HAFS Ensemble in Real Time on AWS Cloud

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NATIONAL WEATHER SERVICE

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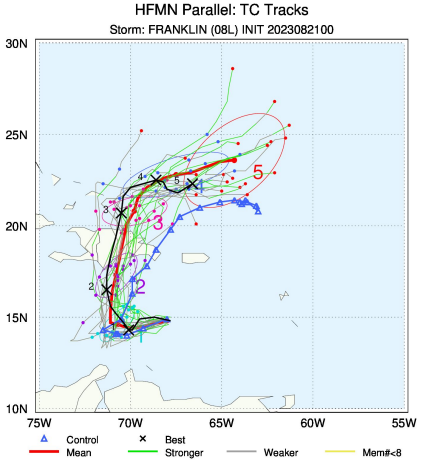
Outline

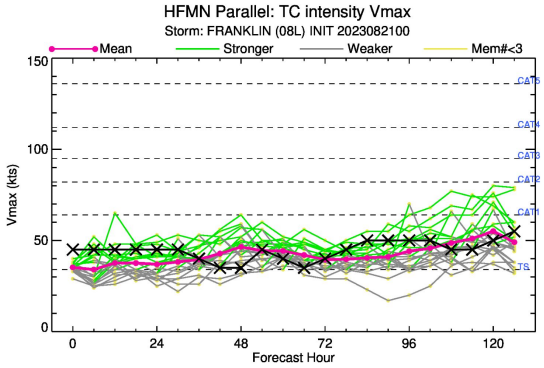
- Hurricane Ensemble in Real-time on the Cloud (HERC)
  - Project goals
  - Configuration
- HERC in 2023 Hurricane Season
  - Products
  - Performance
  - Statistical Characteristics
- Future plan
- Porting HERC on AWS Cloud

Hurricane Ensemble in Real-time on the Cloud (HERC)

Project Goals

- Port HAFS on AWS cloud
- Improve deterministic and probabilistic model forecast products
- Deliver TC ensemble predictions to NHC forecasters in real-time
- Proof of concept for operational hurricane ensemble system on the cloud





HERC Configuration for 2023 Real-time

Basic configuration, based on HAFSv1

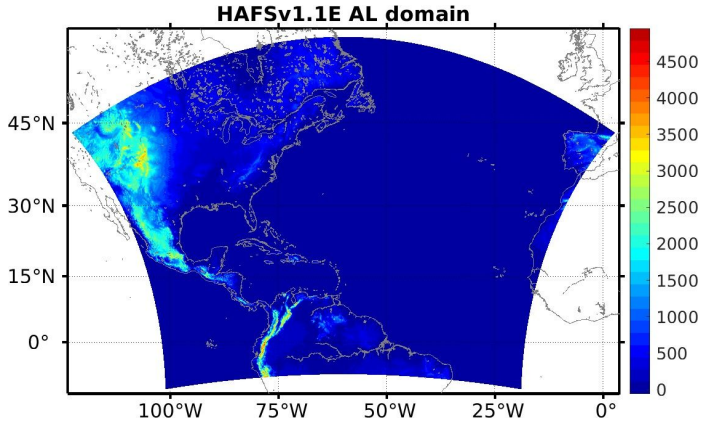
- Lower horizontal resolution: ~6 km (vs. ~6/2 km), Lower vertical resolution: L66 (vs. L81), Single domain with no nest
- No vortex initialization and Data assimilation
- Ocean: Coupled with HYCOM ocean model
- One unperturbed control member and 20 perturbed ensemble members
- Runs 4 times a day (00Z/06Z/12Z/18Z), storms in Atlantic basin only
- Computer resources: AWS Cloud, details see next slide

IC/BC Perturbations:

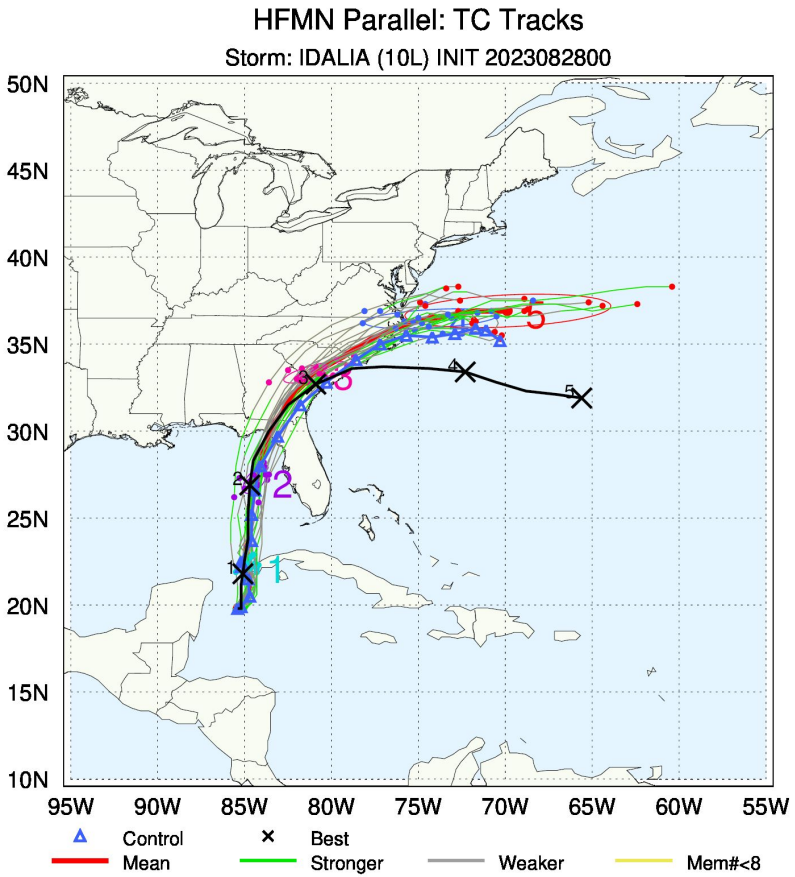
- IC/BC: GEFS grib2 (0.5x0.5) vs. GFS

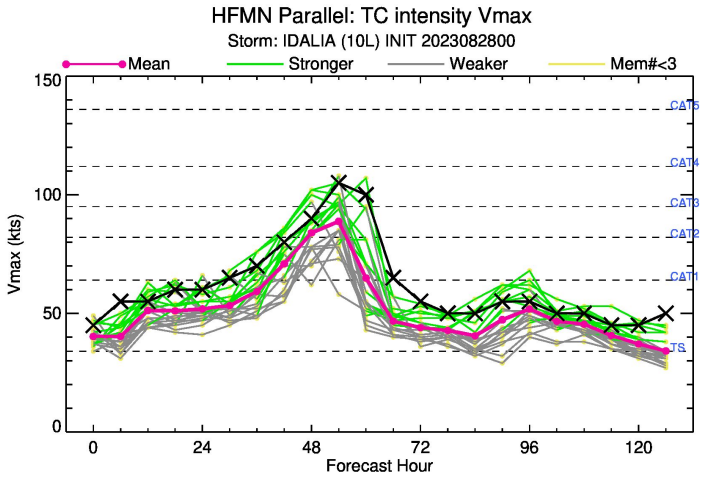
Model Physics Perturbations:

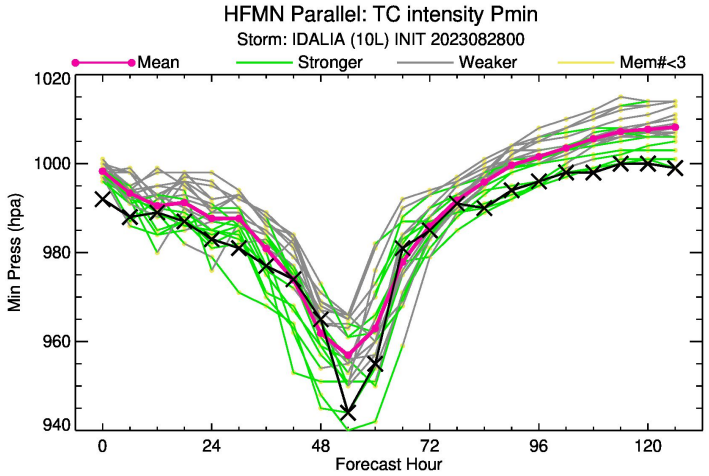
- Stochastically perturbed physics tendencies (SPPT)
- Stochastic kinetic energy backscatter (SKEB)
- Stochastically perturbed PBL humidity (SHUM)



HAFS Ensemble Products

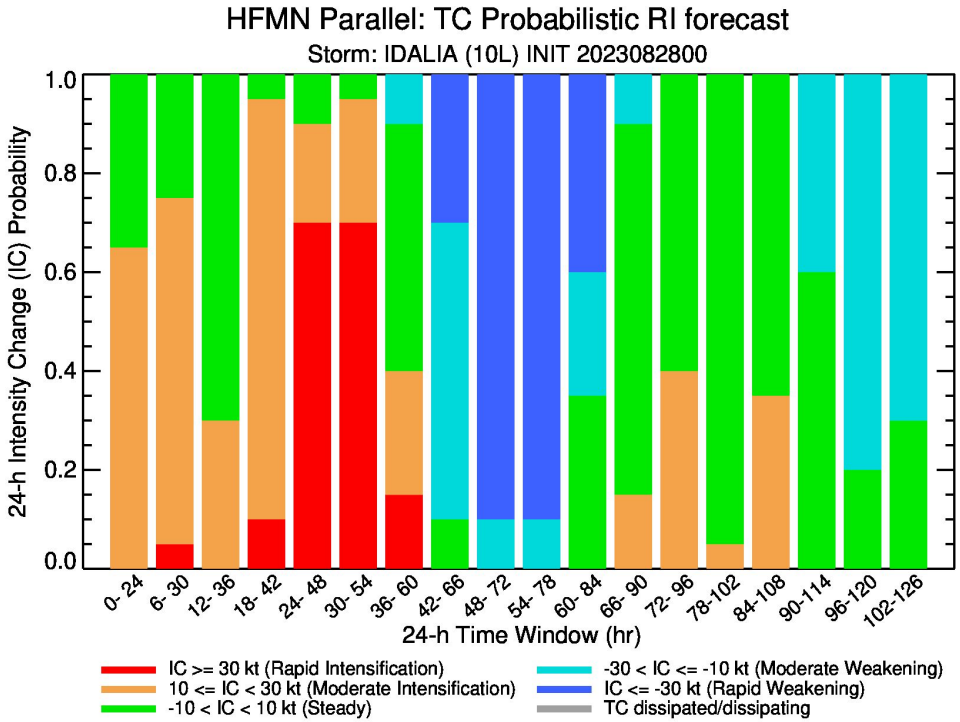






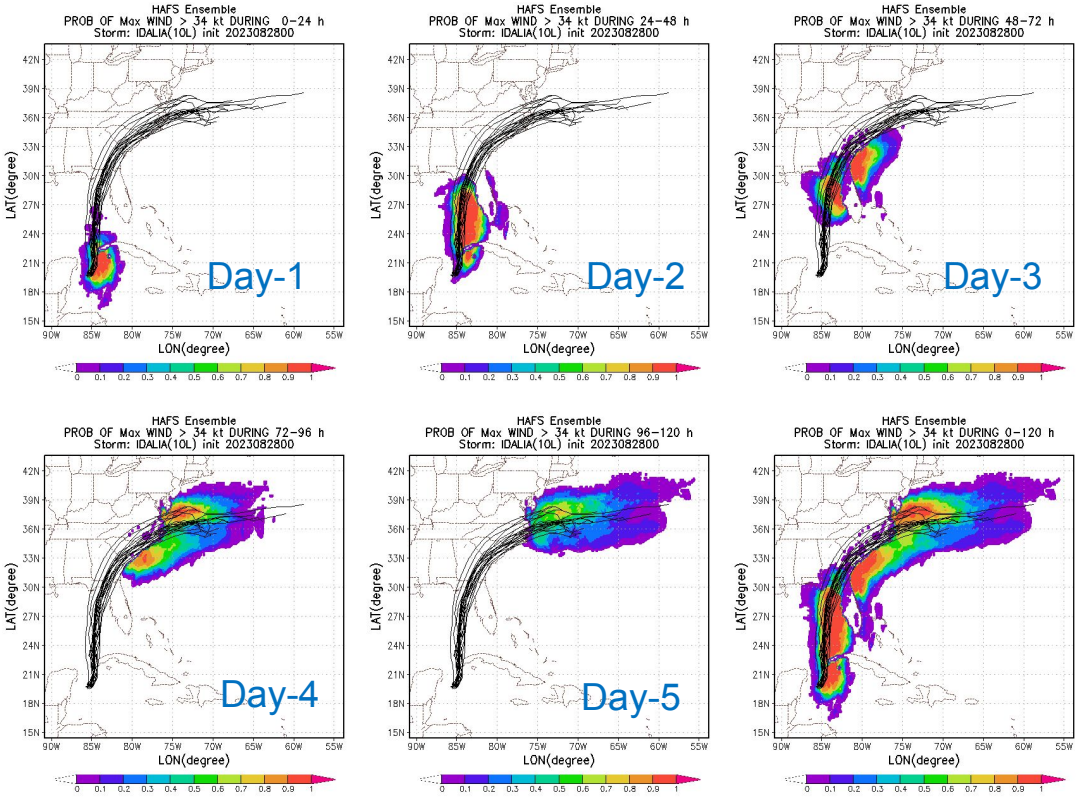
HAFS Ensemble Products

https://www.emc.ncep.noaa.gov/HAFS/HAFSEPS/index.php



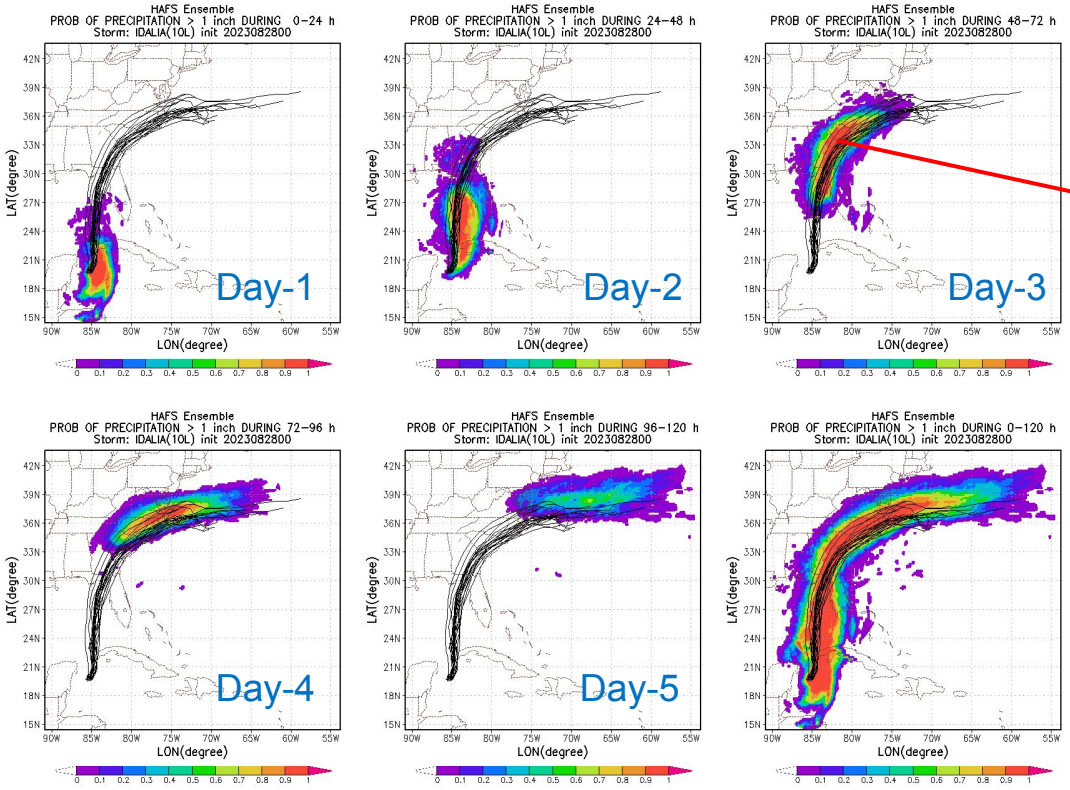
RI happened before Idalia's landfall.

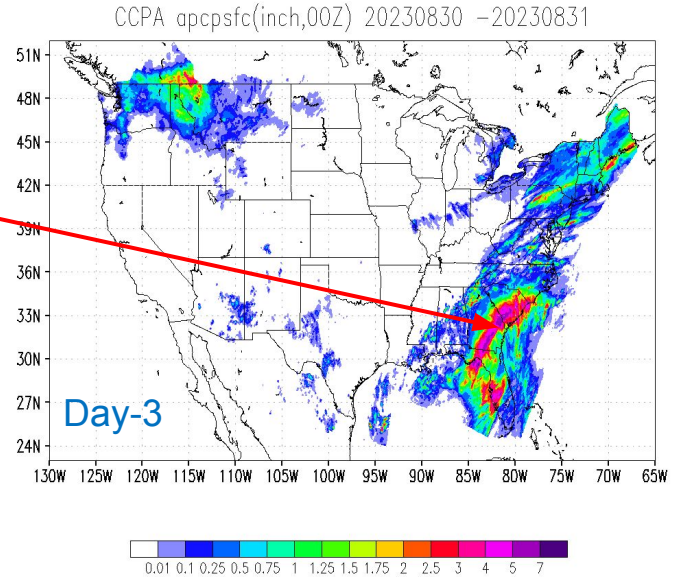
Wind Speed Probability (>34kts; 50kts; 64kts)



HAFS ensemble surface wind fields could be applied to drive the WW3, P-surge model, etc., for hazards forecasts.

Precipitation Probability (> 1;4;8 inches)



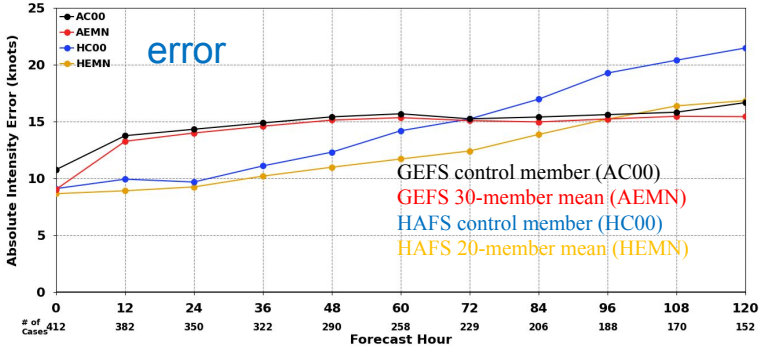


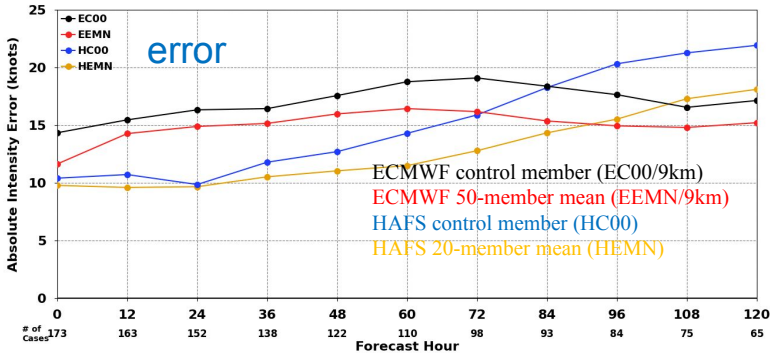
We encourage WPC forecasters to use HAFS PQPF products.

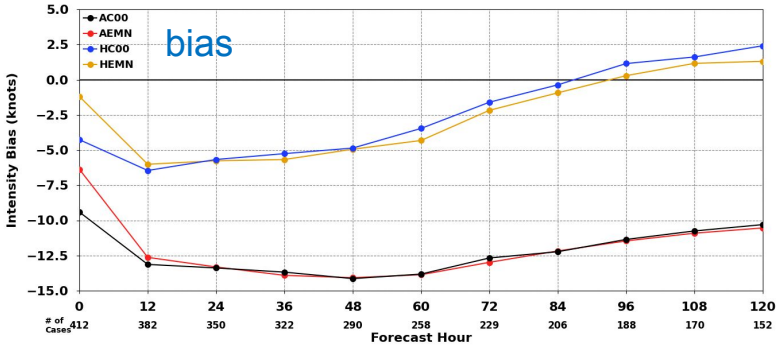
More products, please visit:

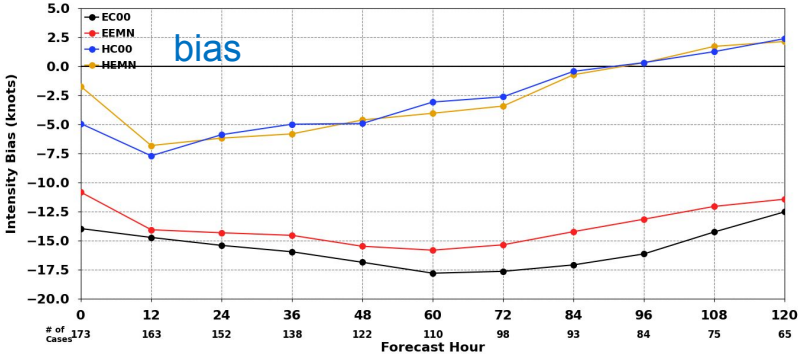
https://www.emc.ncep.noaa.gov/HAFS/HAFSEPS/index.php

Intensity Error and Bias (HAFSens VS. GEFS/EENS)



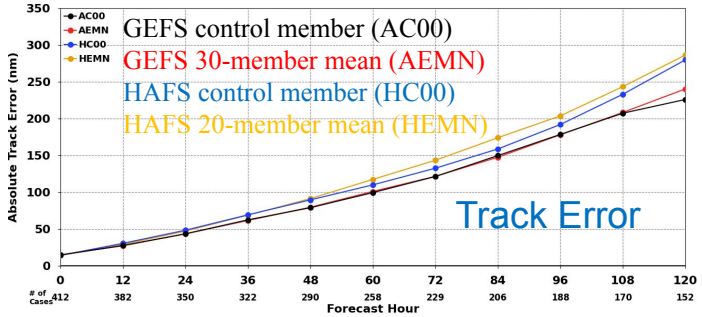


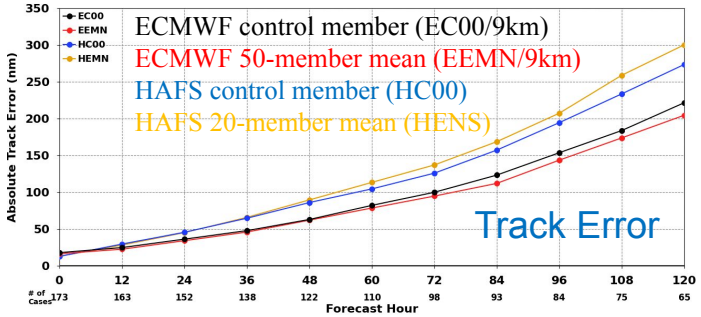


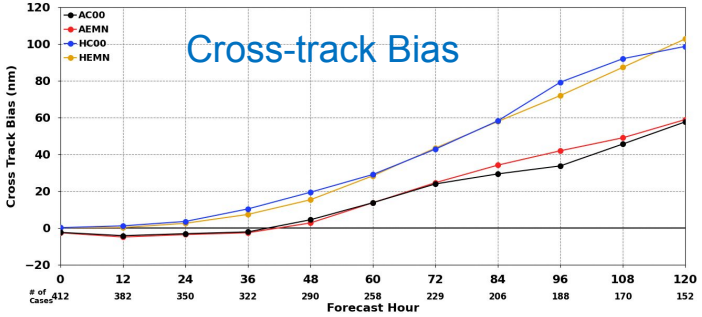


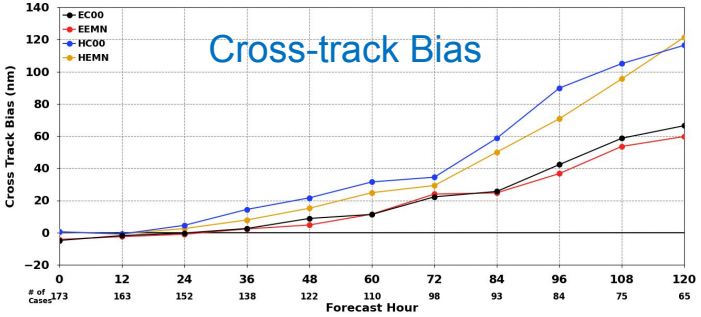
HAFSens: reduced intensity errors in first 4 days; reduced bias by 10kts.

Track Error and Cross-track Bias (HAFSens VS. GEFS/EENS)

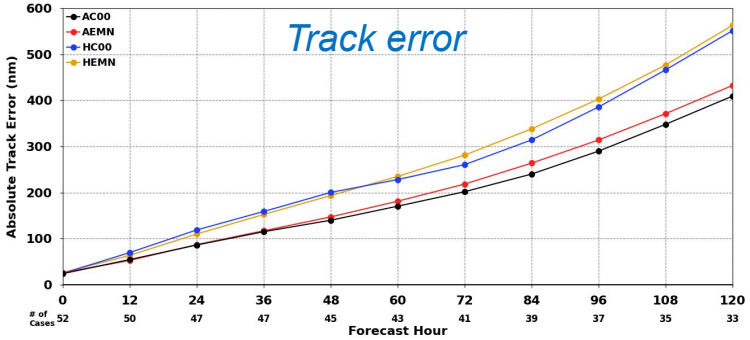


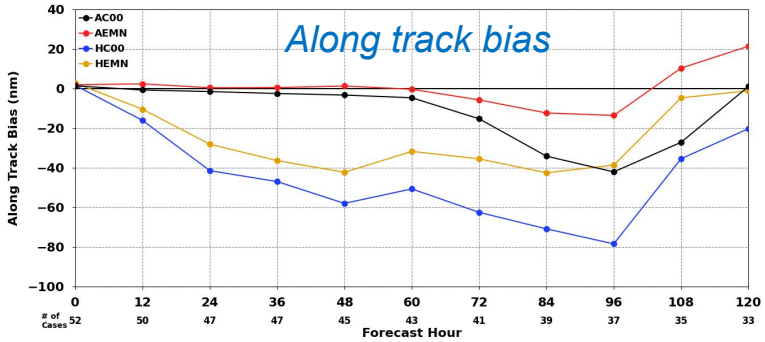


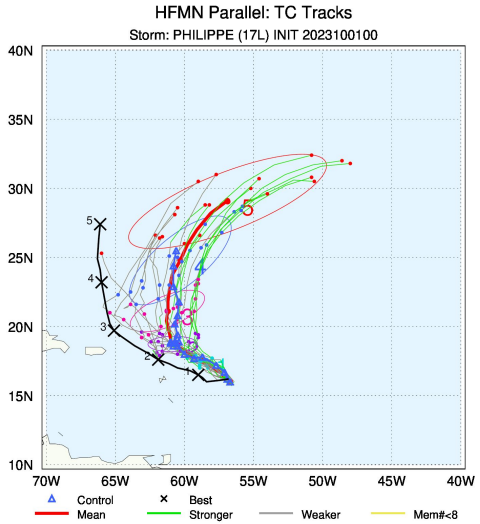


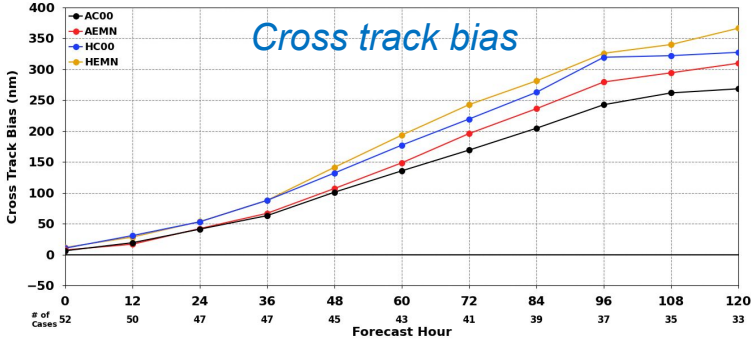


HAFSens: track error increased, most contributed by “Philippe (AL17-2023)”.





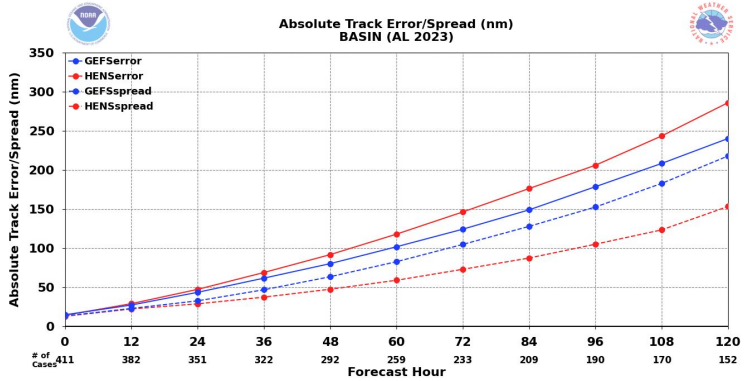


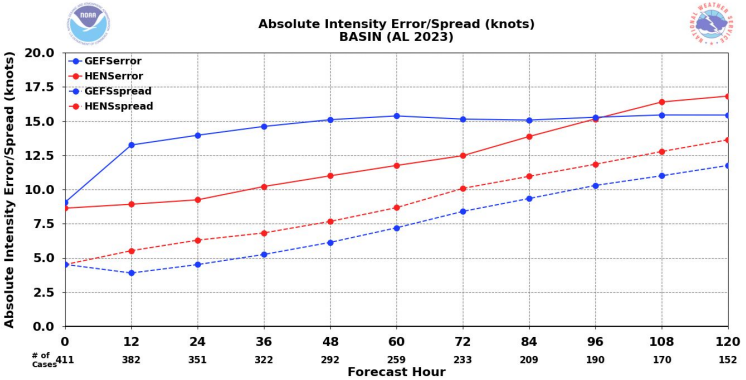


HAFS ensemble VS. GEFS ensemble

Fujiwhara Effect: *Philippe (AL17) and Rina (AL18)*

Intensity and Track Error/Spread Relationship

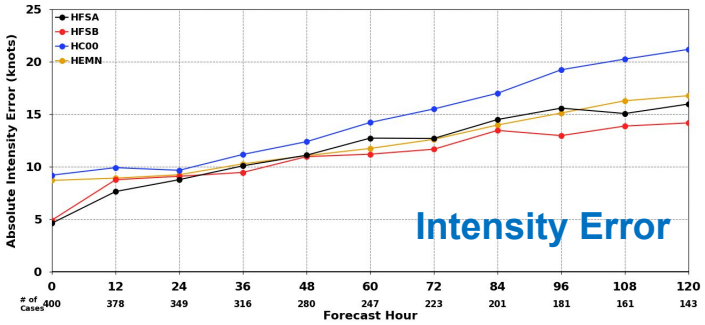


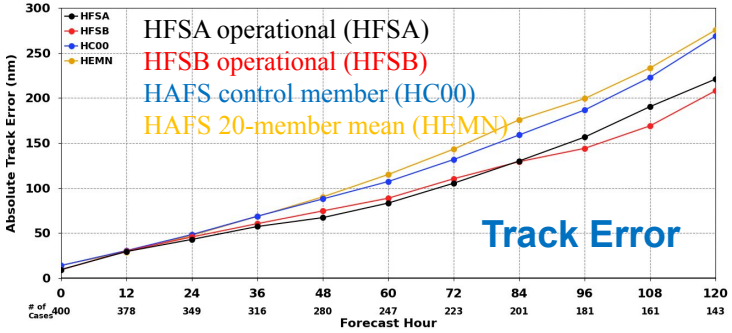


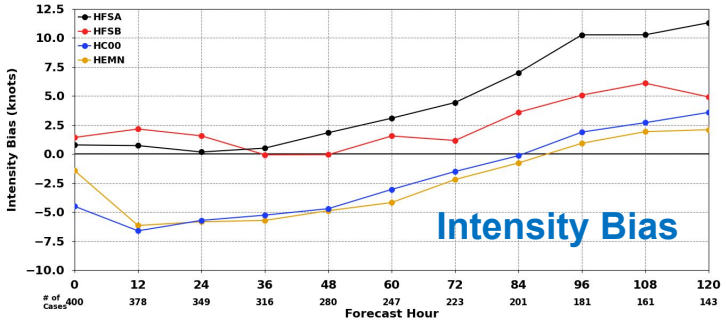
GEFS error (solid blue))
GEFS spread (dashed blue)
HAFSens error (solid red)
HAFSens spread (dashed red)

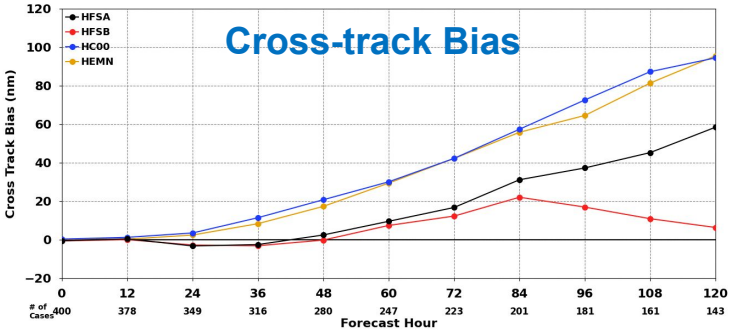
Under dispersive for HAFSens track/intensity forecasts

Intensity Error/Bias, Track Error and Cross-track Bias (HAFSens VS. HFSA/B)









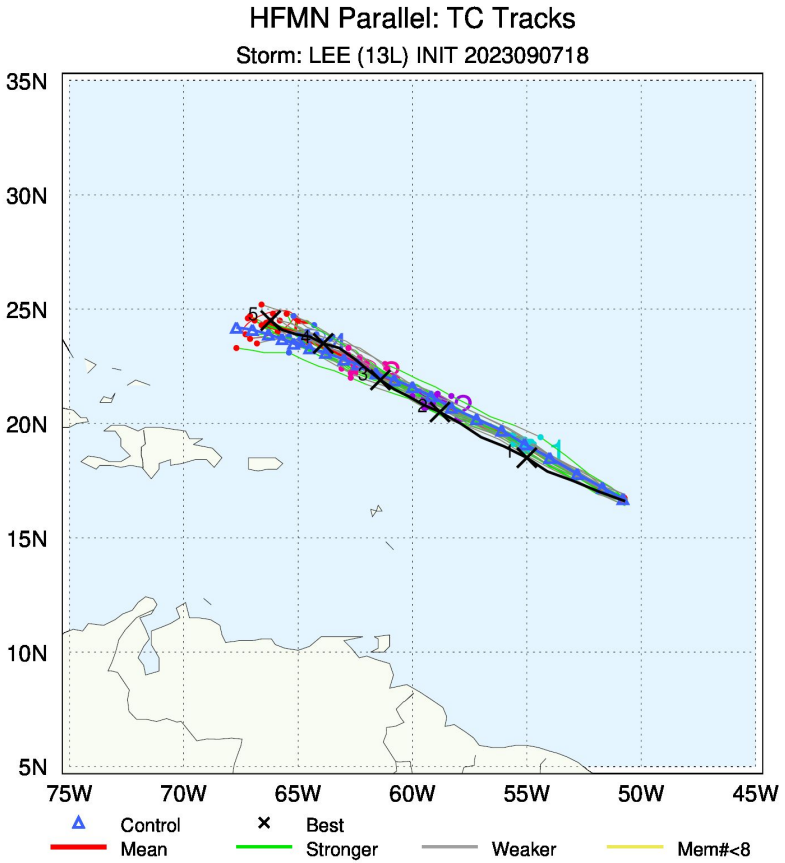
HAFS ens (HEMN):

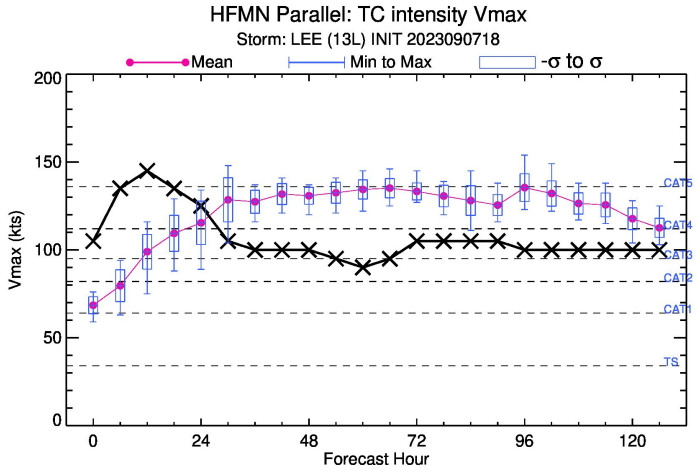
Intensity error is close or better than HFSA after 24 hours.

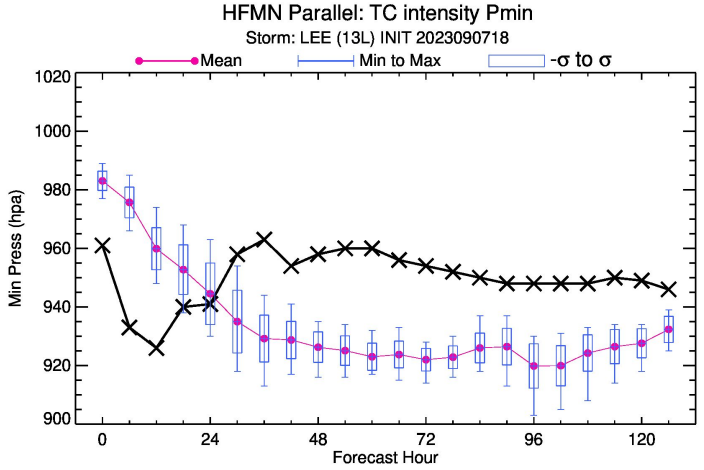
Initial large intensity error /bias due to "no VI/DA".

HAFS-ens has larger cross-track bias

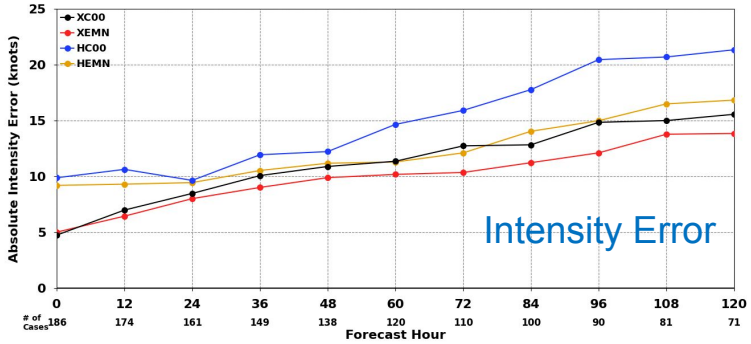
Challenge Storm “Lee”
Initial vortex comes from GEFS (very weak)

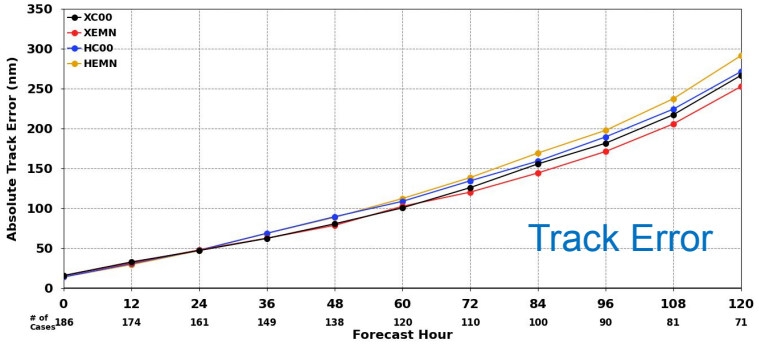


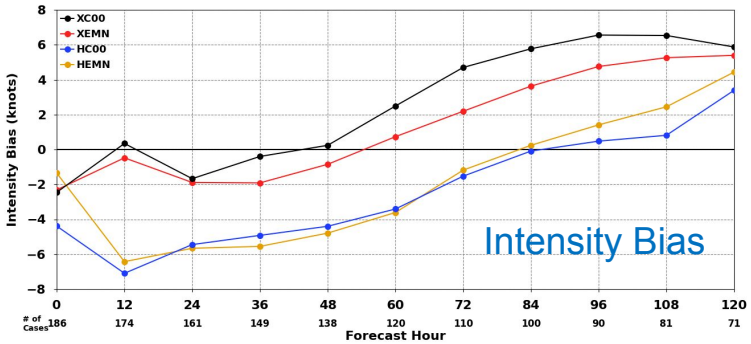




Intensity Error/Bias and Track Error (HAFSens VS. CTCXens)



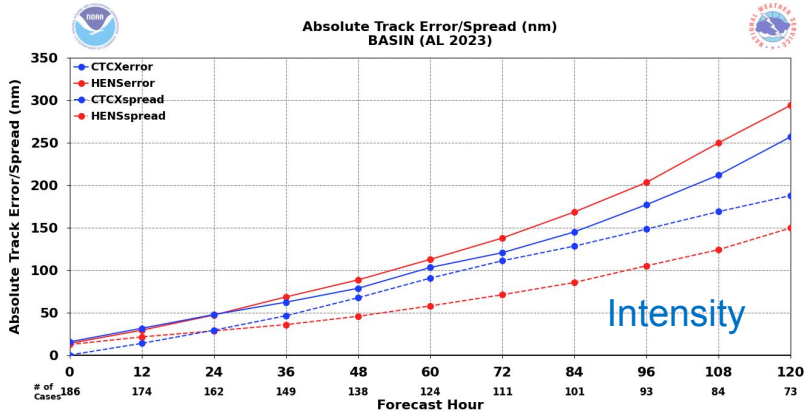


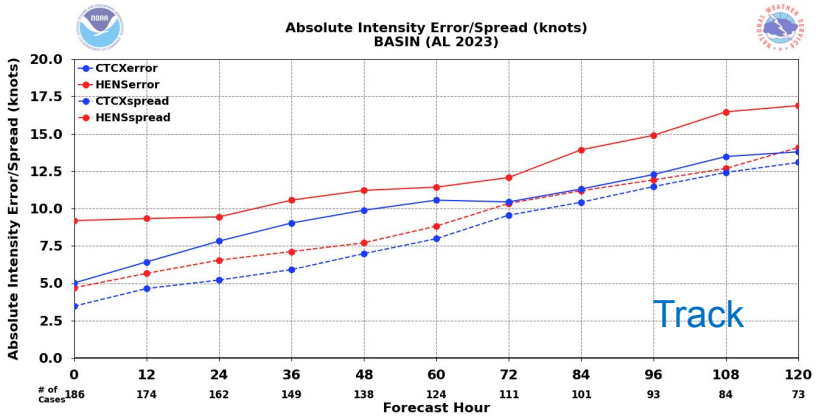


CTCXens control member (XC00)
CTCXens 20-member mean (XEMN)
HAFS control member (HC00)
HAFS 20-member mean (HEMN)

CTCXens did better job for intensity forecast. HAFSens has bigger negative intensity bias in the first 72-hours.

Intensity and Track Error/Spread Relationship



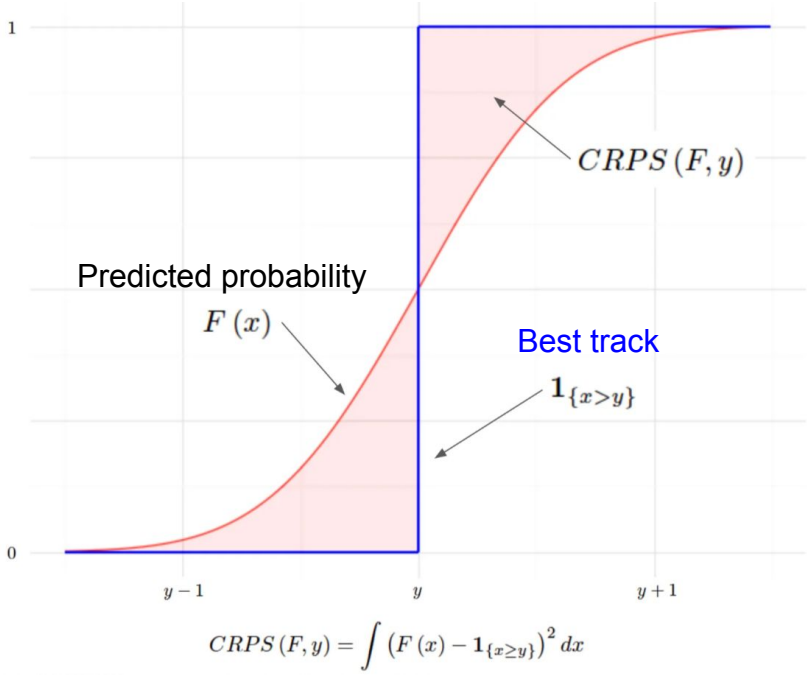


CTCXens error (solid blue))
CTCXens spread (dashed blue)
HAFSens error (solid red)
HAFSens spread (dashed red)

Under dispersive for HAFSens track/intensity forecasts

Continuous Ranked Probability Score

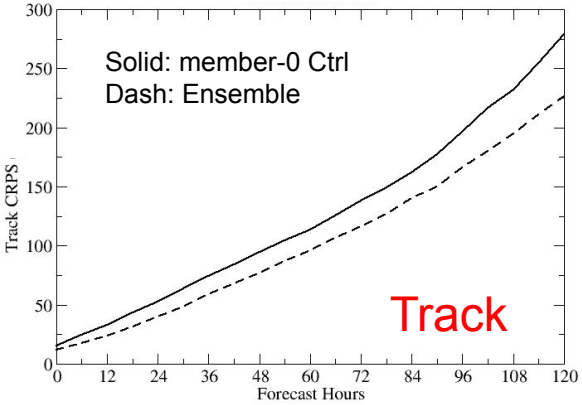
Track and Intensity

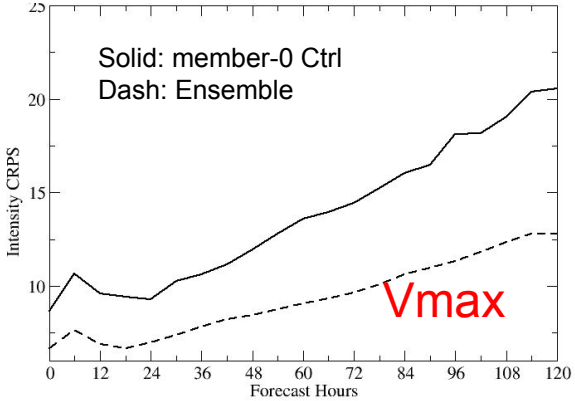


$$CRPS\,(F,y) = \int \left(F\,(x) - \mathbf{1}_{\{x \geq y\}}\right)^2 dx$$

The smaller CRPS indicates better forecast

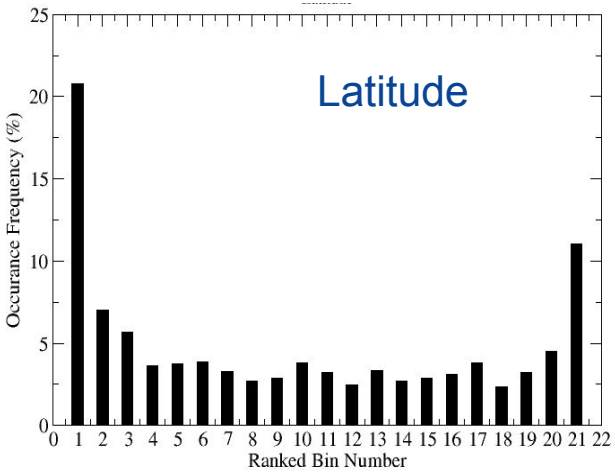
All 2023 NATL Storms



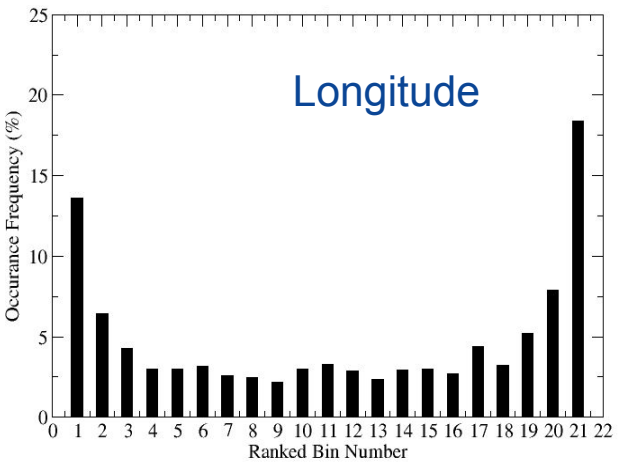


Statistical Characteristics

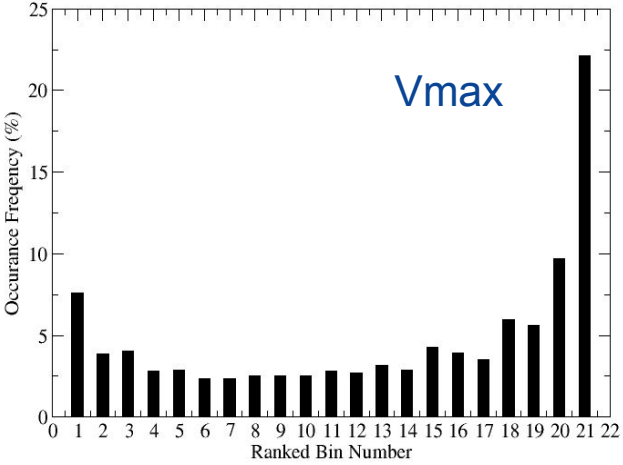
Track/Intensity Rank Histogram (2023 NATL hurricanes)



South → North



East → West



Weak → Strong

Rank histogram shows the frequency of best track value that falls into each ranked bin

Future Plan for FY24 and beyond

- Increase ensemble membership to improve uncertainty spectrums
- Apply re-center process to remove IC perturbation bias.
- Conduct TC VI and DA to improve the initial storm structures
- Improve initial and physics perturbations to have better ensemble spread
- Perform cluster analysis to better represent ensemble forecasts
- Explore use of nested grids for HERC
- Use ML/AI methods for surrogate ensemble members

Porting HERC on AWS Cloud

HAFS ensemble on AWS

- Objective – develop a probabilistic hurricane forecast model using HAFS
  - HAFS (Hurricane Analysis and Forecast System) is a state of the art, deterministic model
  - Run in real-time, a 21-member ensemble using HAFS during the 2023 Atlantic hurricane season (August to November)
- Requirements - features
  - Operational HAFS has many features
    - Ocean coupling, 2km resolution, moving nests, DA (data assimilation) etc.
  - For a first implementation of ensemble, reduced the number of features
    - Ocean coupling, 6km resolution
- Requirements – compute resources
  - Estimated number of Intel Skylake-based nodes is 400+
    - Estimated resources on on-premises systems not available for 4-month continuous use
  - Decided on a Cloud (AWS) implementation of 21-member ensemble
    - Four month capacity reservation using Amazon Reserved Instances

AWS Implementation

- AWS resources and services
  - Compute – 168x hpc6a.48xlarge instances (96 cores/instance)
  - Storage (short term) – 48TB, persistent Lustre file system (AWS FSx for Linux)
  - Storage (long term) – AWS S3 bucket to store results
- Cloud configuration
  - A single parallel cluster is created with
    - 168 Reserved Instances (hpc6a.48xlarge)
    - 42TB Parallel Lustre file system (can store output from 2 cycles)
  - Job scheduler – SLURM
  - Workflow engine – Rocoto
  - Input data – from NODD (NOAA Open Data Dissemination) S3 bucket
    - A small file (SYNDAT) is uploaded from a NOAA on-prem system to Cloud – every 15 minutes
- ”Spin-up” of ensemble model on the Cloud
  - Phase 1: Porting from on-prem system
    - Over a 4-week period using On-Demand instances (prior to reserved capacity turned on)
    - Tested only up to 3-member ensemble model to keep costs low
  - Phase 2: tested 21-member ensemble RI-based cloud configuration – 2 weeks

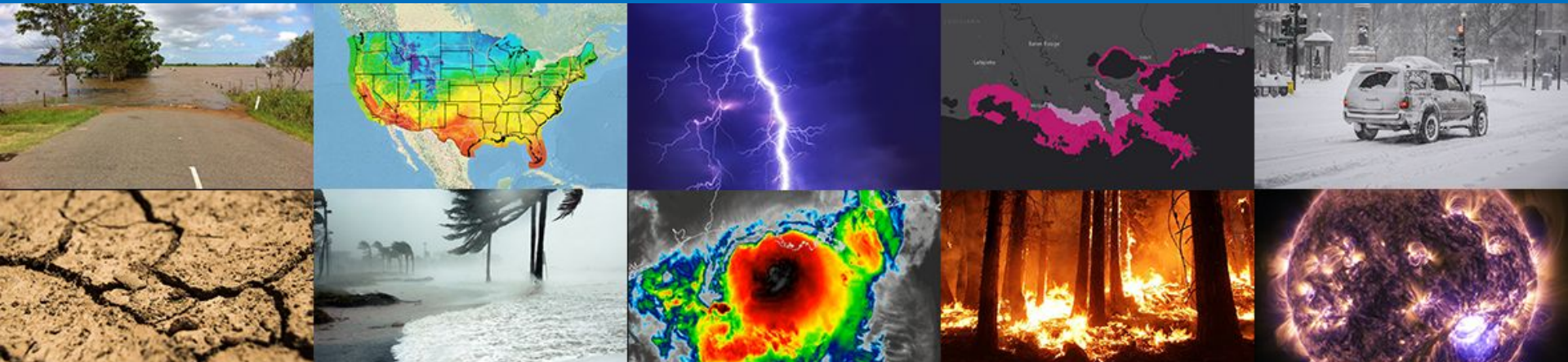
Running HAFS ensemble on Cloud

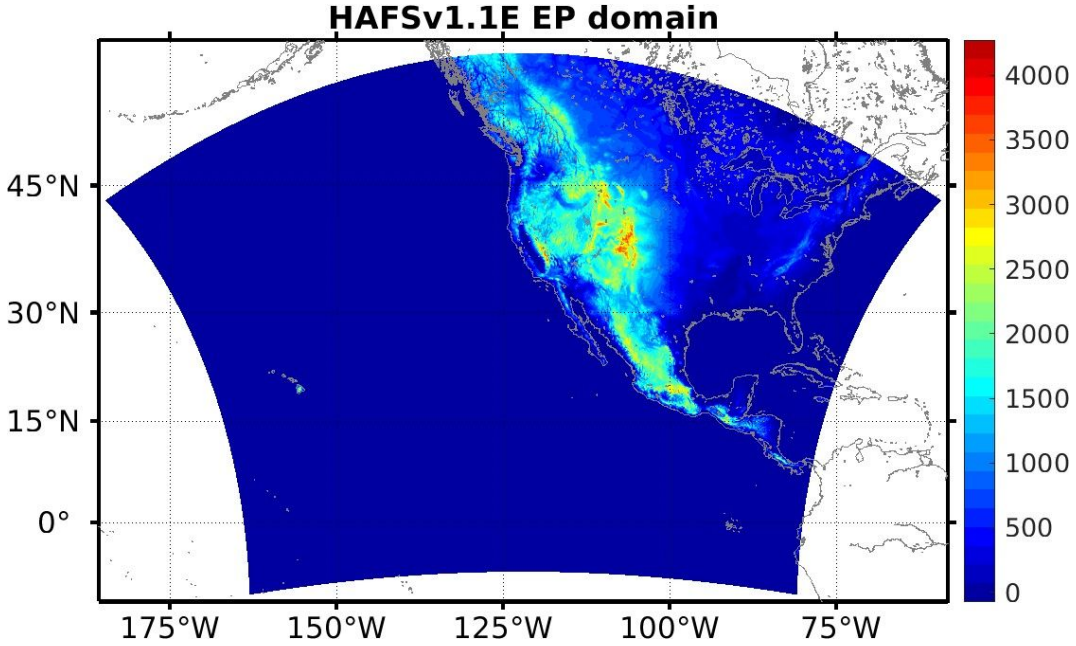
- Computing
  - Using Rocoto, 21 workflows (one per member) are run continuously
  - Each workflow creates multiple jobs - submitted to the same SLURM job queue
  - Number instances per job varies – 7 instances if it is forecast with ocean coupling
  - Entire workflow for a cycle – completes under 6 hours
- Data movement – per cycle
  - Majority of input data accessed from S3 bucket – intra-cloud transfer
  - Output data – 21TB per cycle
    - Output is stored initially in Lustre filesystem
    - When a new cycle starts – output from previous cycle is transferred to S3 bucket
  - Limited set of output files transferred to a NOAA on-prem system
    - Generate graphics for NOAA and other organizations

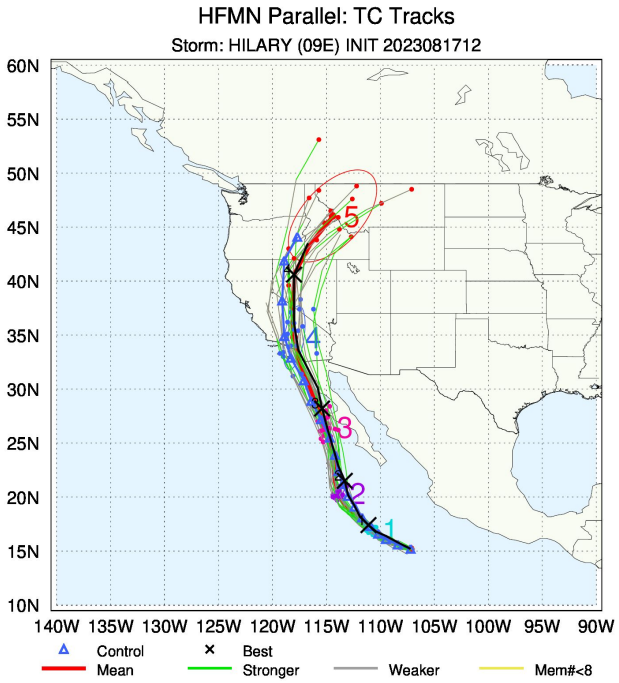
Lessons Learned

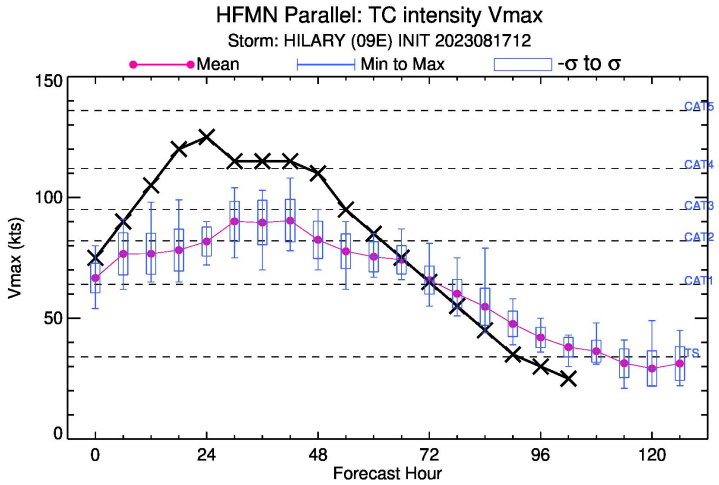
- Accurate estimate of cloud resources
  - ensure defined cloud configuration meets project budget and runtime goals
  - use existing performance (runtime) info from on-prem runs
  - create self-contained benchmarks for critical steps
- Port from an on-prem system
  - similar cloud compute env. as on-prem system – easy to debug
  - verification of results before actual cloud simulation work starts
- Leverage SMEs
  - critical during debug and result verification steps
- Leverage Parallel Works & CSP
  - is the could configuration optimal? – CSPs keep adding new types of instances, services, etc.
  - develop a plan of action for resolving issues as they arise (appl. Level -> PWorks-> CSP)
- Monitor and address issues

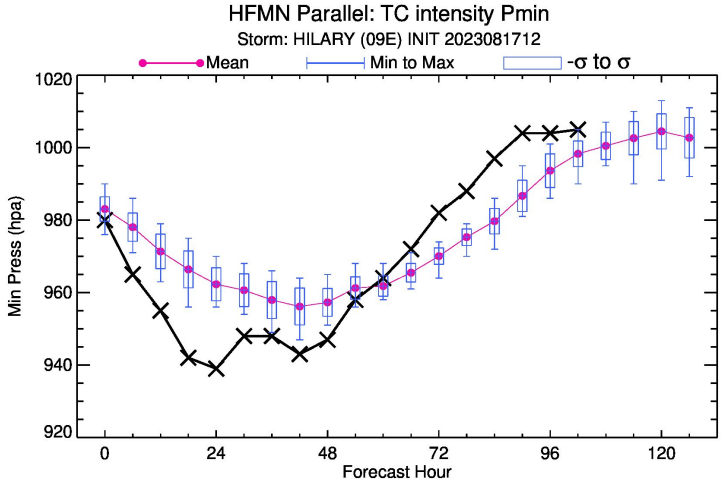
Thank you!

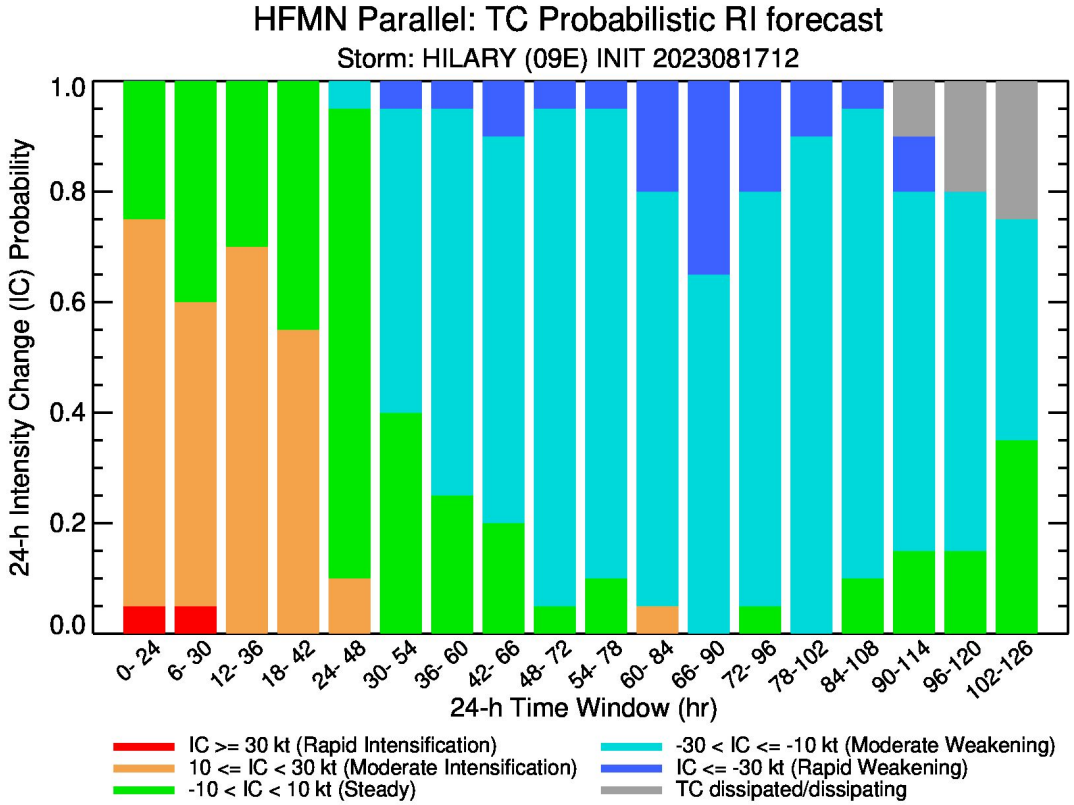


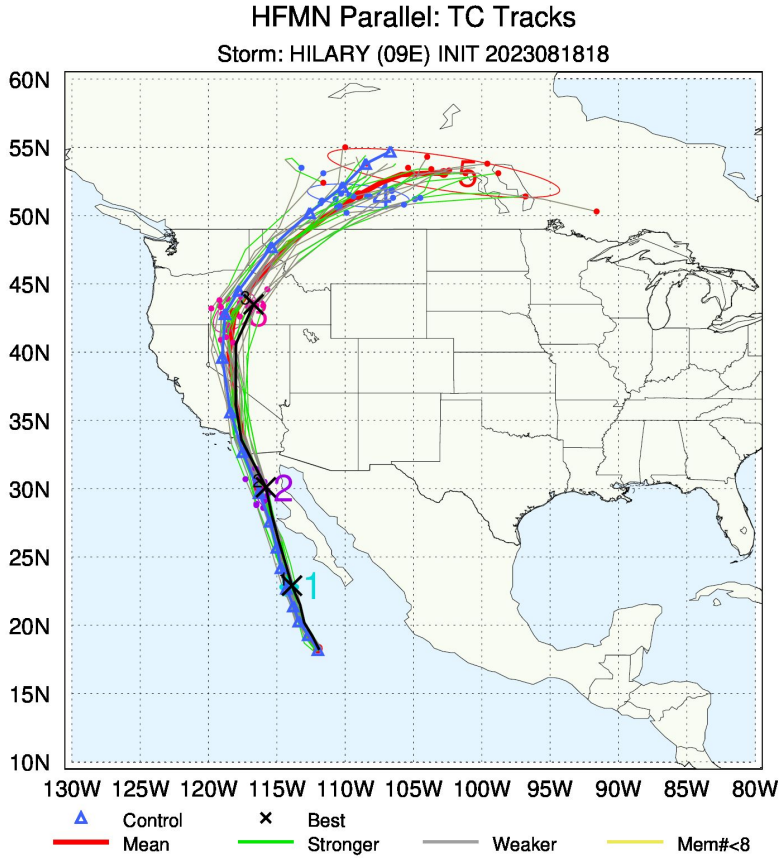

HAFSv1.1E EP domain
45°N
30°N
15°N
0°
175°W
150°W
125°W
100°W
75°W
4000
3500
3000
2500
2000
1500
1000
500
0

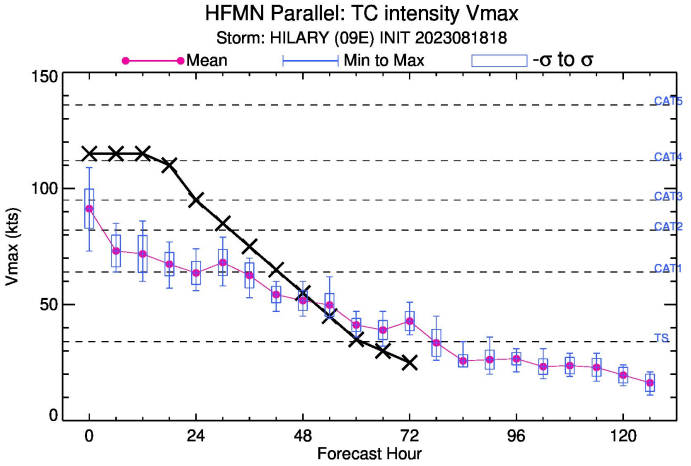

HFMN Parallel: TC Tracks
Storm: HILARY (09E) INIT 2023081712
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
140W 135W 130W 125W 120W 115W 110W 105W 100W 95W 90W
5
4
3
2
1
Control
Mean
Best
Stronger
Weaker
Mem#<8

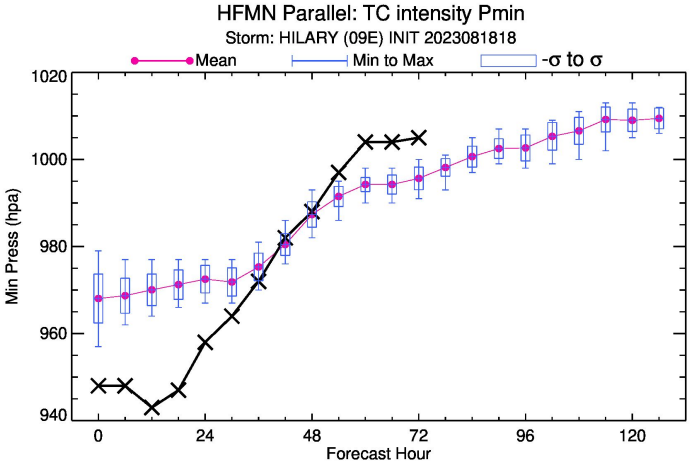

HFMN Parallel: TC intensity Vmax
Storm: HILARY (09E) INIT 2023081712
Mean
Min to Max
-σ to σ
Vmax (kts)
150
100
50
0
CAT5
CAT4
CAT3
CAT2
CAT1
TS
0
24
48
72
96
120
Forecast Hour


HFMN Parallel: TC intensity Pmin
Storm: HILARY (09E) INIT 2023081712
Mean
Min to Max
-σ to σ
Min Press (hpa)
1020
1000
980
960
940
920
0
24
48
72
96
120
Forecast Hour


HFMN Parallel: TC Probabilistic RI forecast
Storm: HILARY (09E) INIT 2023081712
24-h Intensity Change (IC) Probability
1.0
0.8
0.6
0.4
0.2
0.0
0- 24
6- 30
12- 36
18- 42
24- 48
30- 54
36- 60
42- 66
48- 72
54- 78
60- 84
66- 90
72- 96
78-102
84-108
90-114
96-120
102-126
24-h Time Window (hr)
IC >= 30 kt (Rapid Intensification)
10 <= IC < 30 kt (Moderate Intensification)
-10 < IC < 10 kt (Steady)
-30 < IC <= -10 kt (Moderate Weakening)
IC <= -30 kt (Rapid Weakening)
TC dissipated/dissipating


HFMN Parallel: TC Tracks
Storm: HILARY (09E) INIT 2023081818
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
130W 125W 120W 115W 110W 105W 100W 95W 90W 85W 80W
1
2
3
5
Control
Mean
Best
Stronger
Weaker
Mem#<8

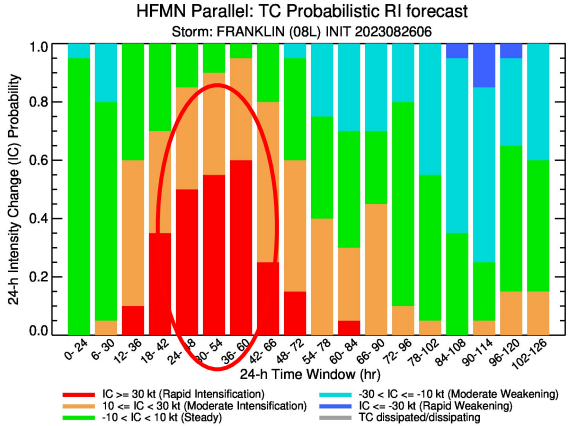

HFMN Parallel: TC intensity Vmax
Storm: HILARY (09E) INIT 2023081818
Mean
Min to Max
-σ to σ
Vmax (kts)
150
100
50
0
CAT5
CAT4
CAT3
CAT2
CAT1
TS
0
24
48
72
96
120
Forecast Hour

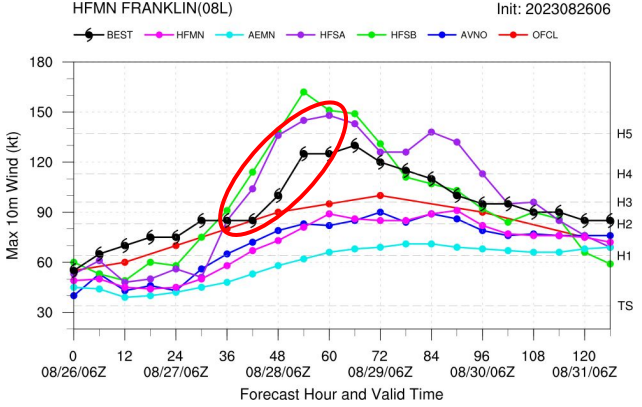

HFMN Parallel: TC intensity Pmin
Storm: HILARY (09E) INIT 2023081818
Mean
Min to Max
-σ to σ
Min Press (hpa)
1020
1000
980
960
940
0
24
48
72
96
120
Forecast Hour

Highlights of HERC Products

RI events, Hurricanes Franklin and Lee, 2023

Hurricane Franklin
202300826 06Z





Hurricane Lee
20230907 12Z