD (p=1)	0.55	0.32	0.24	0.13	0.13
SR (p=1)	0.39	0.57	0.82	0.83	1.00
MSR (p=0)	0.45	0.68	0.76	0.87	0.87
FAR (p=0)	0.61	0.43	0.18	0.17	0.00
Ts (p=1)	0.30	0.26	0.23	0.13	0.13

The time series of the RI forecasts, overlain on the intensity time series, are given in Appendix C.

Here is what we have concluded from the 2020 evaluation, which suggests avenues for improvement in the RI index:

- Half of the 2020 RI events were missed or underpredicted by the NHC RI models, with NHC predicting values >50% only for Laura, Teddy Delta, Eta and Iota.
- CFAN's RI indices also captured the rapid intensification of Zeta, Epsilon, Gamma, Teddy, and Sally, while NHC indices were <50%.
- CFAN's forecast is on occasion late in picking up the RI (especially the 48 hr forecast); further, the forecasts flicker on and off. One problem is a threshold for wind speed change that is too stringent.
- CFAN's 24-hr forecast performed better than the 48-hr forecast; we will evaluate some different input variables for 48-hr forecasts.
- Following the Rapid Intensification of hurricane Delta, there was a rapid de-intensification prior to the Yucatan landfall. CFAN's and NHC SHIPS RI 24 hr forecasts showed 80% chance of continued intensification at the time of peak intensity. However, there was clear signal from the pressure-wind relationship that Delta's intensity had substantially overperformed relative to the surface pressure. The pressure-wind relationship suggested a brake on the RI forecast, that could be applied as part of the fuzzy logic algorithm. Further, Delta had a pinhole eye and very small Radius of Maximum Wind while it was intensifying.

These factors suggest a framework for a fuzzy logic-based rapid de-intensification index.

- Two types of false alarms were identified: a forecast of RI that was too early, especially the 24 hour RI forecast; and random sporadic firing of the index, without any observed rapid intensification. Some of these false alarms were tied to unfavorable environmental conditions
- Sometimes when CFAN's RI Index fires at say the 40-70% level, an RI event (>30 knots in 24 hours) does not ensue, but the storm does intensify significantly (nominally scaling with the magnitude of RI index). This suggests a possible strategy for intensity forecasts for storms having a particular structure that causes CFAN's RI Index to fire.

Landfall Winds

Summary. CFAN's calibration of landfall winds provides considerable improvement relative to raw ECMWF and GFS. Different combinations of background forecast fieldss (ECMWF or GFS) with different intensity calibrations provides a range of forecast solutions for the landfall winds.

The raw GFS wind fields are generally better than ECMWF wind fields. NHC's intensity forecasts are overall better than CFAN's calibrated ECMWF and GEFS intensities; however NHC intensity forecasts are not available until a storm is named and sometimes their forecast cuts out too early inland.

With regards to inland winds, CFAN's intensity calibration often produces wind speeds that are too high, particularly if the magnitude of the calibration is too large.

CFAN's landfall wind forecasts are evaluated relative to CFAN's landfall wind reconstructions. Landfall wind reconstructions are a new product, introduced during the 2020 season.

During 2019, CFAN implemented new calibrations for our forecasts of 2D landfalling wind fields. These calibrations provided options to incorporate CFAN's calibrated intensity forecast from ECMWF HRES and GFS, plus NHC's official intensity forecast.

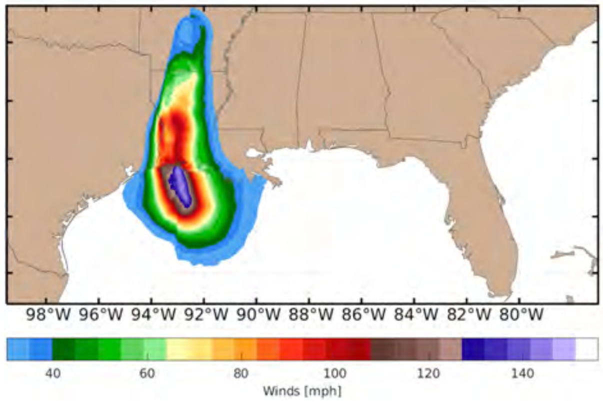
The basis for evaluation of each of these storms is CFAN's post-landfall wind reconstructions. These reconstructions are constructed using analyses from ECMWF and GFS, NHC best tracks data and surface wind observations. These data are integrated using CFAN's radial wind model.

For evaluation, three landfalling hurricanes were selected where the errors in the 24 hour intensity forecasts were relatively small – Laura, Delta, Zeta. Small errors in the intensity forecast allow for interpreting differences in the spatial distribution of wind speeds.

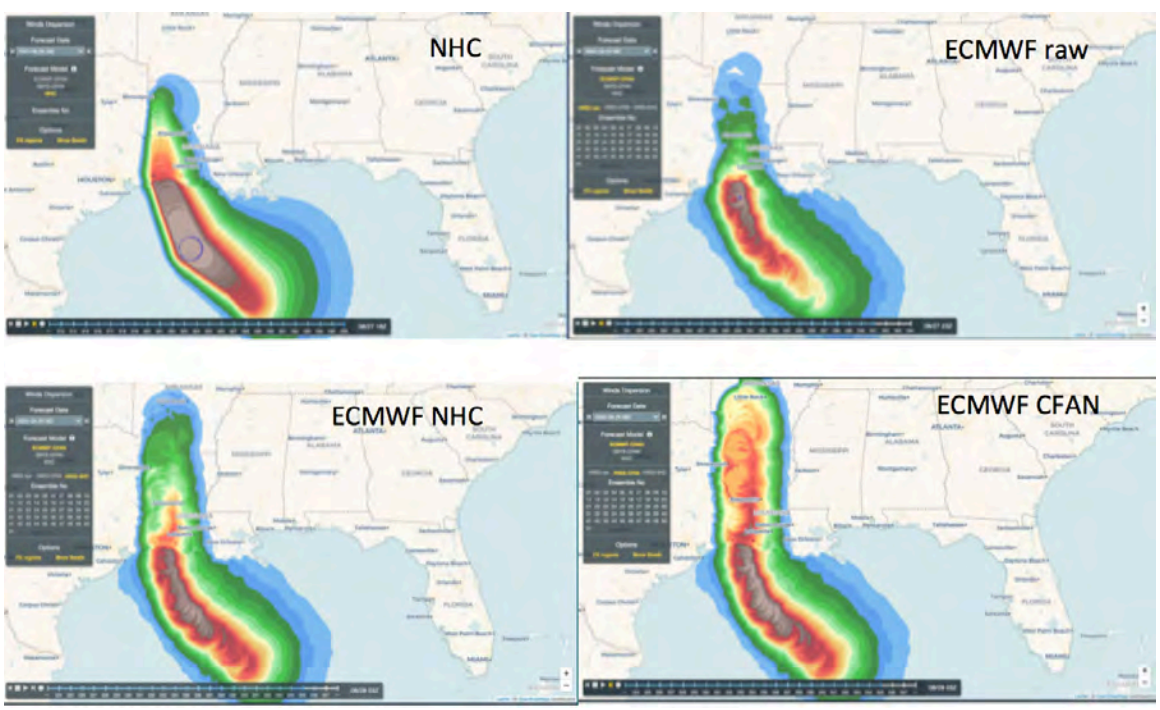
Although not shown here, CFAN's calibrated intensity forecasts have particular difficulties during landfall that that is preceded by a rapid intensification. During a rapid intensification, the forecast model may be tens of knots behind the actual evolution the storm intensity. CFAN adjusts for this time discrepancy by adjusting the initial wind speed, which carries through the entire intensity forecast. This resulted in CFAN calibrated landfall winds that were far too high for the Central American landfalls. This problem will be addressed in the off-season of winter 2021.

Hurricane Laura

Post landfall reconstruction

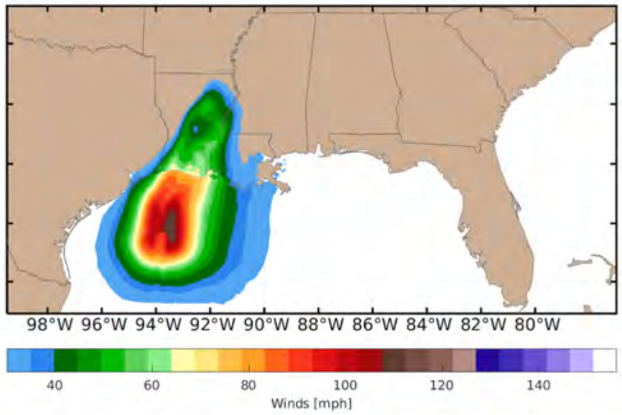


Shown below are 24-hour landfall wind forecasts for Laura. The ECMWF raw wind forecast (upper right) performed relatively well compared with other storms, with a relatively small underprediction of the wind speeds. The NHC forecast (upper left) diminished too quickly inland. The ECMWF calibrated wind speeds (bottom row) showed the NHC-based intensity calibration (lower left) slightly underpredicted the inland winds, while CFAN's intensity calibration (lower right) slightly overpredicted the inland winds.

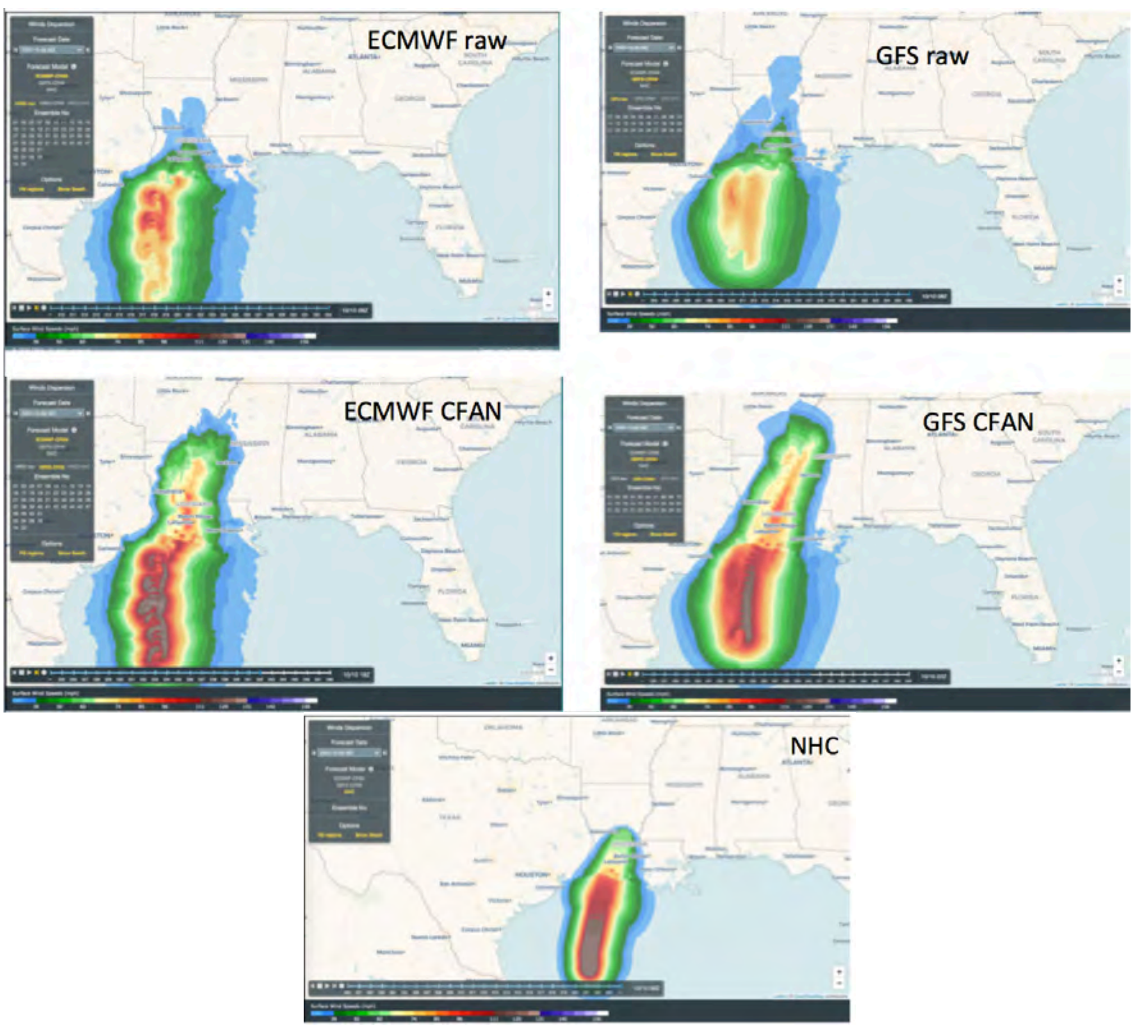


Hurricane Delta

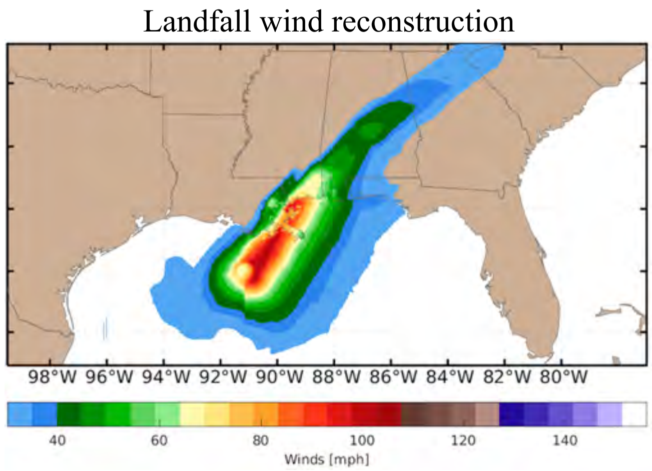
Post landfall reconstruction



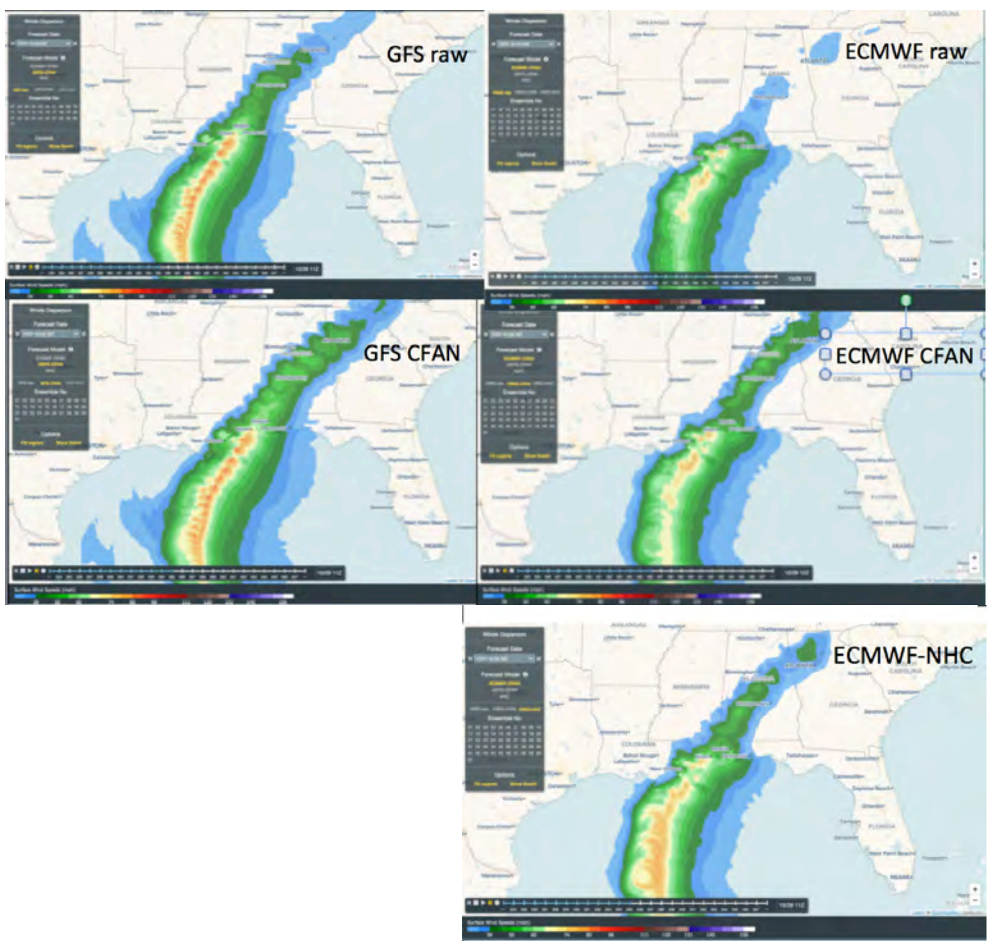
Shown below are 24-hour landfall wind forecasts for Delta. ECMWF and GFS raw wind forecast both were too low, although the GFS better captured the relative strength to the east of the eye prior to landfall and the general pattern of the landfall winds. CFAN's calibrated winds for both ECMWF and GFS (middle row) produced inland winds that were too high. Forecast of inland wind intensities were best from NHC donut model; when combined with GFS, this produced the best forecast.



Hurricane Zeta



Shown below are 24-hour landfall wind forecasts for Zeta. Zeta is an example of relatively strong inland penetration of the winds. The ECMWF raw wind forecast is substantially too low, while GFS is better (top row). CFAN calibrated winds are slightly too high inland (middle row). The best forecast is ECMWF HRES calibrated by NHC (bottom)



INTEGRATED KINETIC ENERGY (IKE)

Summary. CFAN has been making IKE forecasts since the 2019 season, but there has been nothing against which to evaluate our IKE forecasts. This season, HWIND tweeted 16 IKE values during the evolution of 8 different storms. A comparison of CFAN's NHC-based IKE calculation with HWIND shows fairly close agreement (within about 10%); CFAN's ECMWF HRES IKE calculation averaged about 20% too high. This suggests that NHC observations with CFAN's NHC-based IKE calculations could provide the basis for real-time verification of CFAN's IKE forecasts.

IKE is a measure of tropical cyclone strength that accounts for both wind speed and horizontal extent of the storm. IKE is calculated as a summation of the energy (square of wind speed) as integrated over the horizontal extent of the storm (defined as the area with winds ≥ 34 knots.

CFAN's NHC-based calculation of IKE uses NHC observations or intensity and wind radii in conjunction with CFAN's donut model and the same calculation process used in the NHC-based representation of 2D wind fields on the landfall impact page. CFAN's ECMWF- and GFS-based IKE calculation uses the same method for determining winds that is used in the 2D wind forecasts.

NHC previously provided calculations of IKE (based upon the wind speeds observed from radar/scatterometer for hurricane reconnaissance aircraft), but the principals of that effort spun off a private sector company (HWINDS) that was subsequently acquired by RMS. During 2020, HWIND tweeted some of their values of IKE, which provide a basis for evaluating CFAN's calculations at the initial forecast time.

The Table below compares the HWIND values at the designated times with CFAN's NHC based calculation and the ECMWF HRES calculation. It is noted here that there may be some temporal discrepancy in these values (up to 6 hrs) owing to uncertainty in the interpretation of HWINDS time (valid time, or available time).

On average, it is seen that the CFAN-NHC values are within about 10% of the HWIND values, although larger discrepancies are seen in several instances (with NHC-CFAN slightly lower than HWIND). While the IKE forecasts from ECMWF HRES were not available for all of the forecast times, they show general agreement with HWIND and CFAN-NHC, with a ~20% high bias relative to HWINDS.

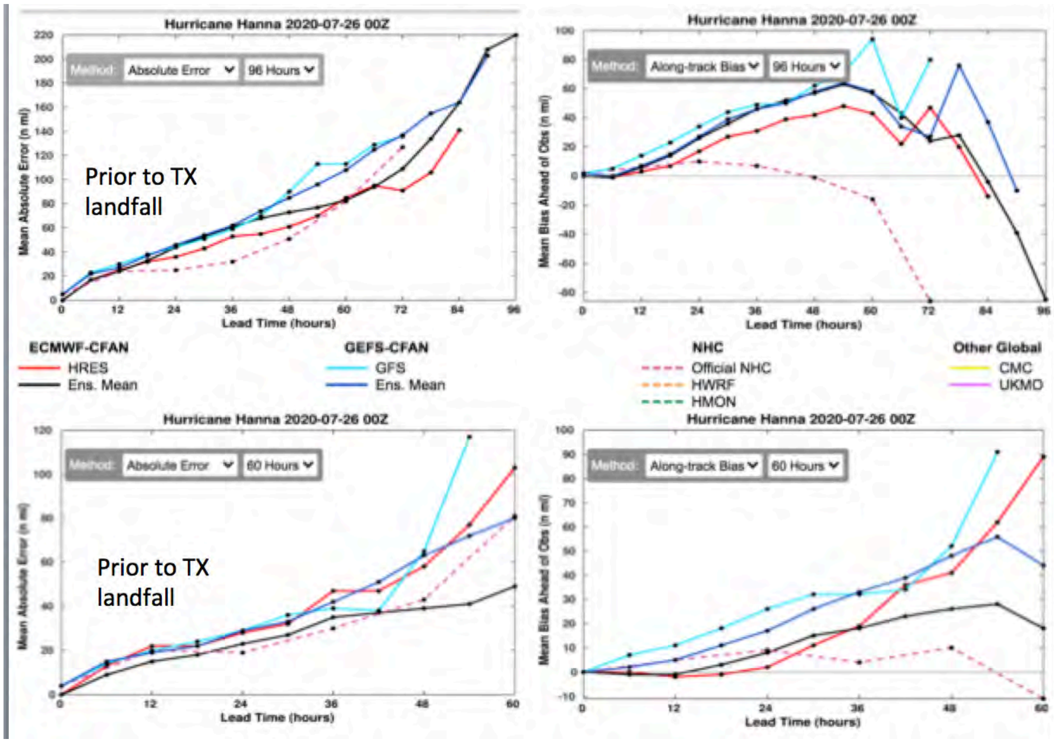
The good agreement of CFAN-NHC with HWINDS suggests that CFAN-NHC calculations based upon observed parameters from NHC could be used as a verification data set for CFAN's IKE forecasts.

Storm/Date	HWIND	CFAN-NHC	CFAN-EC HRES
Hurricane Eta			
11/11 12Z	13	8	
11/03 12Z	20	19	20
Hurricane Zeta			
10/28 18Z	22	15	32
Hurricane Delta			
10/09 18Z	37	32	43
10/08 18Z	35	30	48
Hurricane Teddy			
9/18 18Z	63	60	
Hurricane Paulette			
9/14 18Z	51	30	
9/13 18Z	39	25	
Hurricane Sally			
9/14 18Z	21	14	17
9/13 18Z	7	7	
Hurricane Laura			
8/26 18Z	38	48	50
8/24 12Z	7	15	
Isaias			
8/02 18Z	10	8	15
8/01 18Z	7	7	9
7/31 18Z	10	19	15
7/30 18Z	21	17	
AVERAGE	25	22	

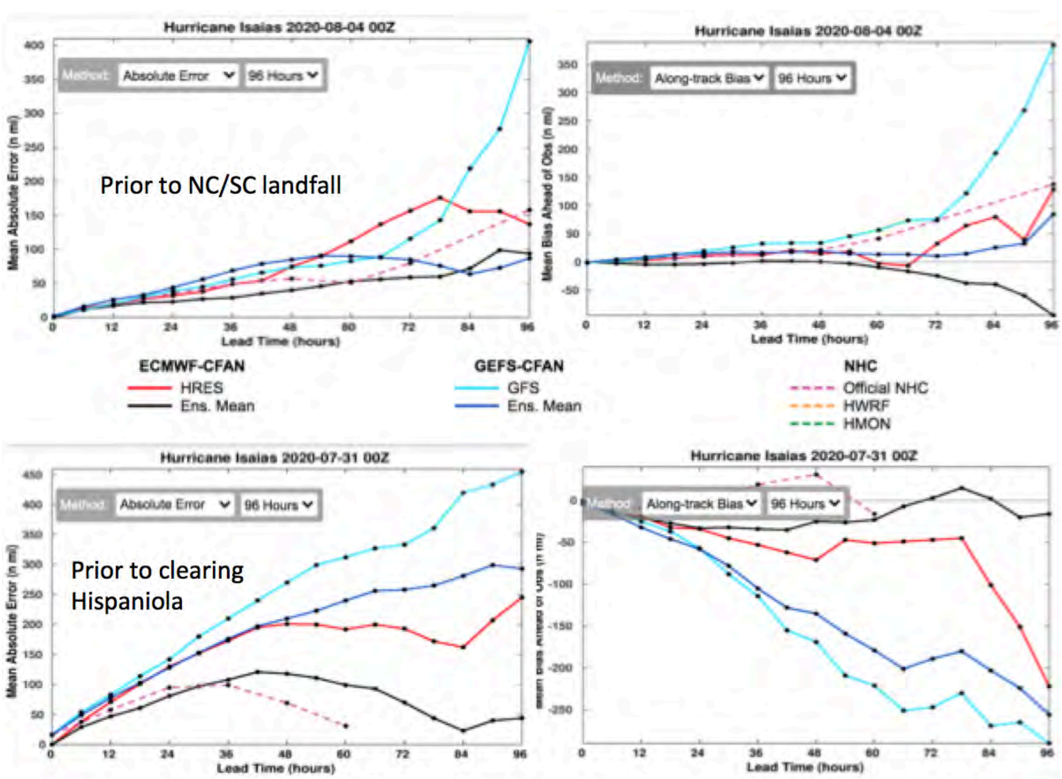
APPENDICES

Appendix A - real-time track verification plots

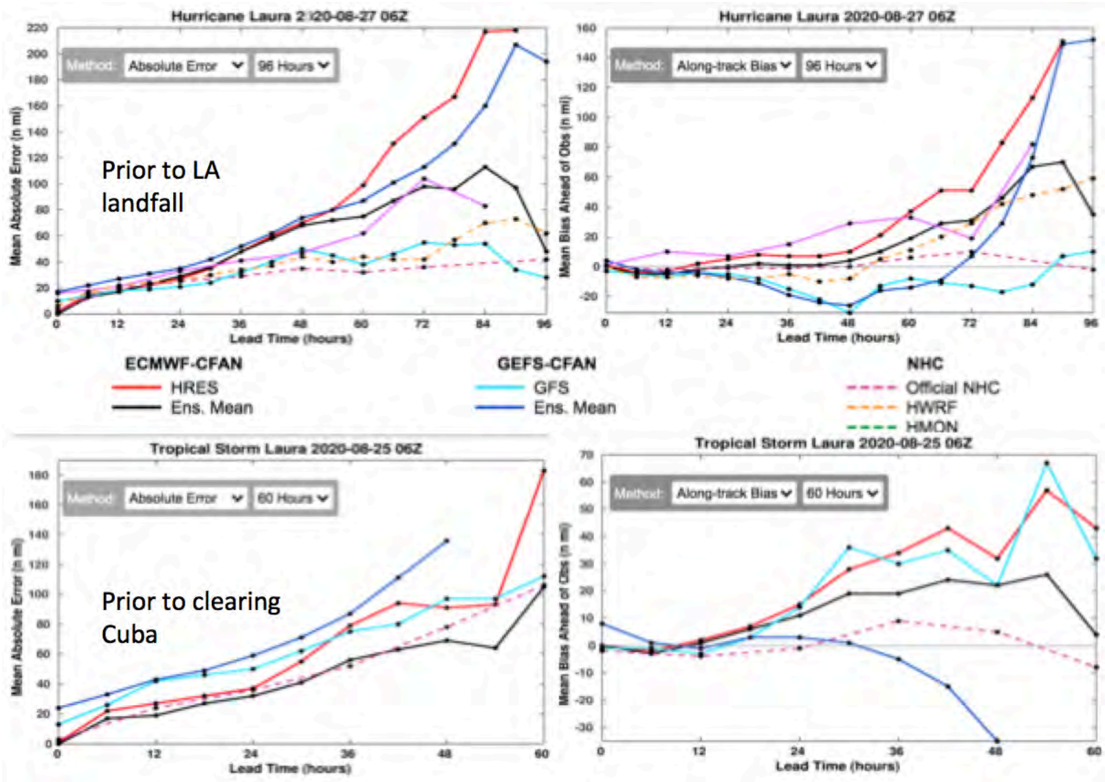
Hurricane Hanna



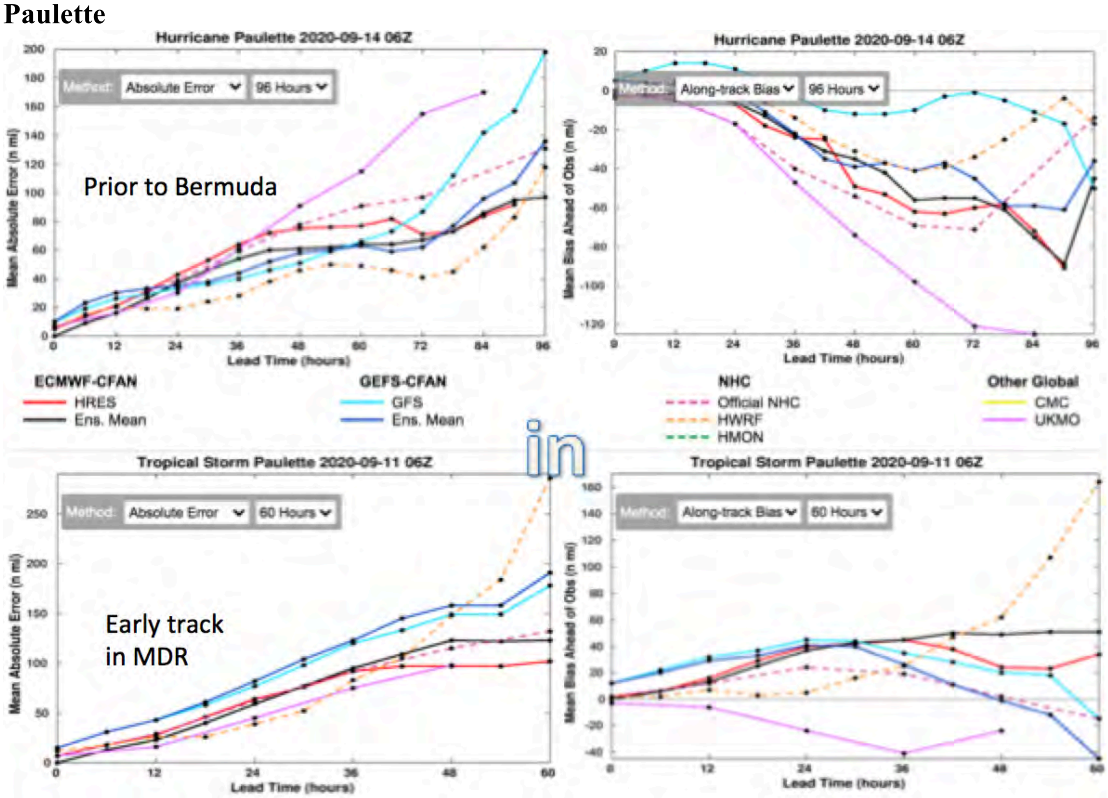
Hurricane Isaias



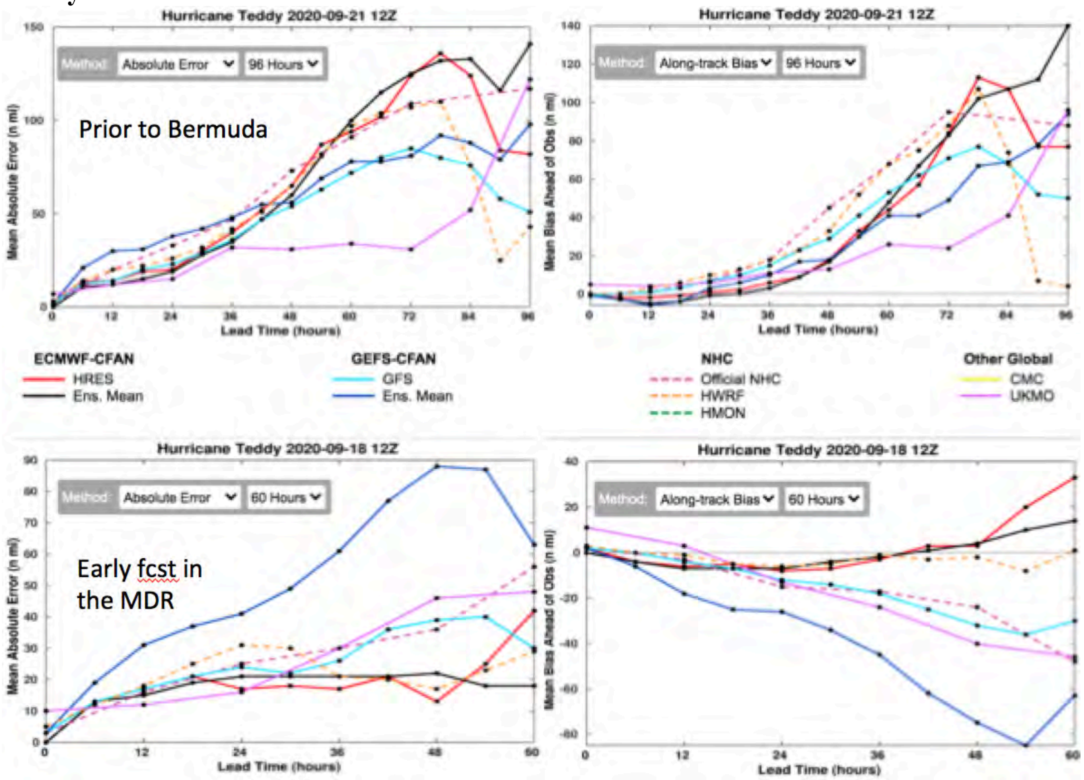
Laura



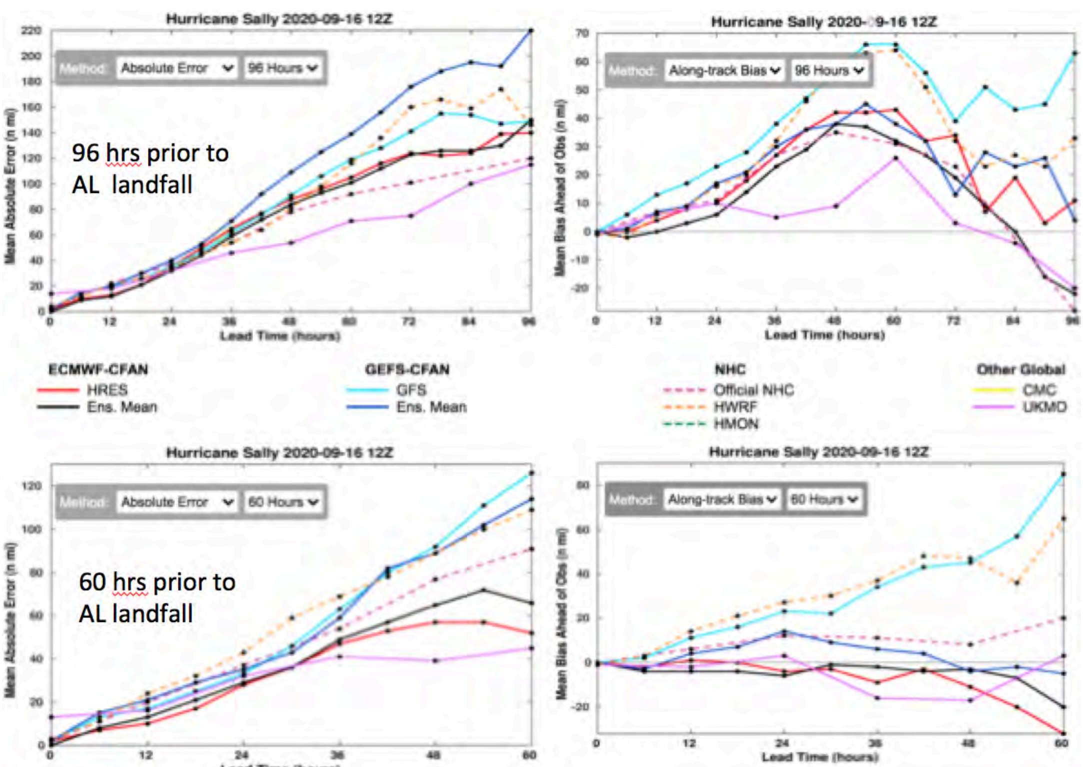
Paulette



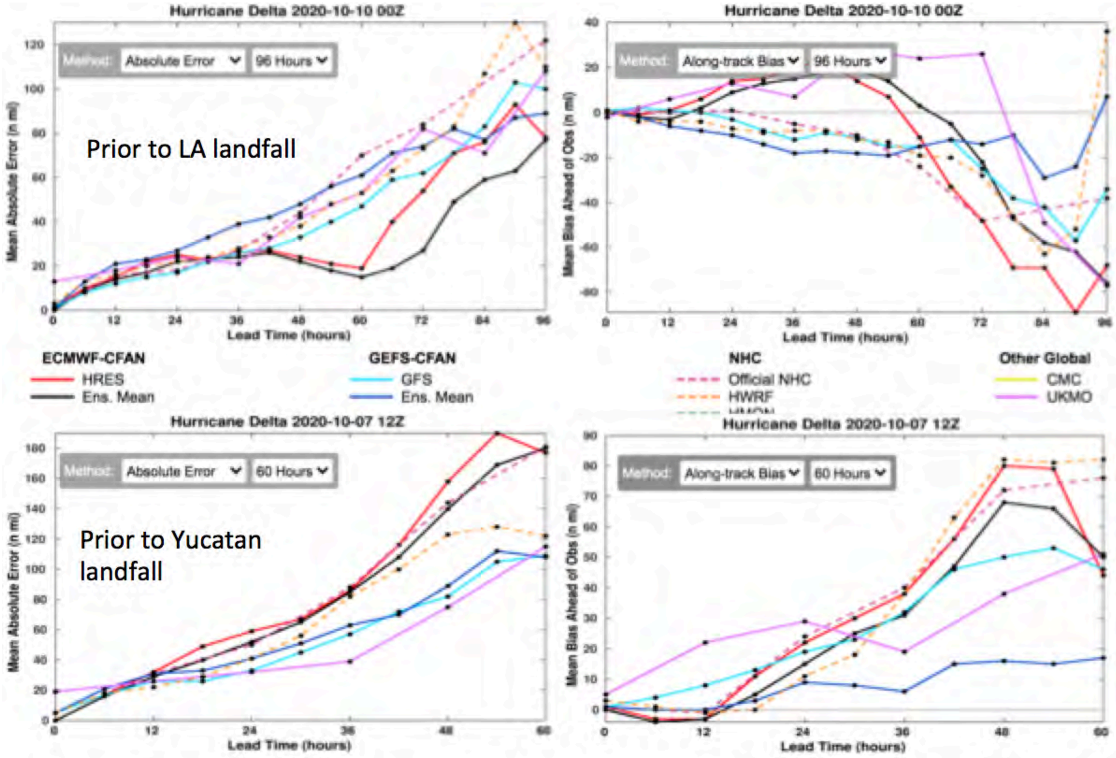
Teddy


Hurricane Teddy 2020-09-21 12Z
Method: Absolute Error
96 Hours
Prior to Bermuda
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Teddy 2020-09-21 12Z
Method: Along-track Bias
96 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)
ECMWF-CFAN
HRES
Ens. Mean
GEFS-CFAN
GFS
Ens. Mean
NHC
Official NHC
HWRF
HMON
Other Global
CMC
UKMO
Hurricane Teddy 2020-09-18 12Z
Method: Absolute Error
60 Hours
Early fcst in the MDR
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Teddy 2020-09-18 12Z
Method: Along-track Bias
60 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)

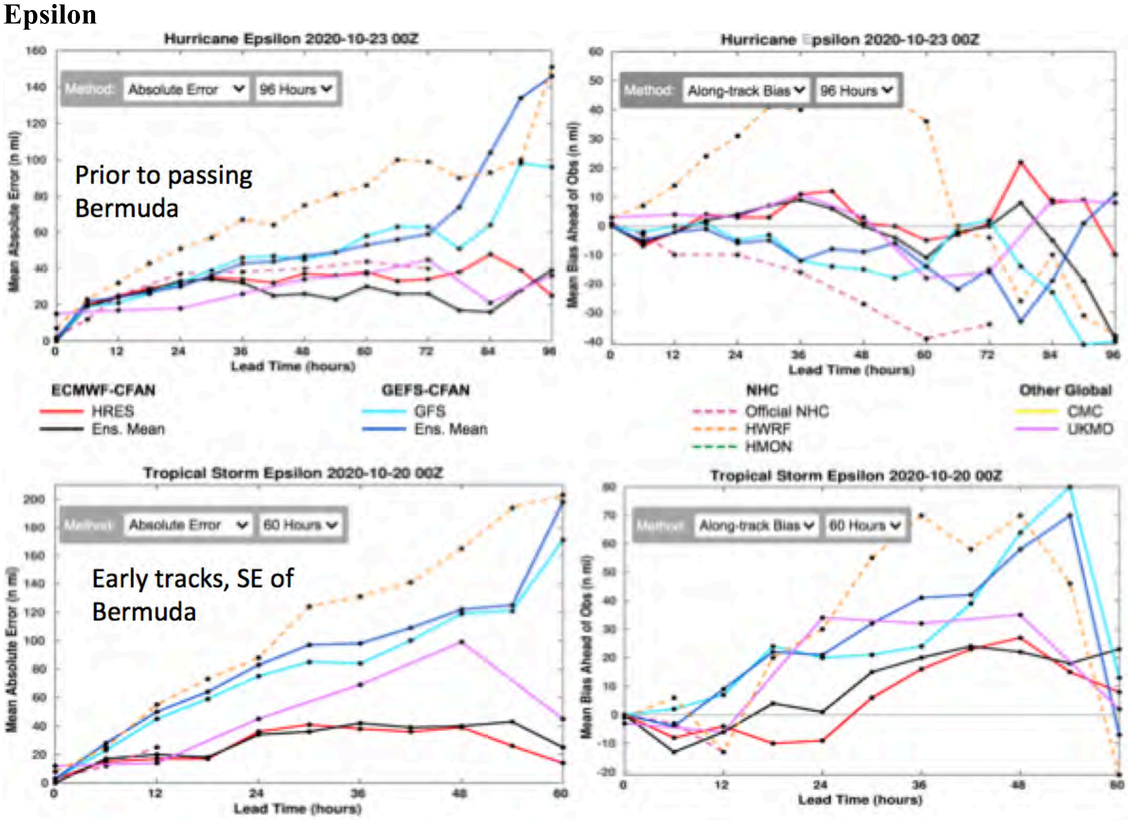
Sally


Hurricane Sally 2020-09-16 12Z
Method: Absolute Error
96 Hours
96 hrs prior to AL landfall
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Sally 2020-09-16 12Z
Method: Along-track Bias
96 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)
ECMWF-CFAN
HRES
Ens. Mean
GEFS-CFAN
GFS
Ens. Mean
NHC
Official NHC
HWRF
HMON
Other Global
CMC
UKMO
Hurricane Sally 2020-09-16 12Z
Method: Absolute Error
60 Hours
60 hrs prior to AL landfall
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Sally 2020-09-16 12Z
Method: Along-track Bias
60 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)

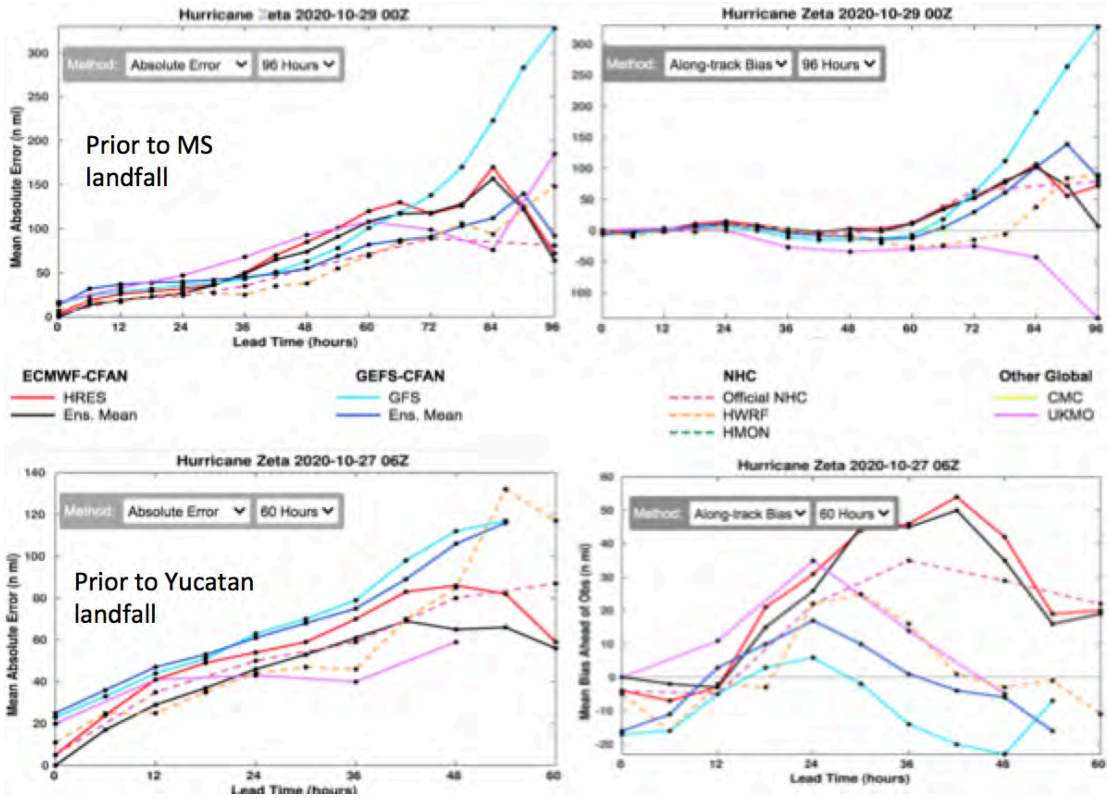
Delta



Epsilon

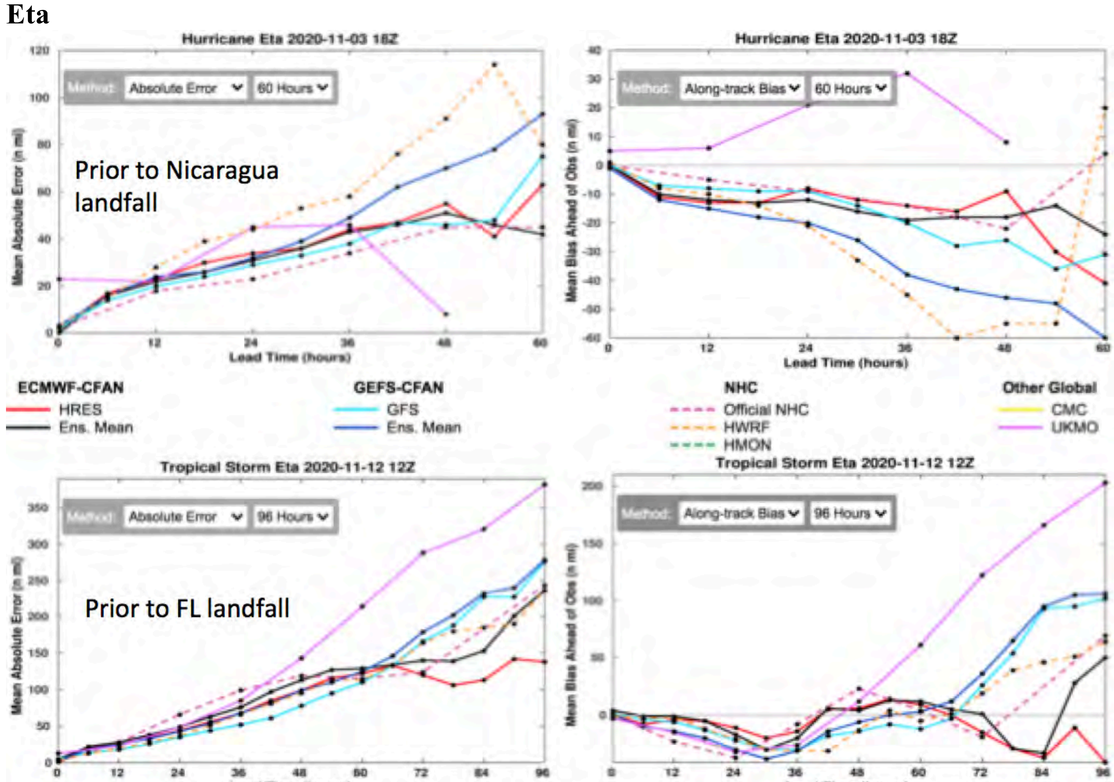


Zeta



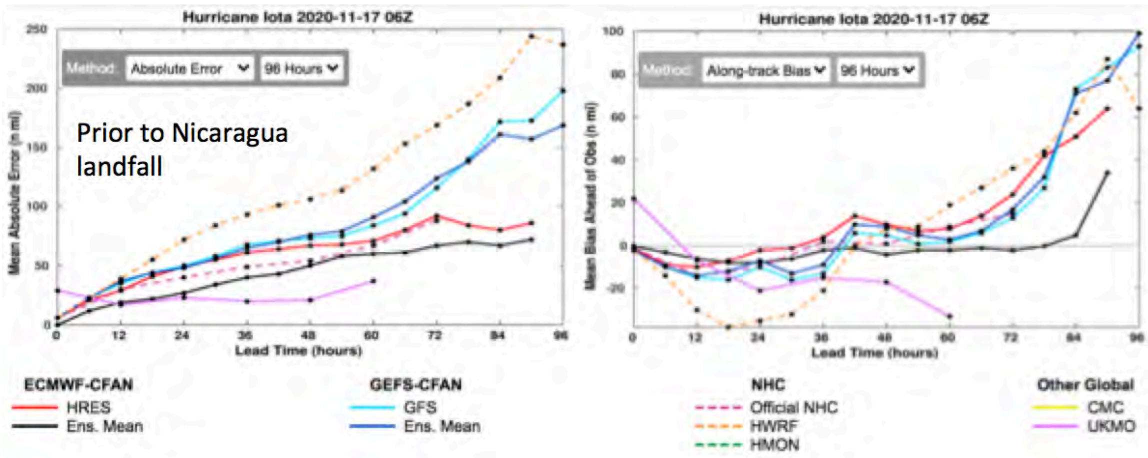
Hurricane Zeta 2020-10-29 00Z
Method: Absolute Error
96 Hours
Prior to MS landfall
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Zeta 2020-10-29 00Z
Method: Along-track Bias
96 Hours
ECMWF-CFAN
HRES
Ens. Mean
GEFS-CFAN
GFS
Ens. Mean
NHC
Official NHC
HWRF
HMON
Other Global
CMC
UKMO
Hurricane Zeta 2020-10-27 06Z
Method: Absolute Error
60 Hours
Prior to Yucatan landfall
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Zeta 2020-10-27 06Z
Method: Along-track Bias
60 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)

Eta



Hurricane Eta 2020-11-03 18Z
Method: Absolute Error
60 Hours
Prior to Nicaragua landfall
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Eta 2020-11-03 18Z
Method: Along-track Bias
60 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)
ECMWF-CFAN
HRES
Ens. Mean
GEFS-CFAN
GFS
Ens. Mean
NHC
Official NHC
HWRF
HMON
Other Global
CMC
UKMO
Tropical Storm Eta 2020-11-12 12Z
Method: Absolute Error
96 Hours
Prior to FL landfall
Mean Absolute Error (n mi)
Lead Time (hours)
Tropical Storm Eta 2020-11-12 12Z
Method: Along-track Bias
96 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)

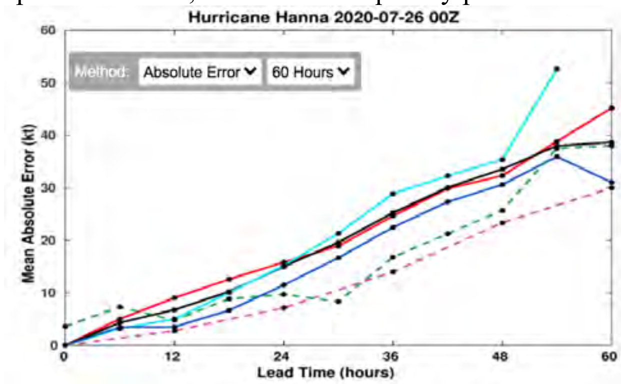
Iota


Hurricane Iota 2020-11-17 06Z
Method: Absolute Error
96 Hours
Prior to Nicaragua landfall
Mean Absolute Error (n mi)
Lead Time (hours)
Hurricane Iota 2020-11-17 06Z
Method: Along-track Bias
96 Hours
Mean Bias Ahead of Obs (n mi)
Lead Time (hours)
ECMWF-CFAN
HRES
Ens. Mean
GEFS-CFAN
GFS
Ens. Mean
NHC
Official NHC
HWRF
HMON
Other Global
CMC
UKMO

Appendix B - real time verification of intensity forecasts

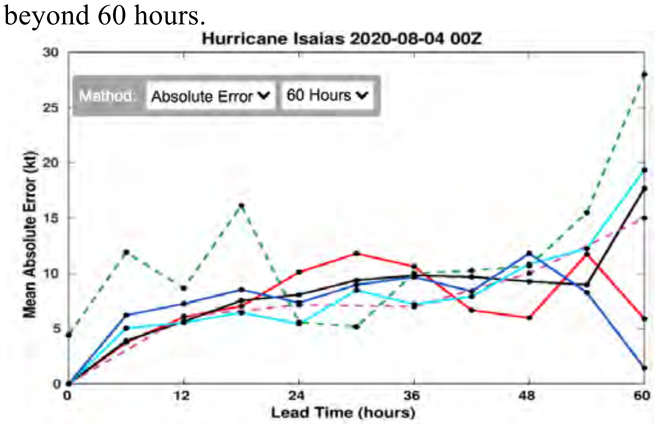
Hanna

60 hours prior to TX landfall, at 78 kts. All models had a low bias; NHC performed best. HMON was the first to predict a Cat 1, but also subsequently predicted a Cat 2.



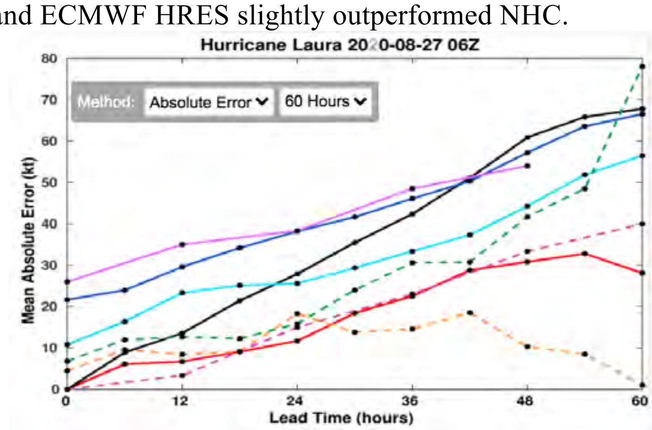
Isaias

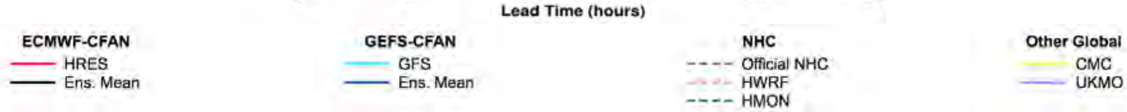
60 hours prior to NC/SC landfall, at 70 kts. Intensity errors were low overall, with ECMWF outperforming NHC beyond 60 hours.



Laura

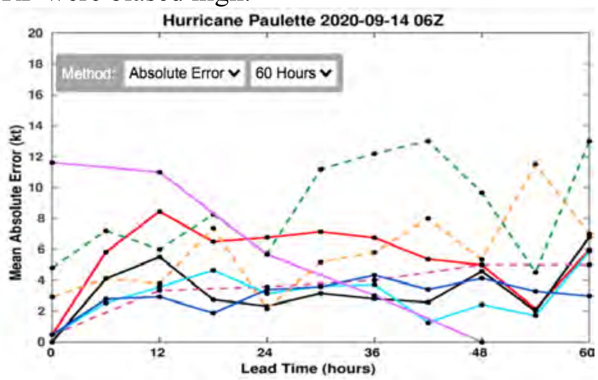
60 hours prior to LA landfall, at 130 knots. All intensity forecasts were biased low. HWRF performed the best, and ECMWF HRES slightly outperformed NHC.





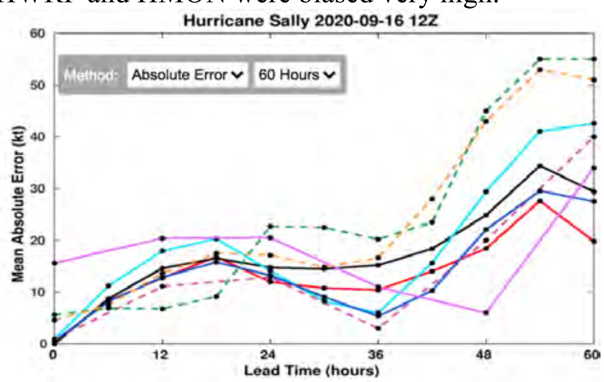
Paulette

60 hours prior to Bermuda landfall, at 78 knots near landfall. Intensity forecast errors were very low, with the GFS, GEFS and ECMWF Ens Mean slightly outperforming the NHC beyond 24 hours. HMON and HWRF were biased high.



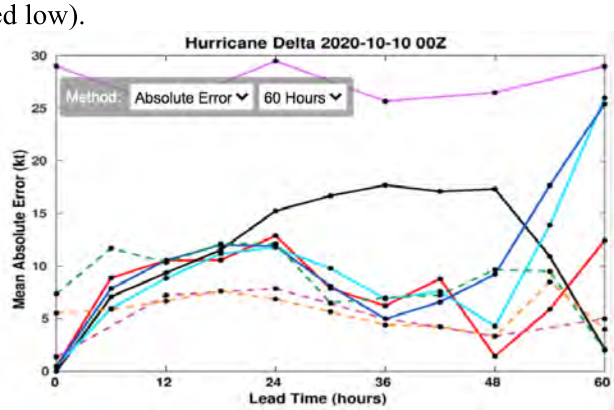
Sally

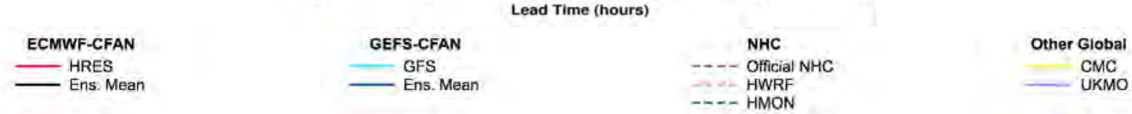
60 hours prior to landfall in AL at 90 knots. HC, GEFS and ECMWF HRES performed comparably beyond 36 hours, although examination of the prior 96 hour forecasts showed NHC to be the clear winner. HWRF and HMON were biased very high.



Delta

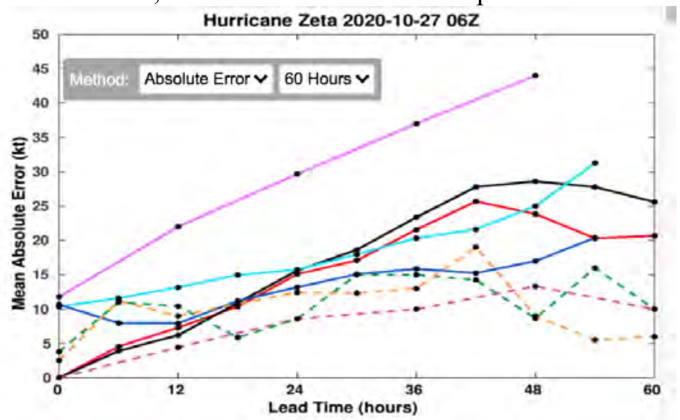
60 hours prior to LA landfall at 87 knots. Intensity forecast errors were overall small for Delta prior to the LA landfall. However, intensity forecast errors were extremely large prior to the Yucatan landfall (biased low).



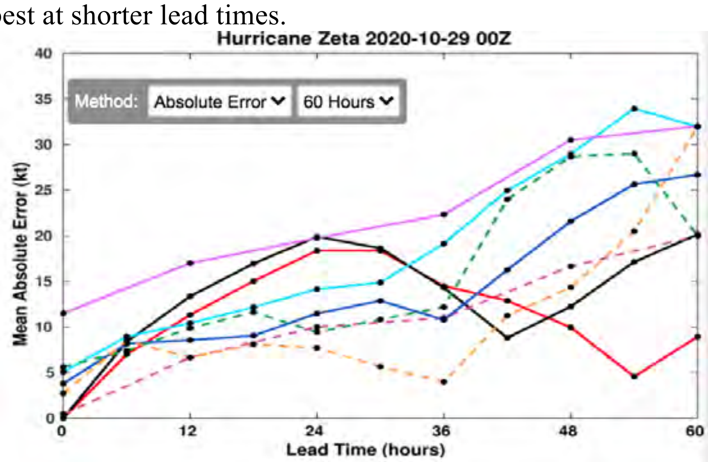


Zeta

60 hours prior to Yucatan landfall, at 70 knots. NHC overall performed the best.

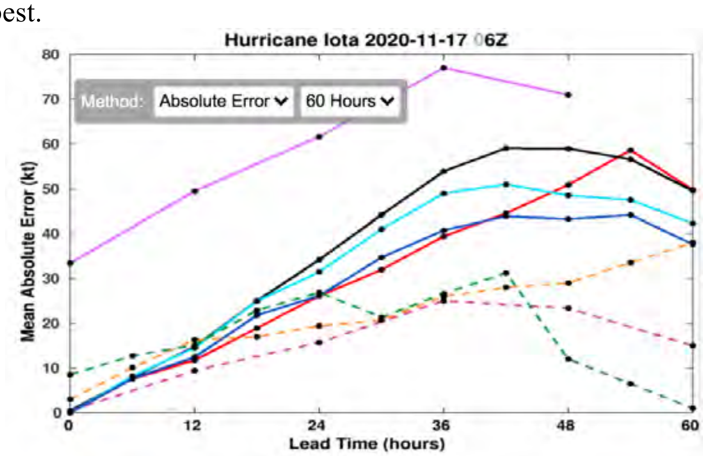


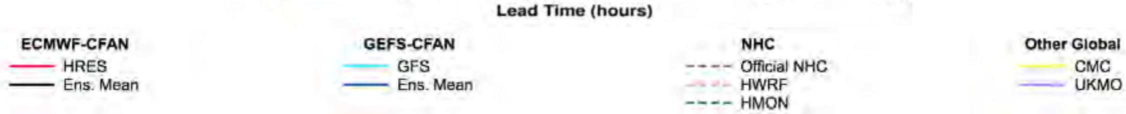
60 hours prior to MS landfall at 96 knots. ECMWF HRES performed best beyond 36 hours, with NHC performing best at shorter lead times.



Iota

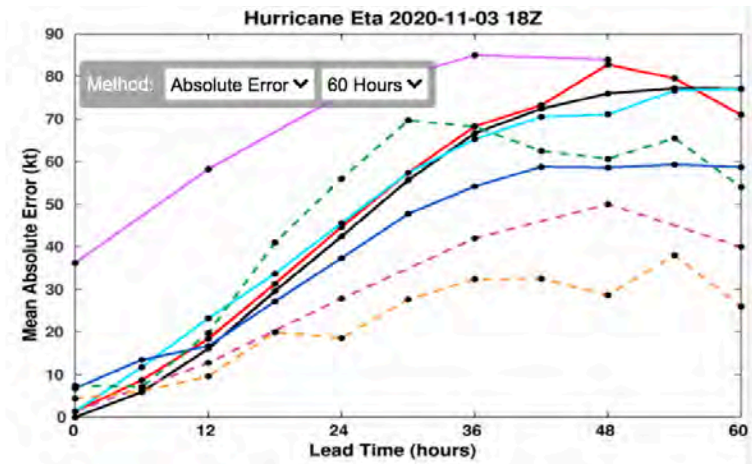
60 hours prior to Nicaragua landfall at 130 knots. Forecast errors were large (biased low), with NHC performing best.



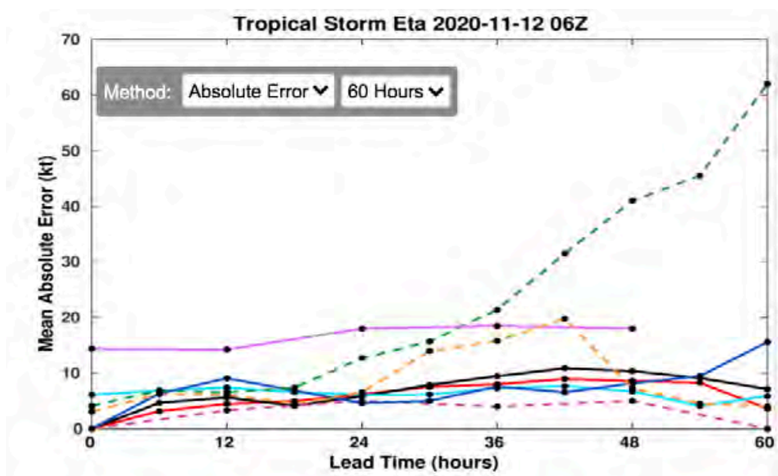


Eta

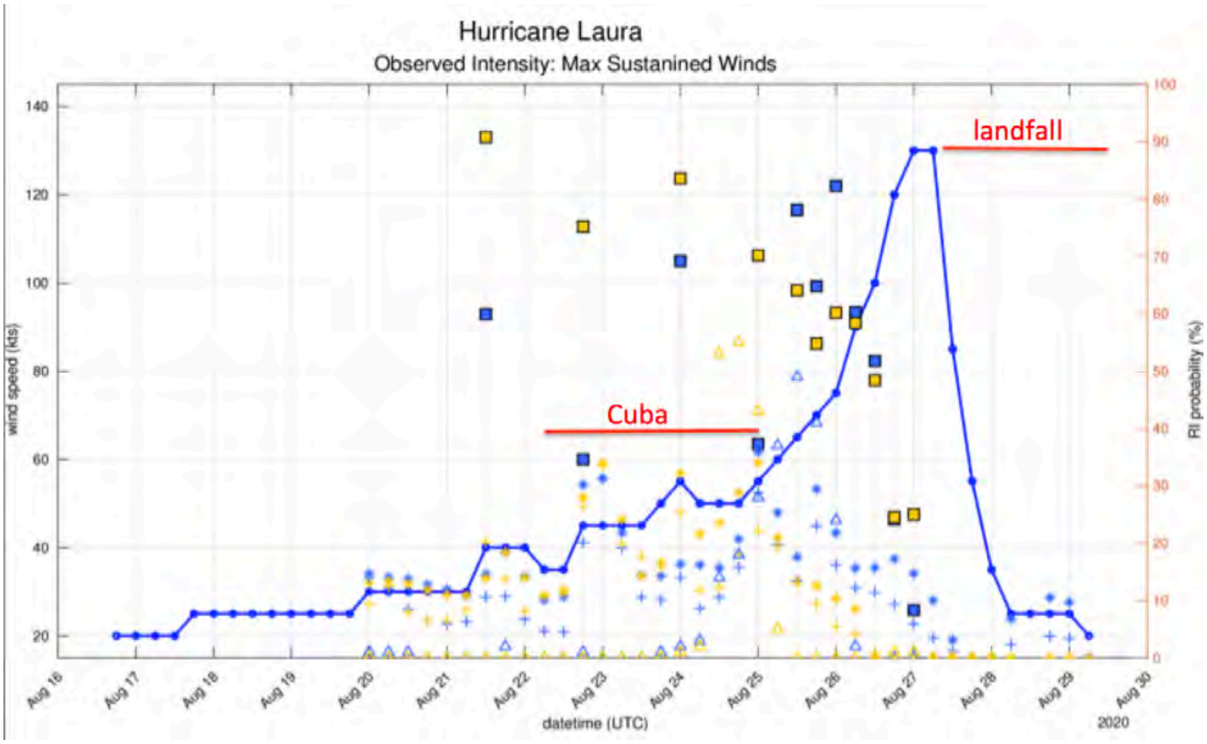
60 hours prior to Nicaragua landfall at 130 knots. Intensity forecast errors were very high (biased low), with HWRF performing best

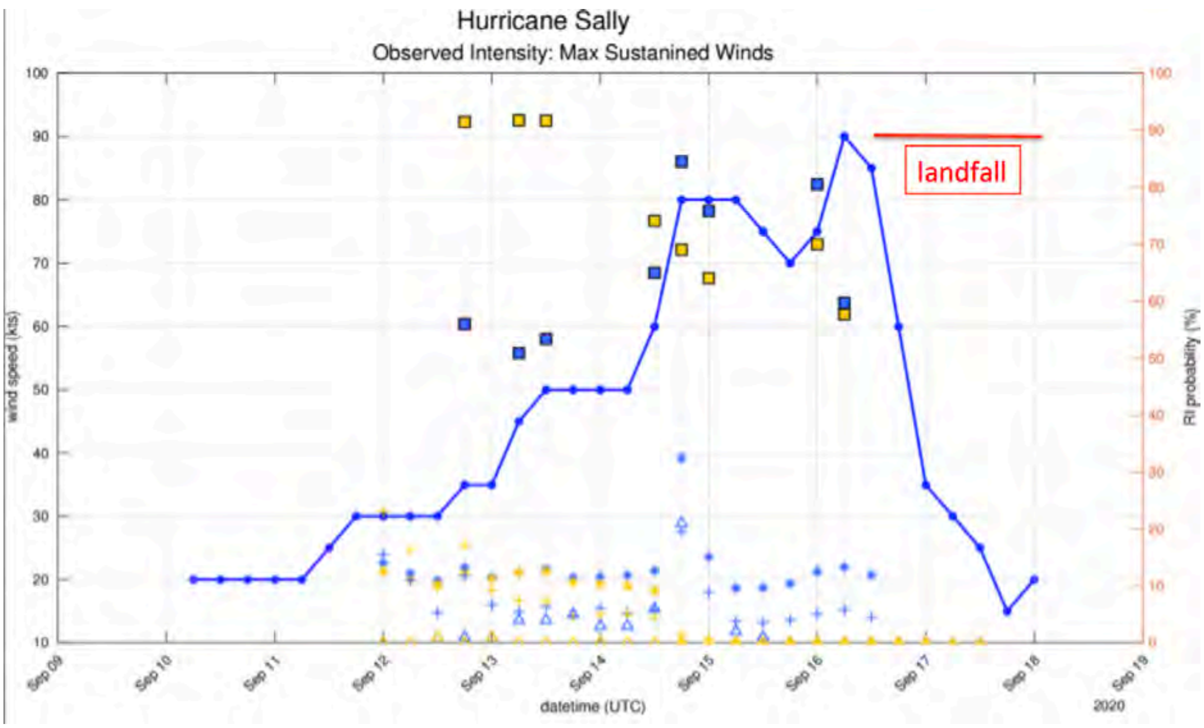


60 hours prior to the 2nd FL landfall as a TS. Overall intensity forecast errors were very low, except for HWRF and especially HMON that were biased high.

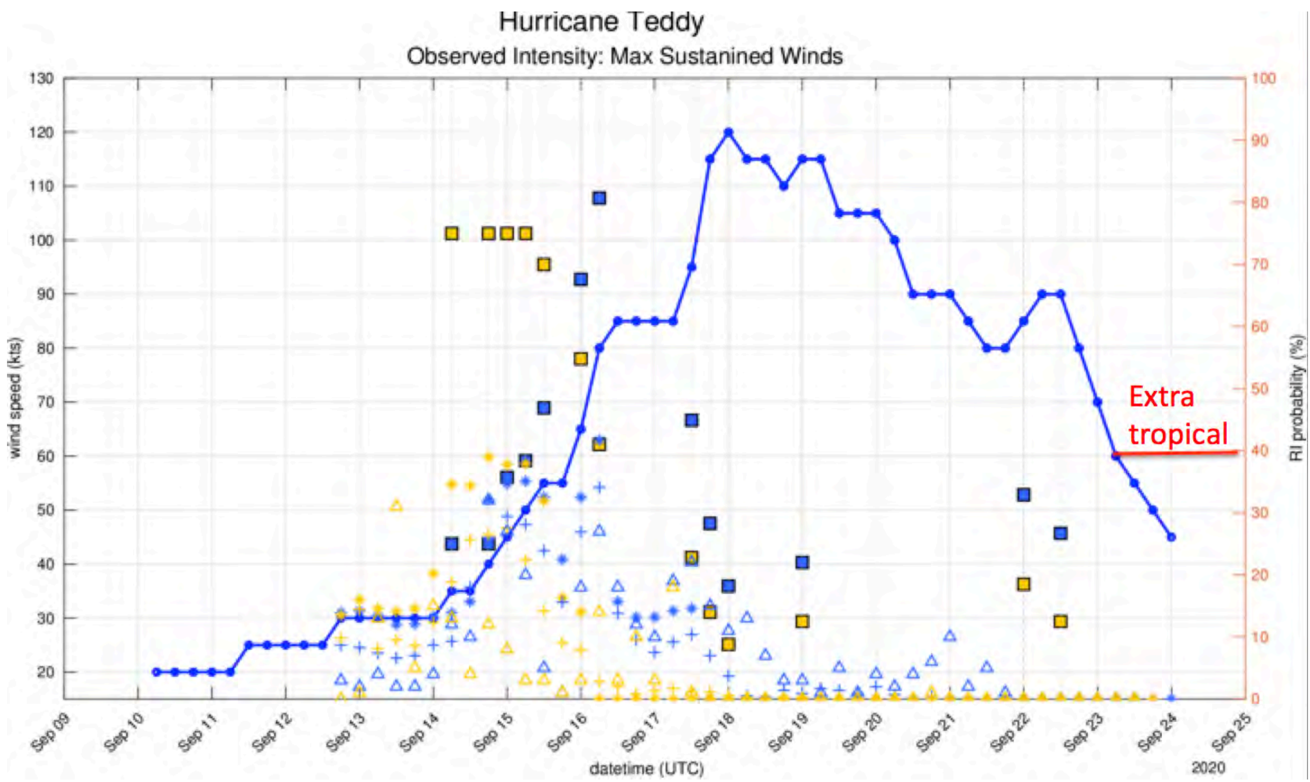


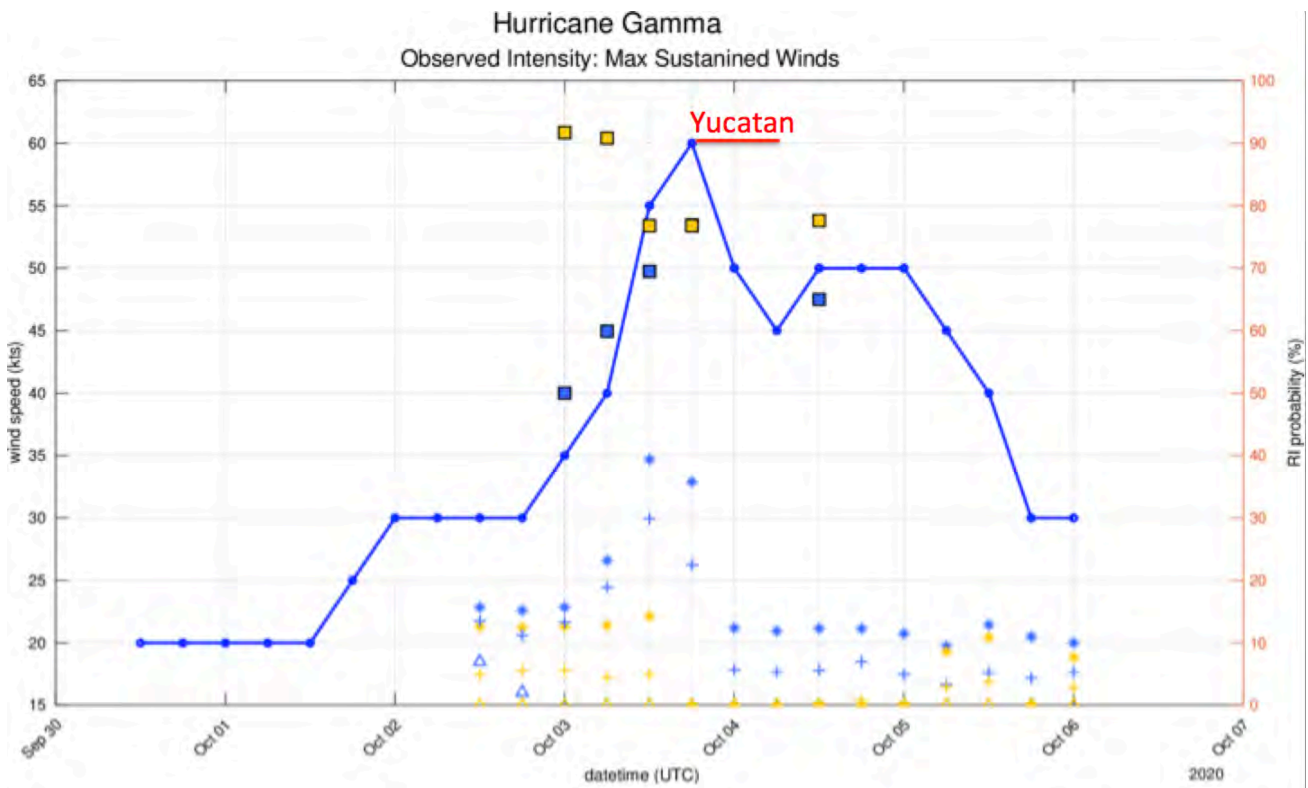
Appendix C - Rapid Intensification



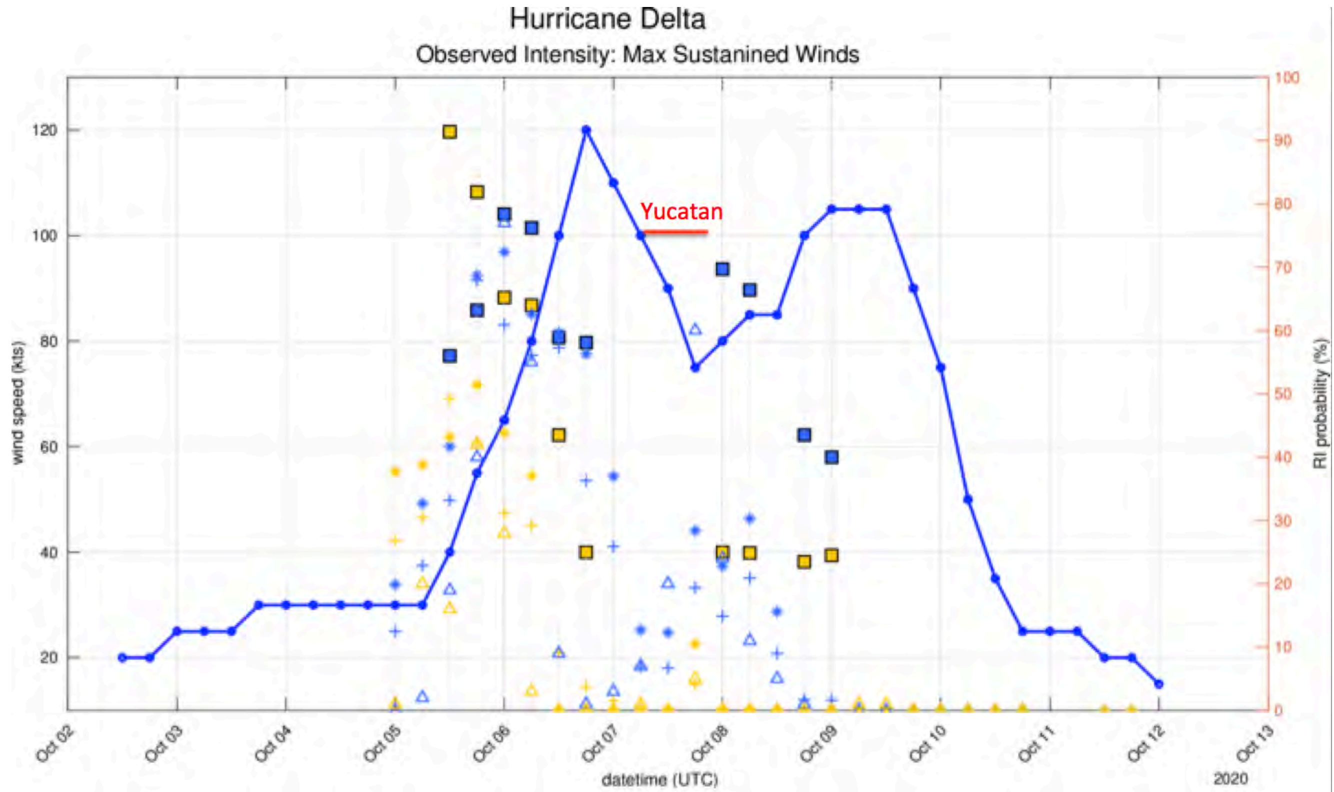


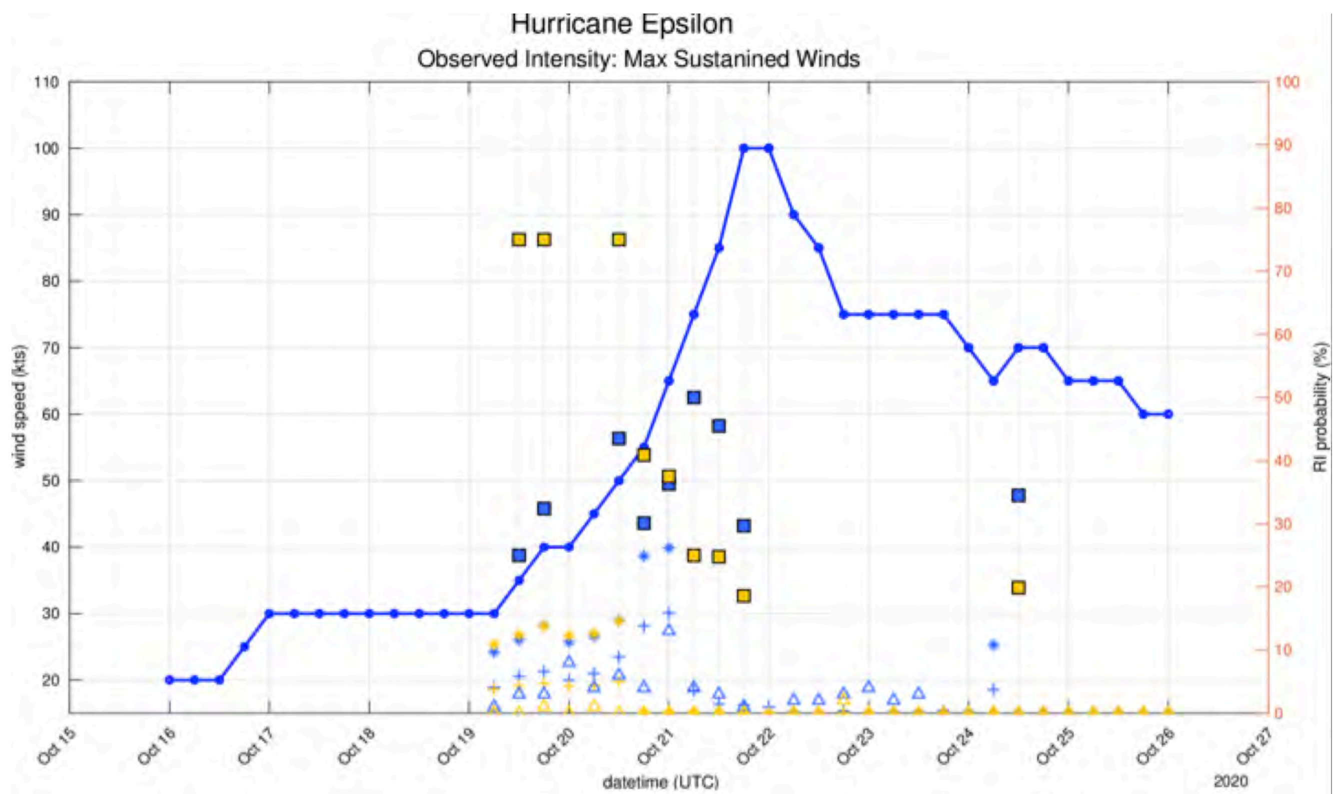
■ CFAN ✱ SHIPS RII ✚ Consensus ▲ DTOPS 24 hr 30 kts 48 hr 55 kts



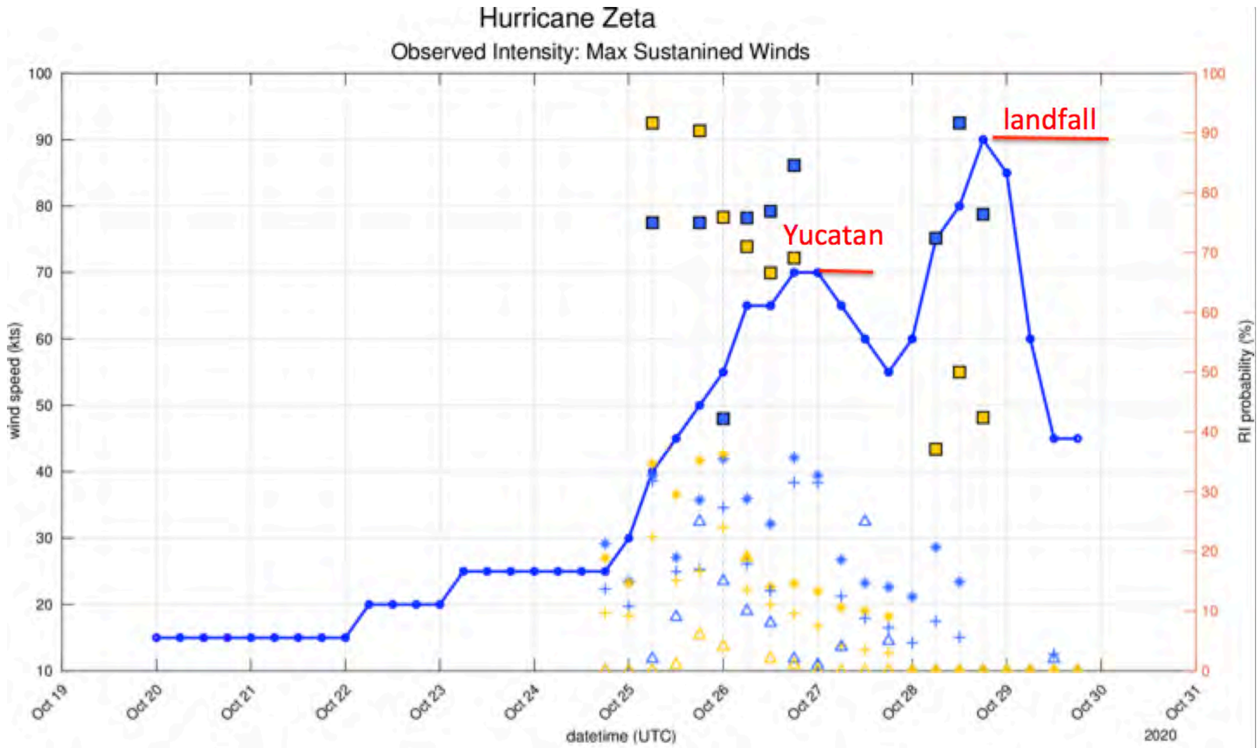


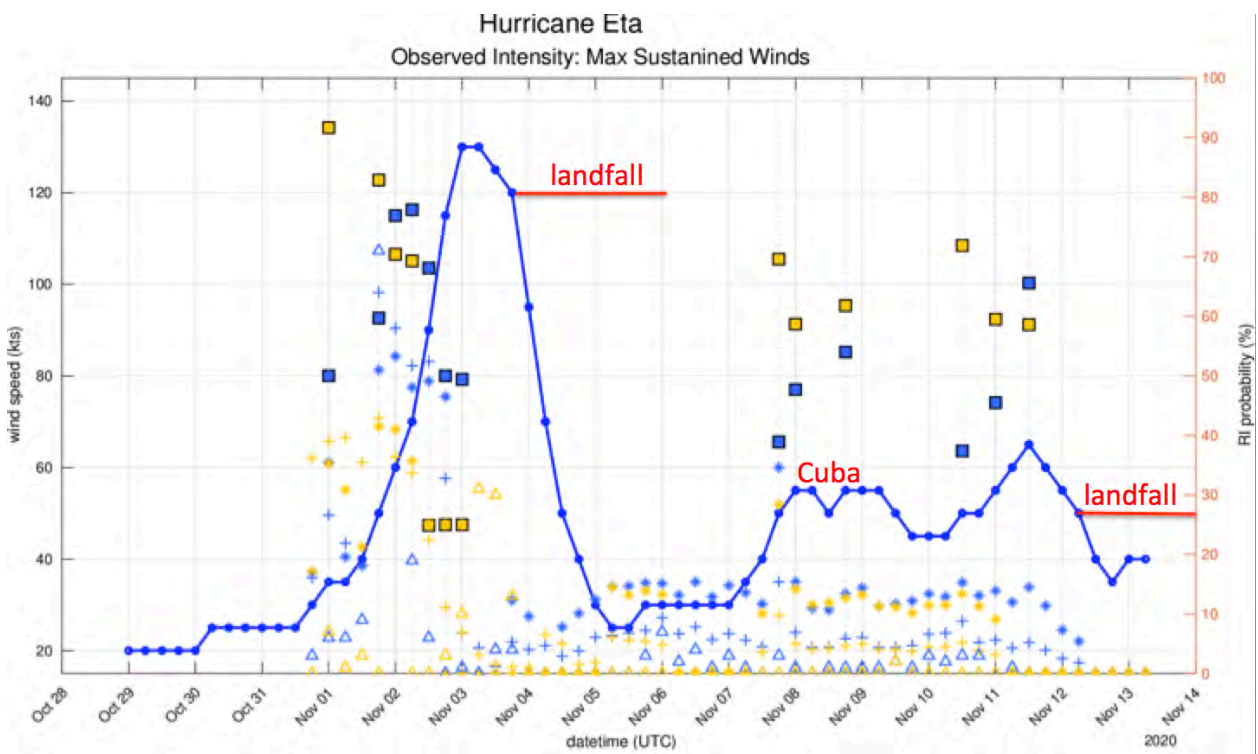
■ CFAN ✱ SHIPS RII ✚ Consensus ▲ DTOPS 24 hr 30 kts 48 hr 55 kts



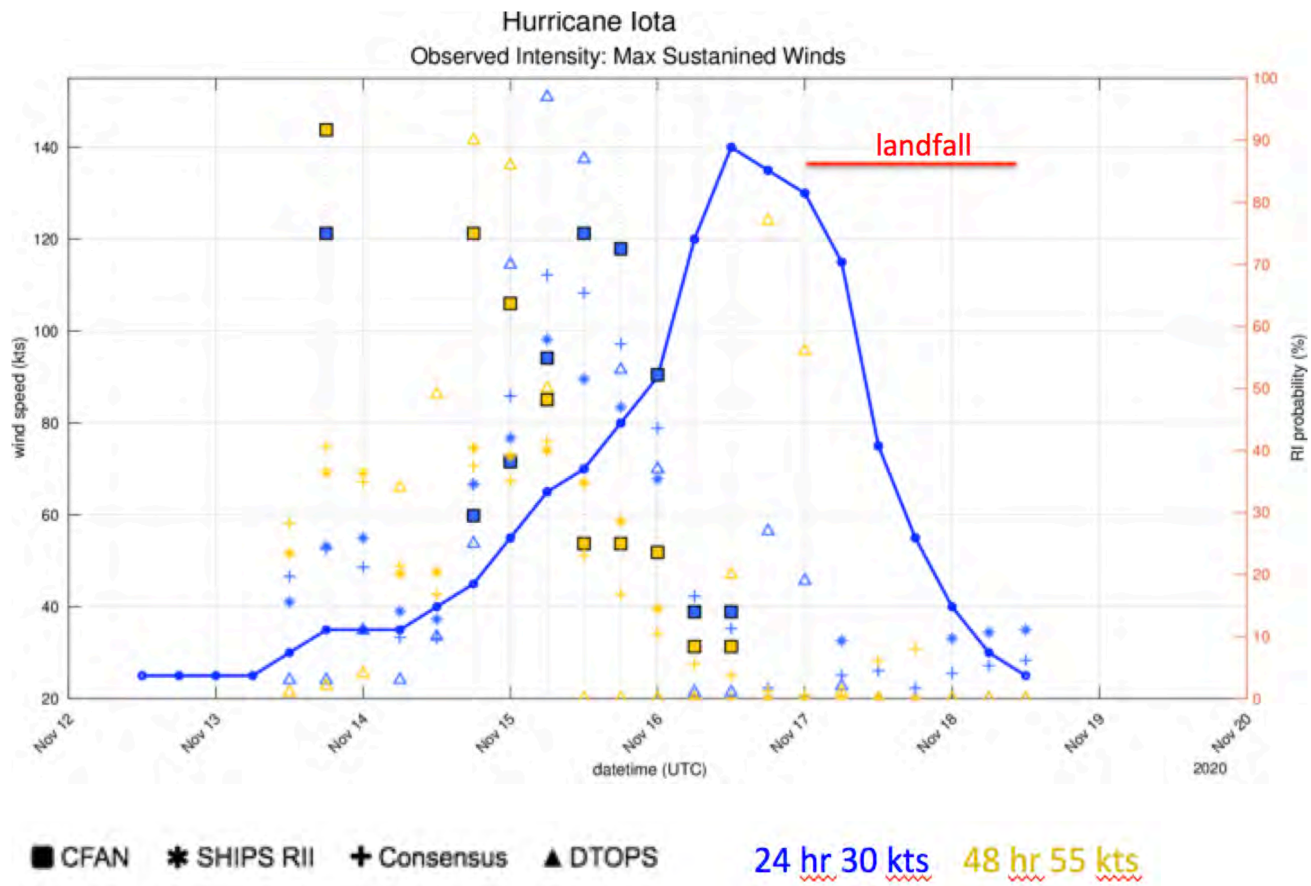


■ CFAN ✱ SHIPS RII ✚ Consensus ▲ DTOPS 24 hr 30 kts 48 hr 55 kts





■ CFAN ✱ SHIPS RII ✚ Consensus ▲ DTOPS 24 hr 30 kts 48 hr 55 kts



Hurricane Iota
Observed Intensity: Max Sustanined Winds
landfall
wind speed (kts)
RI probability (%)
datetime (UTC)
Nov 12
Nov 13
Nov 14
Nov 15
Nov 16
Nov 17
Nov 18
Nov 19
Nov 20
2020
CFAN
SHIPS RII
Consensus
DTOPS
24 hr 30 kts
48 hr 55 kts