Applications of a Machine Learning Model for Estimating Tropical Cyclone Track and Intensity Forecast Uncertainty

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HFIP Annual Review
Nov 12-15, 2024
Miami, FL

Outline

- The Tropical Cyclone Artificial Neural-network Error (TCANE) model
- Results from 2024 independent forecasts
  - Sample products
  - Product website
  - Verification
- Future Plans

Hurricane Helene

Satellite | Buoys | Grids | Storm Archive

...HELENE BECOMES A HURRICANE... ...EXPECTED TO BRING LIFE-THREATENING STORM SURGE, DAMAGING WINDS, AND FLOODING RAINS TO A LARGE PORTION OF FLORIDA AND THE SOUTHEASTERN UNITED STATES...

10:00 AM CDT Wed Sep 25
Location: *21.6°N 86.3°W*
Moving: *NNW at 10 mph*
Min pressure: *979 mb*
Max sustained: *80 mph*

Public Advisory #9
1000 AM CDT

Forecast Advisory #9
1500 UTC

Forecast Discussion #9
1000 AM CDT

Wind Speed Probabilities #9
1500 UTC

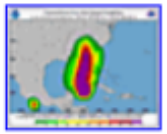
NWS Local Products
1148 AM EDT

US Watch/ Warning
1107 AM EDT

Productos en español: (más información)

Aviso Publico

Pronóstico Discusión


Wind Speed Probabilities


Arrival Time of Winds


Wind History


Warnings/Cone Interactive Map


Warnings/Cone Static Images


Warnings and Surface Wind

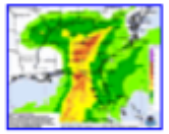

Key Messages


Mensajes Claves


Storm Surge Inundation


Storm Surge Watch/Warning


Peak Surge

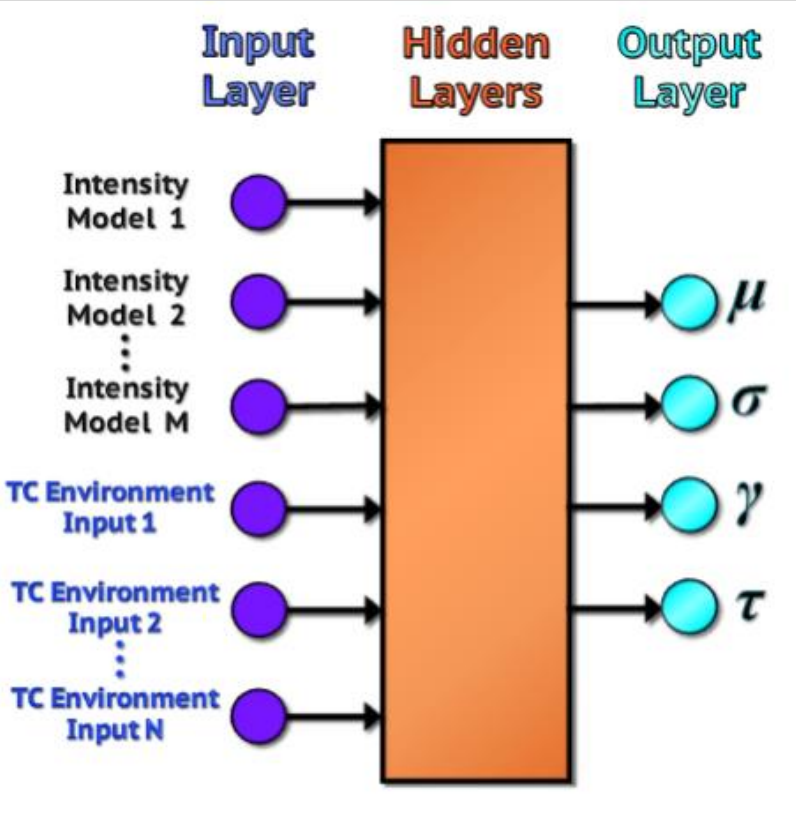

Rainfall Potential


Flash Flooding Potential

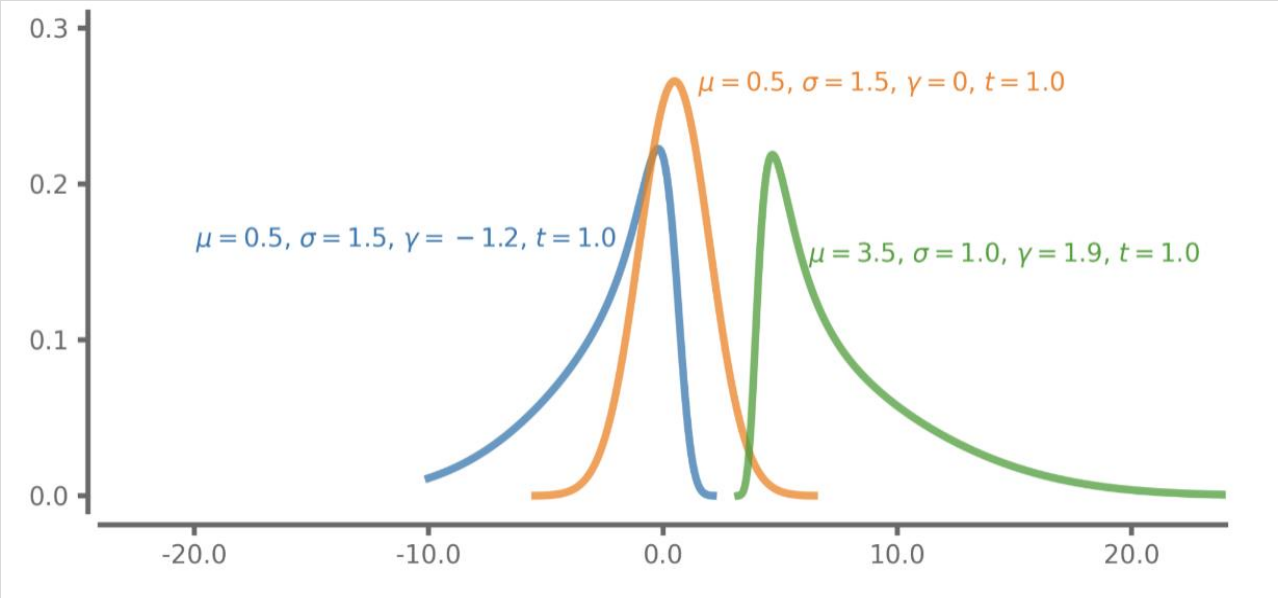
The TCANE Model

- A Machine-Learning model developed at CIRA and being evaluated and improved under NOAA Hurricane and Ocean Testbed (HOT) support
- Predicts the track and intensity error distributions
  - Assumes SHASH distribution for intensity, Bivariate normal distribution for track
  - Input includes multi-model track and intensity forecasts and storm environmental predictions
- Input
  - Multiple model track and intensity forecasts
  - SHIPS predictors
    - Shear, SST, distance to land along forecast track
    - t=0 h max wind and t=-12 to 0 h max wind tendency
- Output
  - Consensus model error distributions (early version)
  - *NHC official forecast error distributions (late version)*

TCANE Intensity Model Design

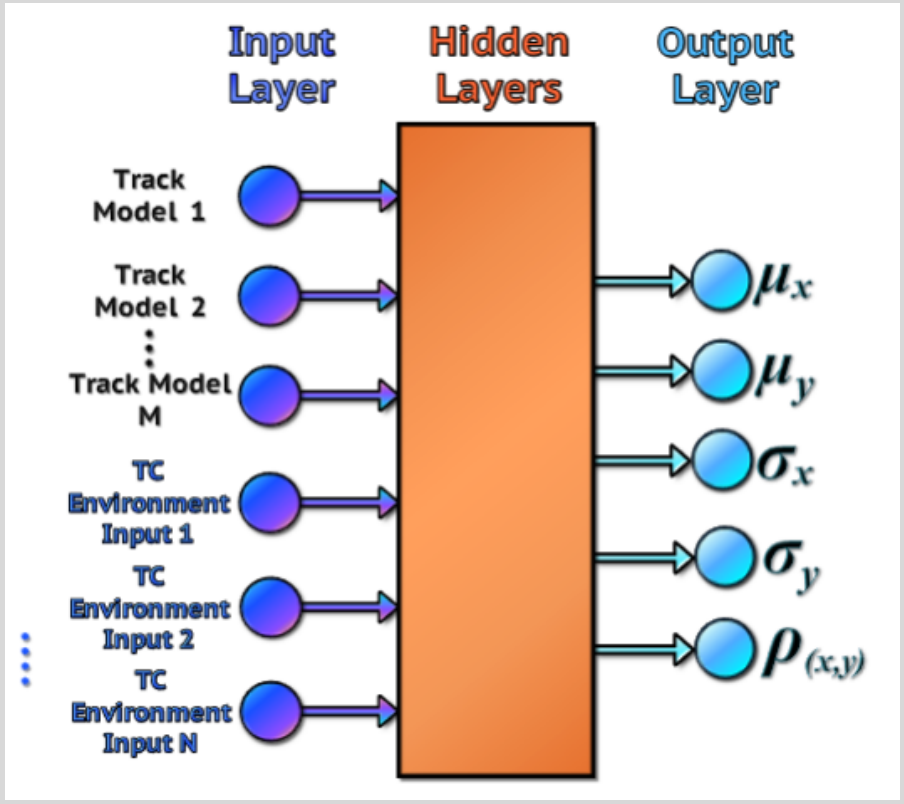


Sinh-ArcSinh Distribution (SHASH) for Various Input Parameters



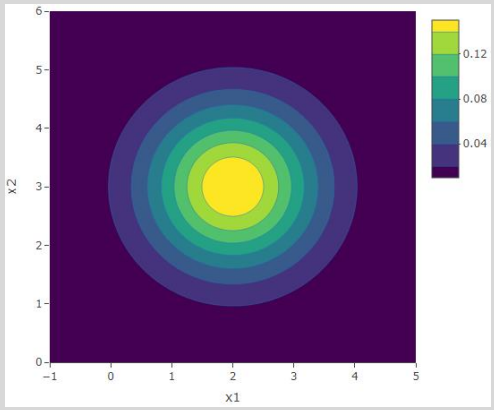
μ = length (similar to normal distribution mean)
σ = scale (similar to normal distribution standard deviation)
γ = skewness
τ = tail

TCANE Track Model Design

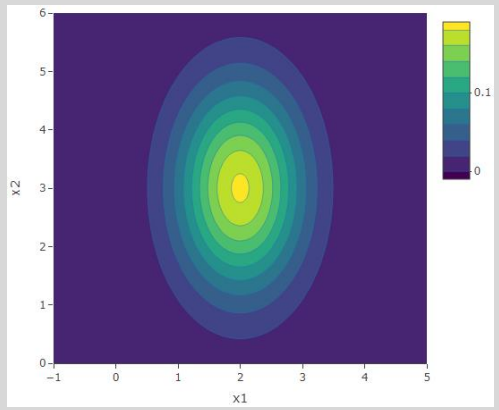


μ_x , μ_y = forecast biases in the x,y directions
σ_x ,σ_y = standard deviations of x and y errors
$\rho(x,y)$ = correlation of x and y errors

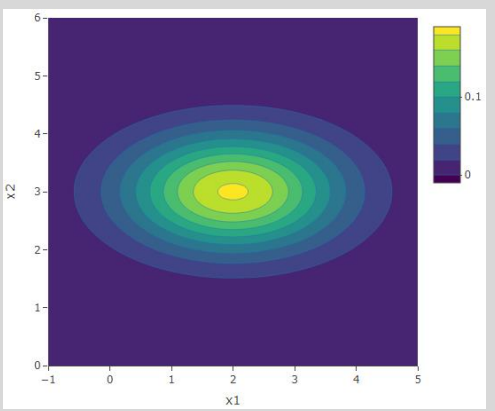
Bivariate normal distributions for various input parameters



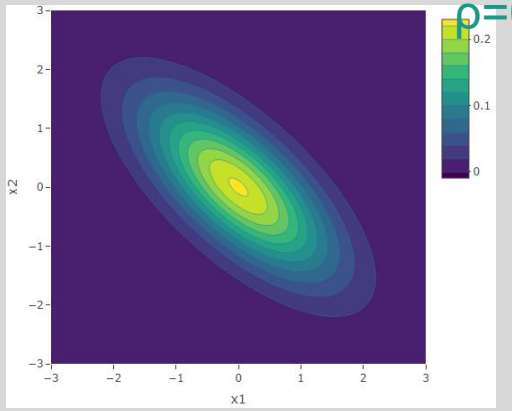
$\sigma_x=\sigma_y$ $\rho=0$



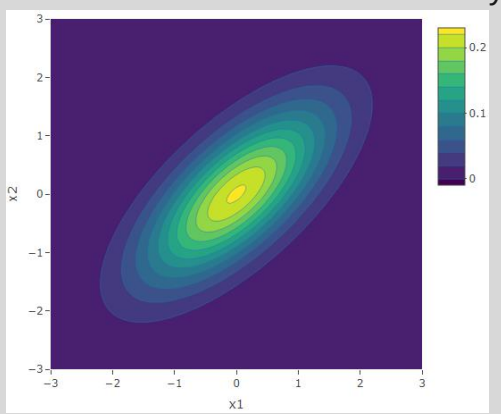
$\sigma_x<\sigma_y$ $\rho=0$



$\sigma_x>\sigma_y$ $\rho=0$



$\sigma_x=\sigma_y$
$\rho<0$



$\sigma_x=\sigma_y$
$\rho>0$

BVND plots from https://datasciencegenie.com/

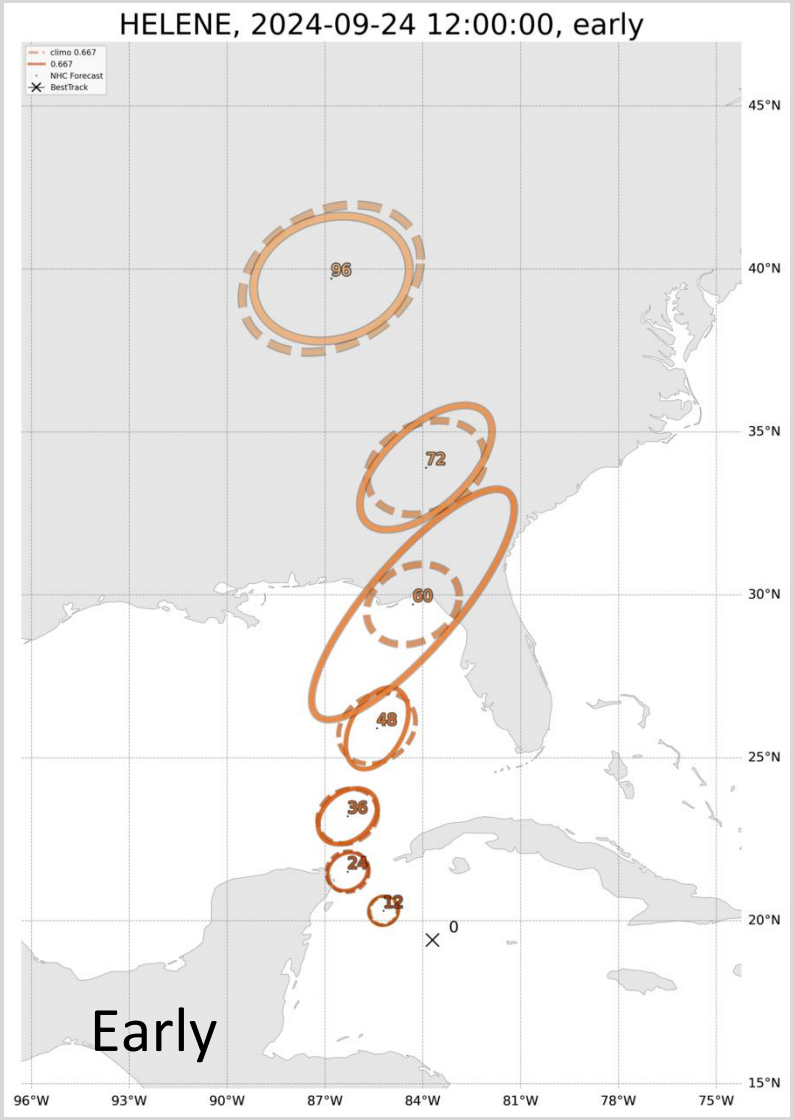
TCANE v1.0

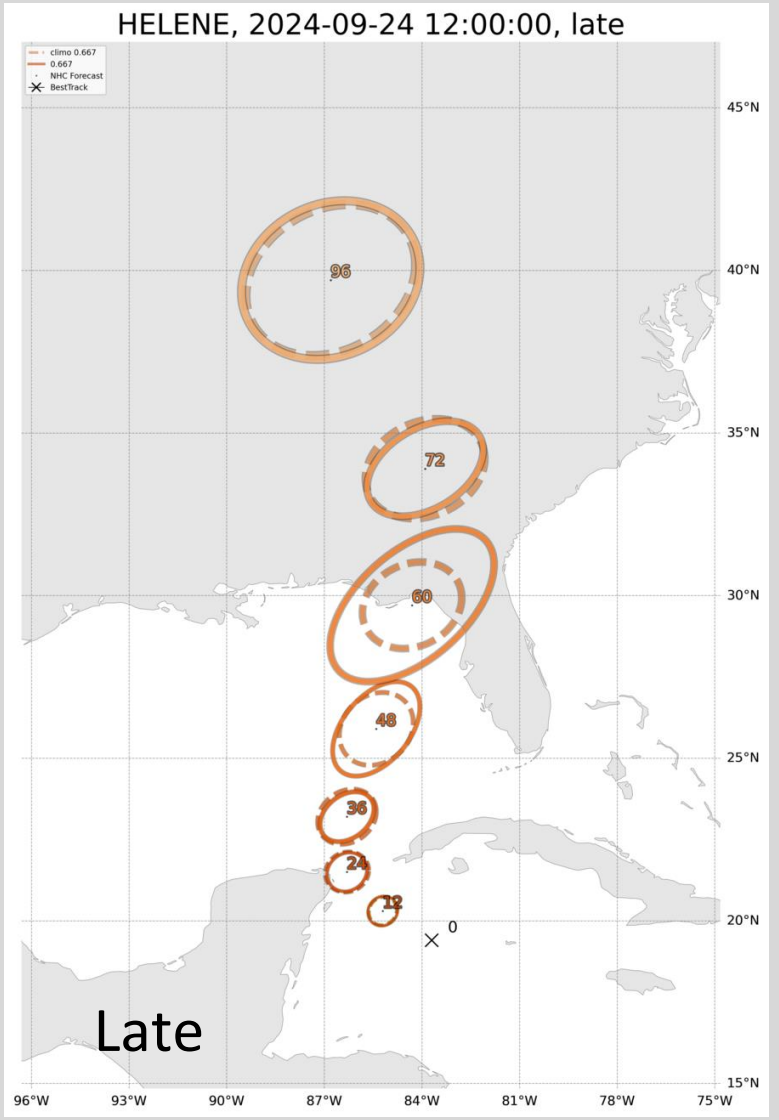
- Input
  - Track: Early HWRF, GFS, ECMWF, UKMet, storm environment predictors
  - Intensity: DSHP, LGEM, Early HWRF, GFS, storm environment predictors
- Output
  - Parameters of the track and intensity error distributions
  - Text and graphical forecast uncertainty products
- Early run – error distributions of the 4-model consensus
  - Potential use as forecaster guidance
- Late run – error distributions of NHC official forecasts
  - Potential use to add situational forecast dependence to public-facing uncertainty products
    - Input to NHC's Wind Speed Probability and P-Surge models
    - Cone of Uncertainty
- Graphical products developed based on NHC/TSB coordination

Products for 2024 Demonstration

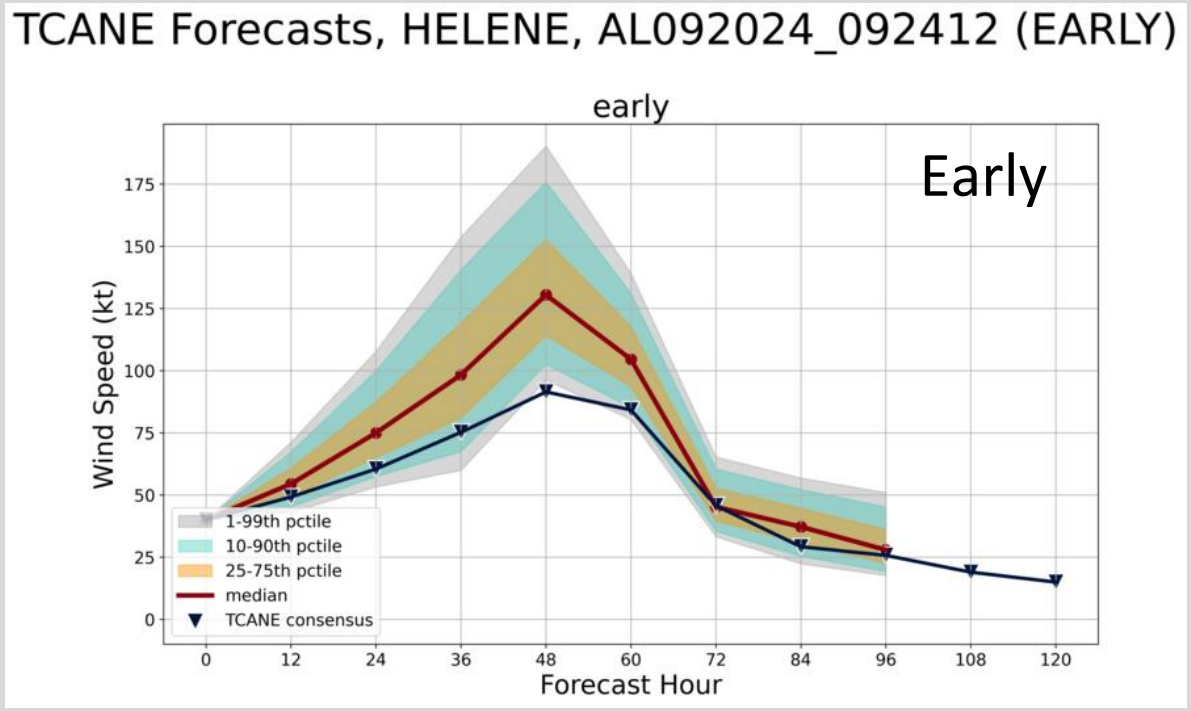
- Track Uncertainty
  - Uncertainty ellipses from TCANE and climatology for the 67th percentile
- Intensity Uncertainty
  - Uncertainty time series from TCANE and climatology
  - Probability of cat 1, 2, 3, 4 and 5 hurricane
  - Probabilities of rapid intensification
- Explainable AI products (still under development)
  - SHAP values for guidance on which predictors are affecting error distributions

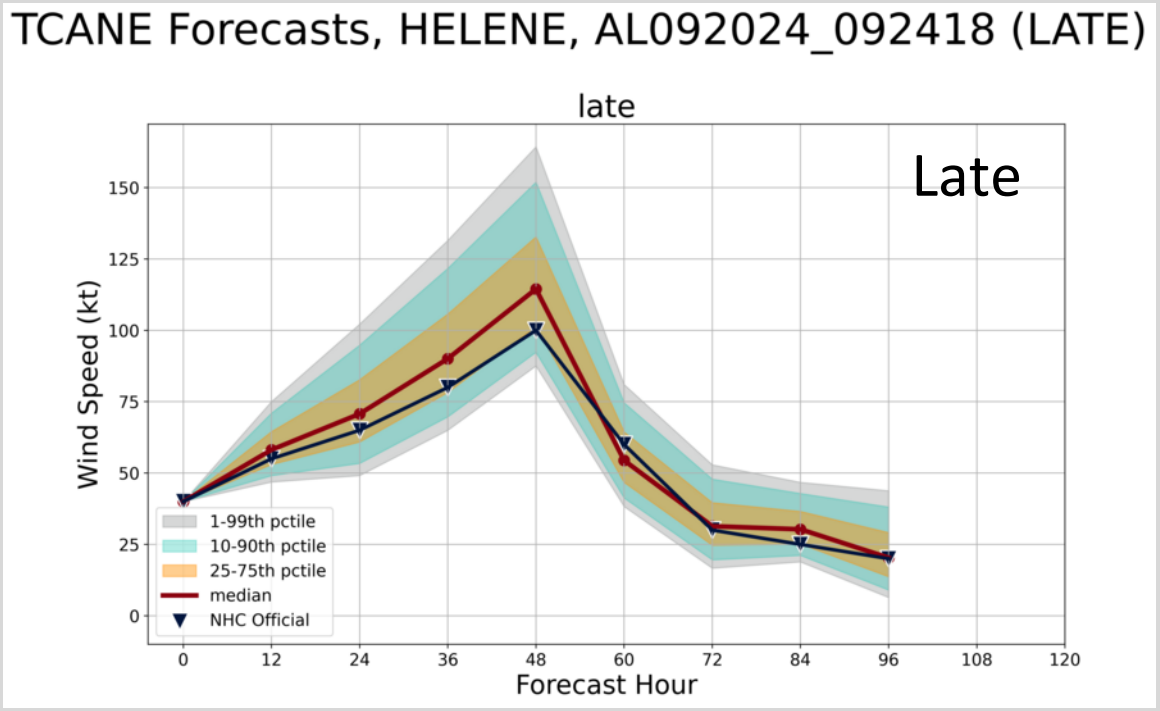
TCANE Track Error Distribution Predictions
Hurricane Helene 24 Sept 2024 12 UTC



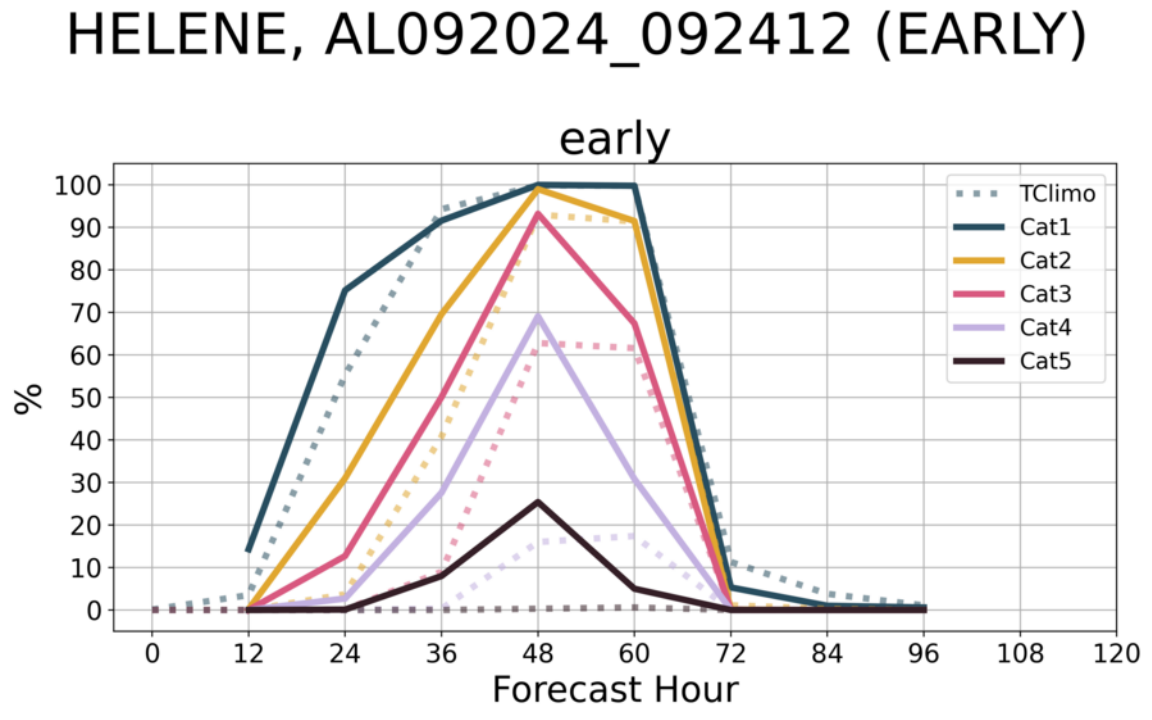


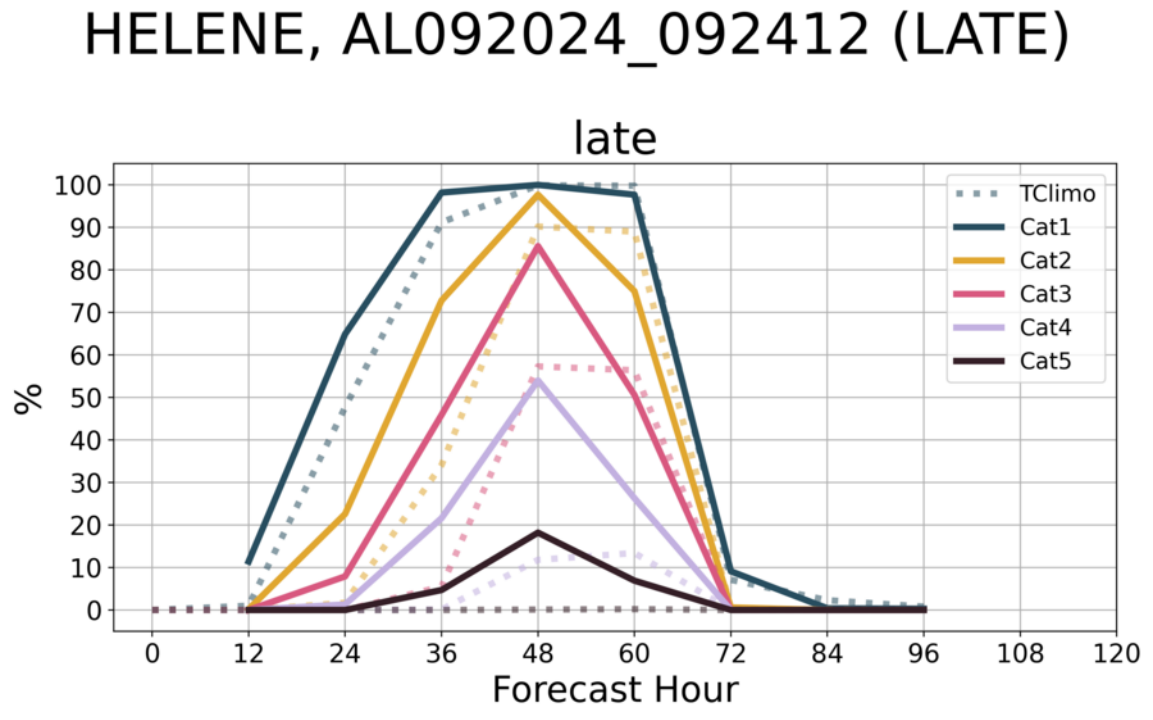
TCANE Intensity Error Distribution Predictions Hurricane Helene 24 Sept 2024 12 UTC



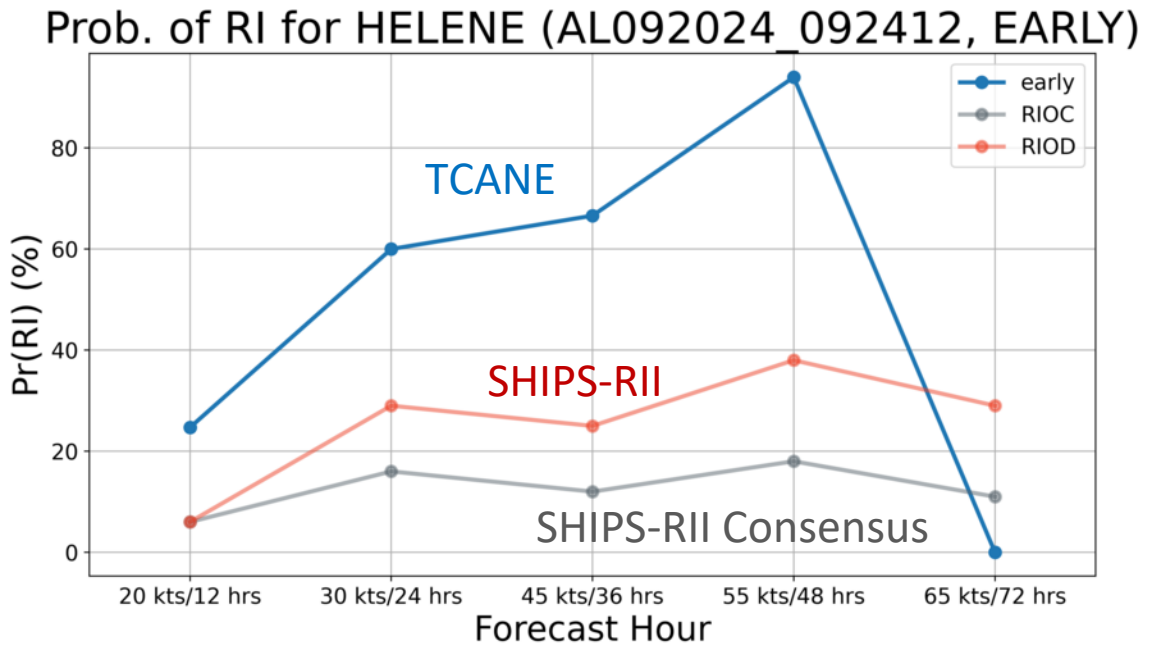


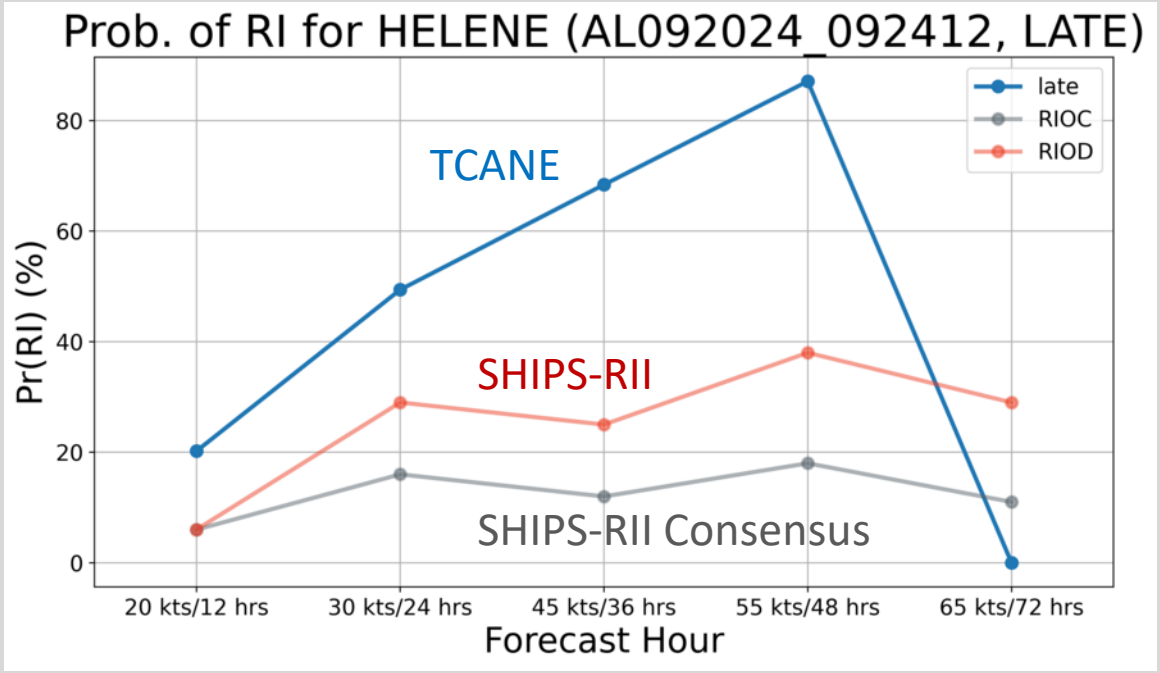
TCANE Probabilities of Hurricane Categories
Hurricane Helene 24 Sept 2024 12 UTC





TCANE Probability of Rapid Intensification Hurricane Helene 24 Sept 2024 12 UTC





TCANE Real-Time Website

- Python programs for model training (2013-2023 cases)
- Fortran and shell scripts for real-time TCANE runs for 2024 cases
- Python programs for graphical products
- 2024 version ready late in the season
  - No real-time ECMWF forecasts, so cases run after NHC provides post-storm a-decks
- Full season being back-filled on CIRA development TC real-time page for evaluation
- Real-time tests in 2025

Regional and Mesoscale Meteorology Branch

Home | Real-Time Data | Research Projects | Training/Outreach | Resources

TC Realtime

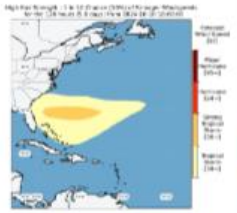
AL142024 - Major Hurricane MILTON

Storm Synopsis | Satellite | Model Data | **Wind Hazards** | Experimental

- Current Active Cyclones
- Archive
  - 2025 Season
  - 2024 Season
  - 2023 Season
  - 2022 Season
  - 2021 Season
  - 2020 Season
  - 2019 Season
  - 2018 Season
  - 2017 Season
  - 2016 Season
  - 2015 Season
  - 2014 Season
  - 2013 Season
  - 2012 Season
  - 2011 Season
  - 2010 Season
  - 2009 Season
  - 2008 Season
  - 2007 Season
  - 2006 Season
- Additional Information
- Additional Links

Wind Exceedance Guidance

Experimental WTCM-based Wind Exceedance 10th percentile



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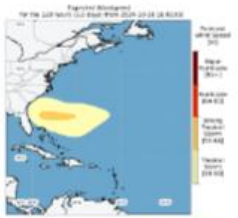
Experimental WTCM-based Wind Exceedance 50th percentile



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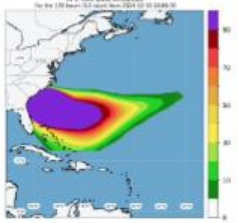
Experimental 34-kt Wind Speed Probabilities

Experimental WTCM-based 34-kt WSP



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Machine-Learning Forecast Uncertainty Estimates

Consensus model track error distribution

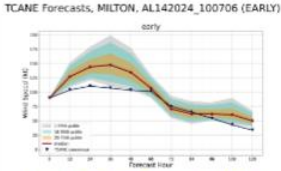
Loop | Latest Image | Archive | About
Time of This Image: 2024-10-07 06:00

NHC official forecast track error distribution

Loop | Latest Image | Archive | About
Time of This Image: 2024-10-07 06:00

Consensus model intensity error distribution

TCANE Forecasts, MILTON, AL142024_100706 (EARLY)



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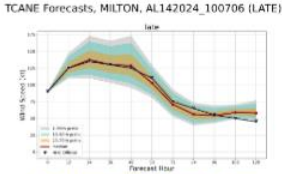
NHC official forecast intensity error distributions

TCANE Forecasts, MILTON, AL142024_100706 (LATE)



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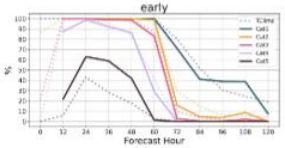
Consensus model probability of a category 1-5 hurricane

MILTON, AL142024_100706 (EARLY)



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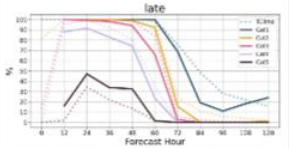
Probability of a category 1-5 hurricane from NHC forecast error distribution

MILTON, AL142024_100706 (LATE)



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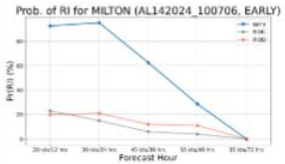
Time of This Image: 2024-10-07 06:00

Probability of rapid intensification from consensus model error distribution

Prob. of RI for MILTON (AL142024_100706, EARLY)



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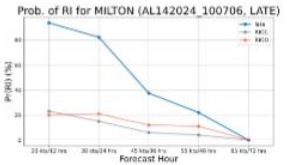
Time of This Image: 2024-10-07 06:00

Probability of rapid intensification from NHC forecast error distribution

Prob. of RI for MILTON (AL142024_100706, LATE)



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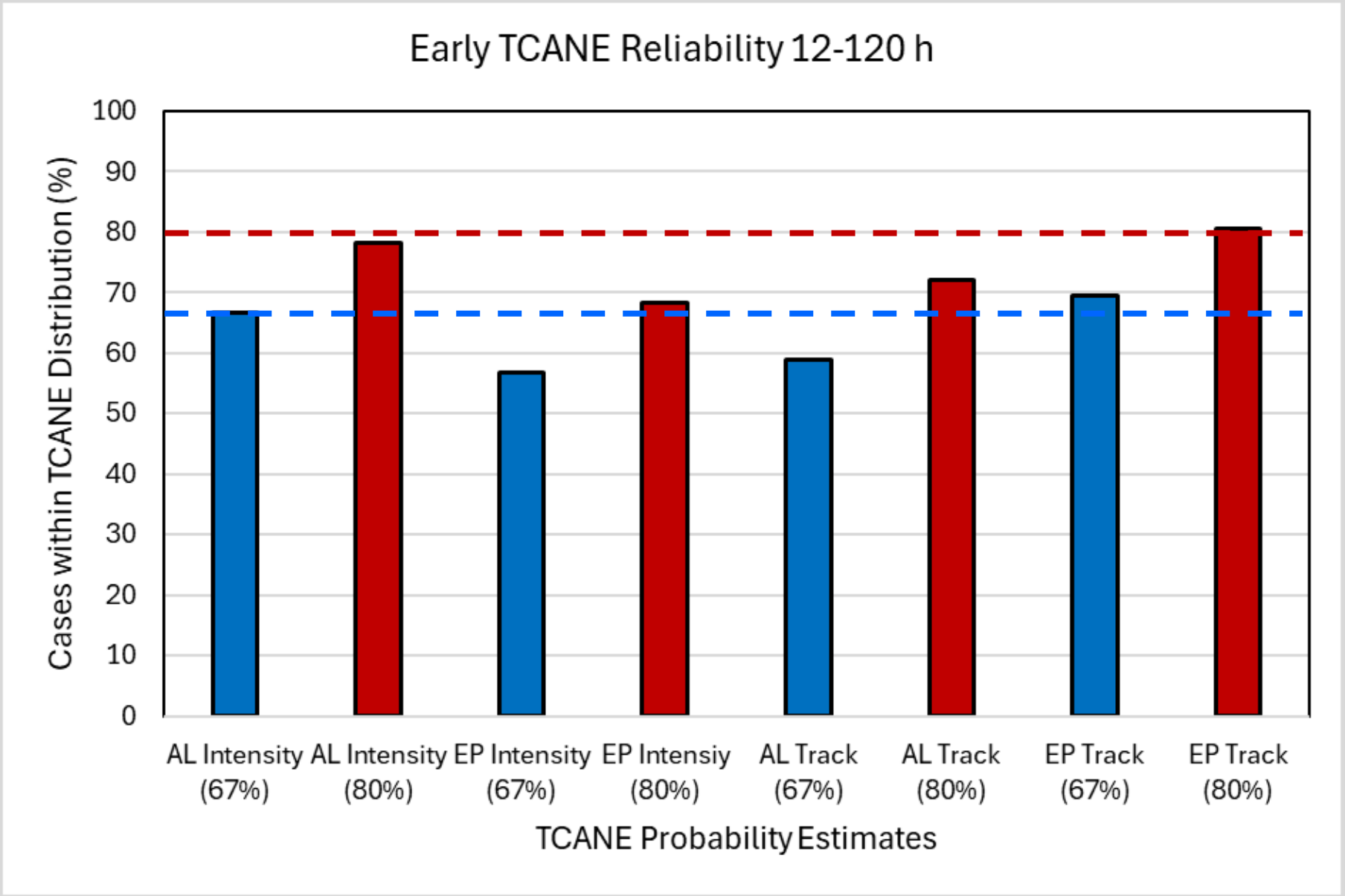
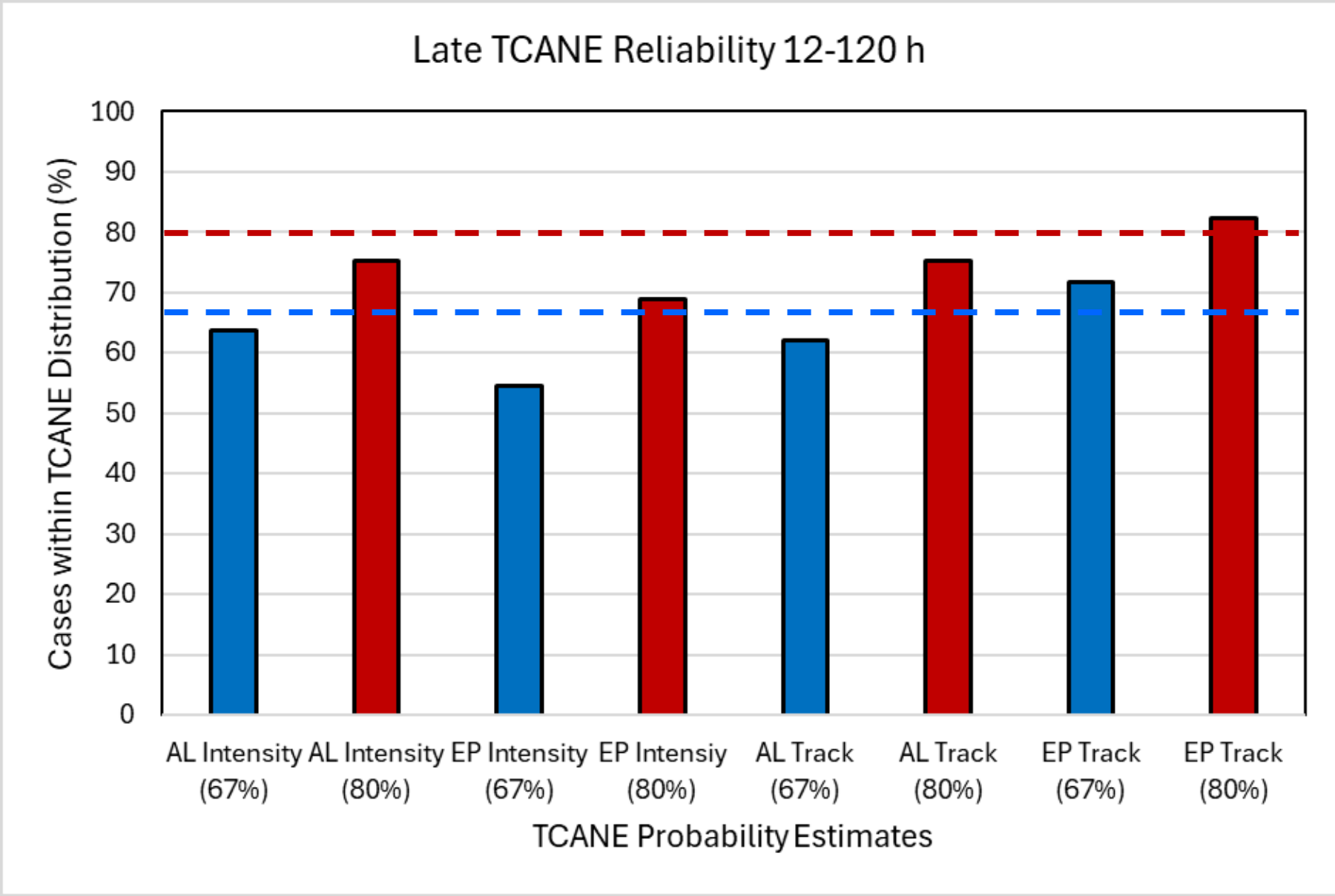
Time of This Image: 2024-10-07 06:00

2024 TCANE Verification

- TCANE trained on 2013-2023 data
- Verification of 2024 near-real time AL and EP/CP cases through 11/7/2024
- Verification measures
  1. Reliability – How often did the consensus (early) or NHC forecast (late) fall within estimated error bounds?
  2. Error-spread relationships – Is the TCANE predicted error spread a measure of the observed error spread?
- Early and Late runs evaluated separately



For perfect reliability, blue (red) bars would reach the 67th (80th) percentile dashed lines

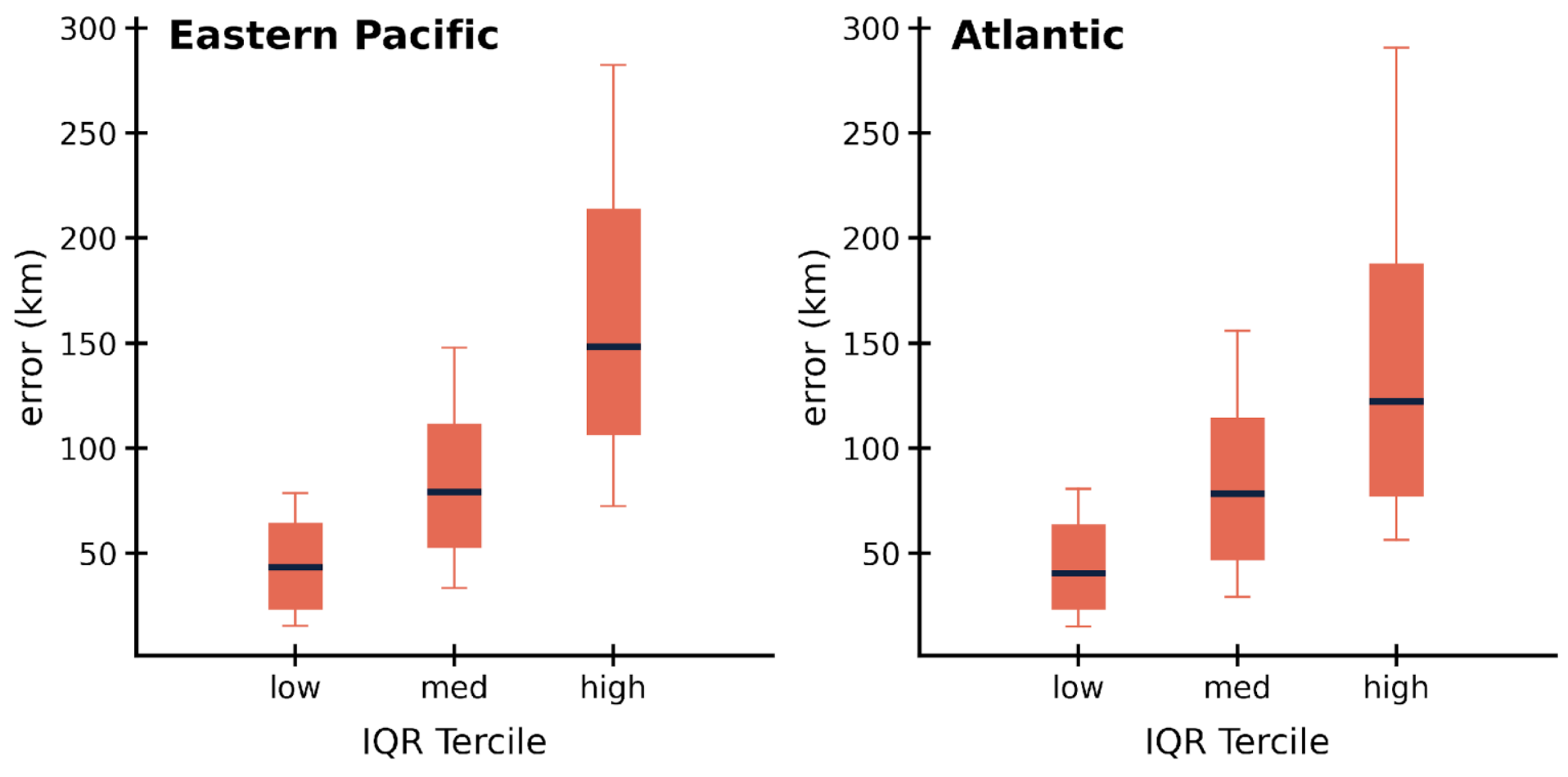


For perfect reliability, blue (red) bars would reach the 67th (80th) percentile dashed lines

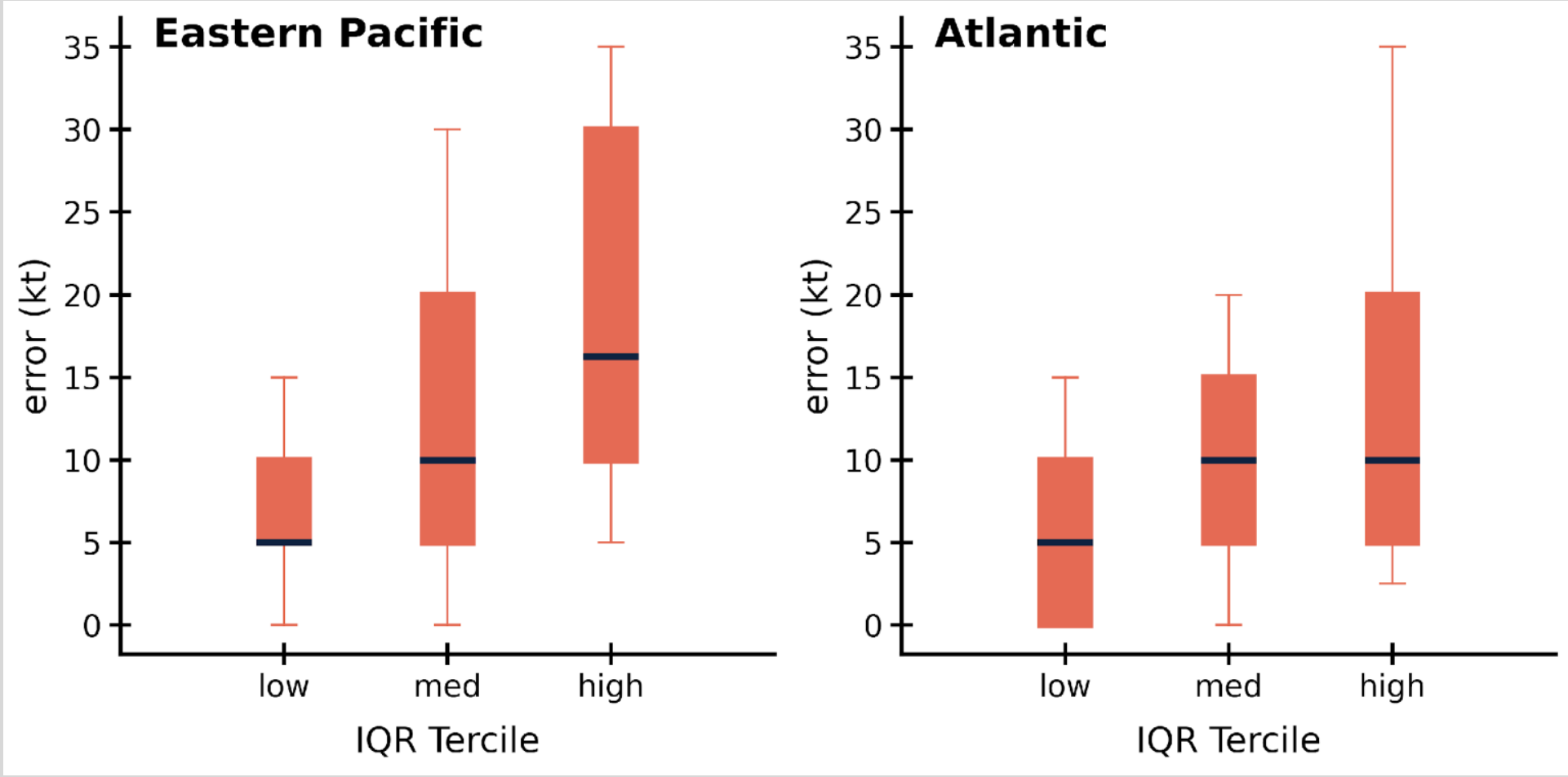
Error-Spread Relationships

- Are the NHC error distributions wider when TCANE predicts wider distributions?
- Stratify the post-storm NHC intensity/Track errors by the TCANE Inter-Quartile Range (IQR)
  - Intensity - 75th percentile-25th percentile
  - Track – Average of the IQR along the major and minor ellipse axes
- Make box-whiskers plots for NHC errors for each IQR group
  - Individual forecast times and summed over all forecast times

Track Error-Spread Summary Statistics 12-120 h Combined



Intensity Error-Spread Summary Statistics 12-120 h Combined



Summary and Next Steps

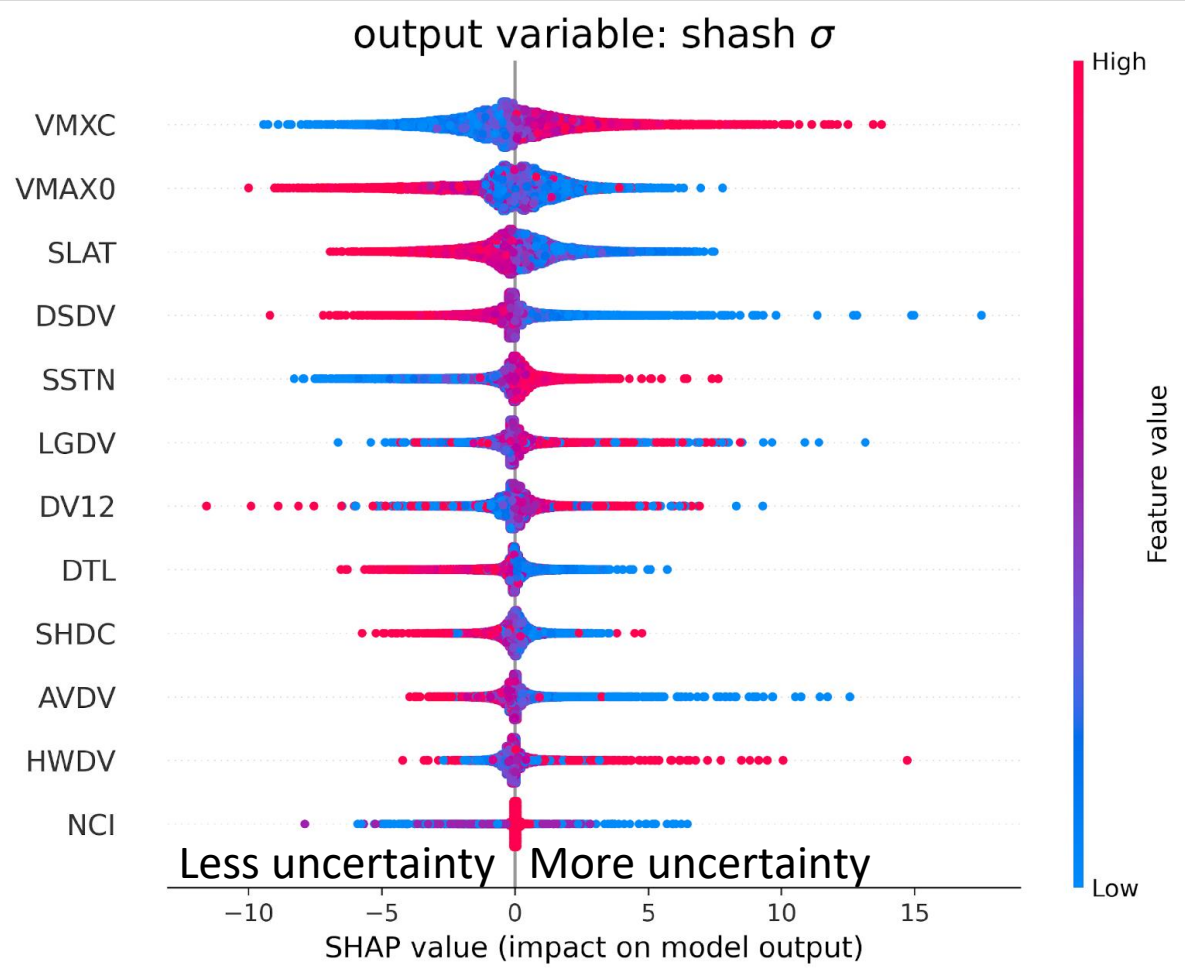
- Summary
  - TCANE estimates consensus and NHC official track and intensity forecast uncertainty
    - Input from multi-model ensembles and TC environment parameters
  - 2024 independent tests showed mostly good reliability (slightly under-dispersive) and strong error-spread relationships for track and intensity in AL and EP
  - Track/intensity uncertainty graphical products for 2024 cases available on CIRA developmental TC-Realtime website
- Next Steps (Year 3)
  - TCANE v2.0
    - Include HAFS model and GFS ensemble track forecast spread as TCANE inputs
    - Develop version for western North Pacific (WP)
    - Real-time products on TC-Realtime
    - Add explainable AI graphics to TC-Realtime webpage
  - Quick guides for TCANE products
  - Coordinate with HOT facilitator to test TCANE training on NHC infrastructure
  - Test impact of TCANE error distributions on NHC wind speed probability model

Back-up Slides

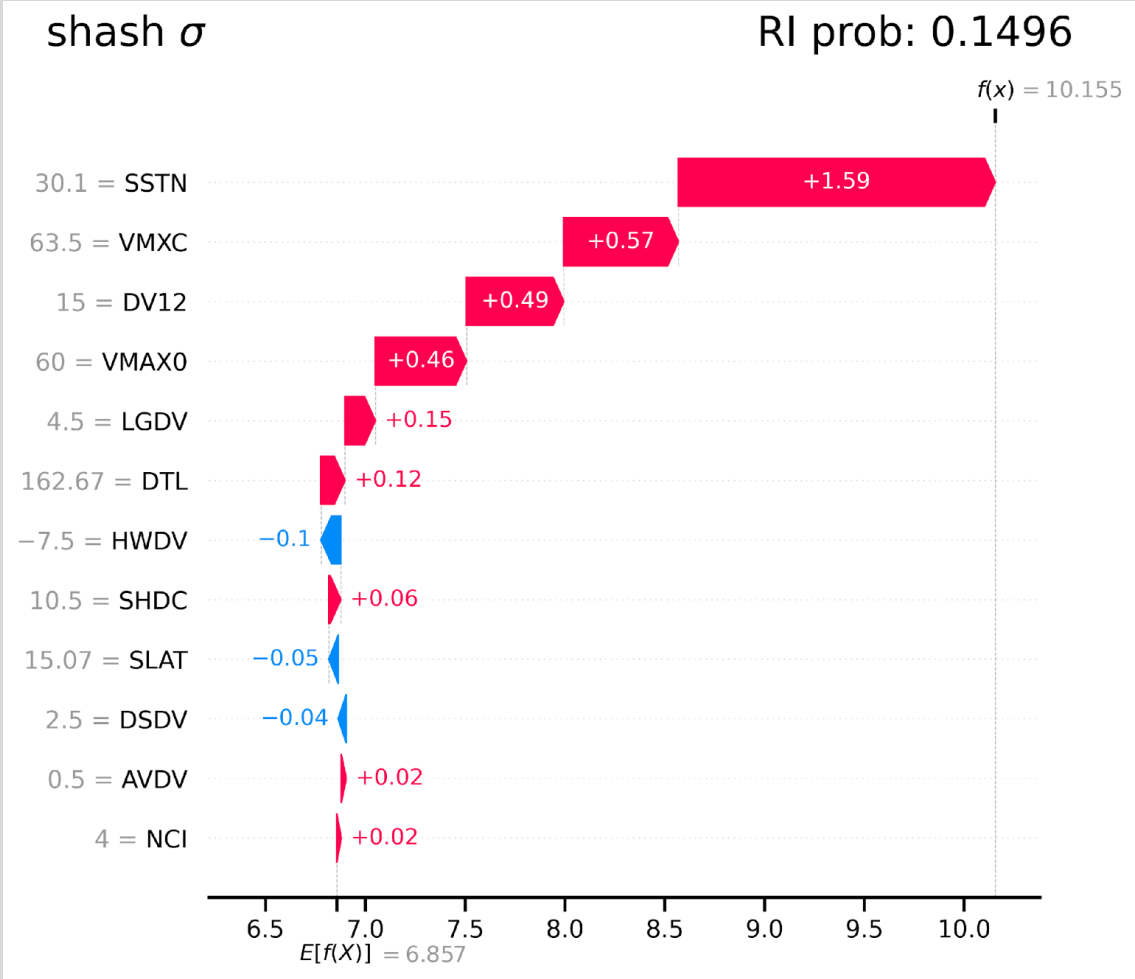
Explainable AI Methods –Shapley Values

- Explainable AI – Post-processing methods to provide insight into why a ML model made the forecast it did
- Shapley values – based on game theory to estimate the contributions from various "players" in a game
  - Takes into account interactions of predictors
  - Computationally expense, scales by 2^N
  - Feasible for TCANE due to low dimension of neural network input vector
- Shapley Additive Global Importance (SAGE)
  - Importance of input parameters for the entire model
- SHapley Additive Explanations (SHAP)
  - Importance of input parameters for a single forecast
  - "Waterfall" plots

SAGE and SHAP Examples

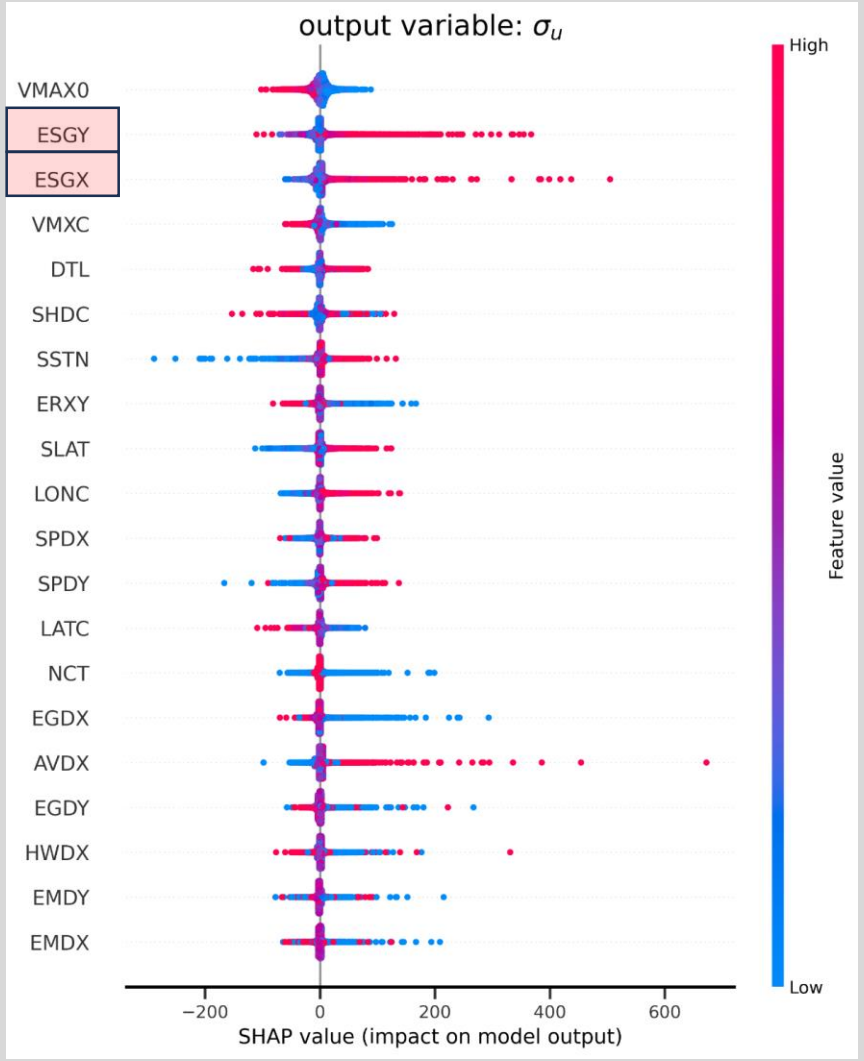


SAGE Plot for Intensity Spread σ
Atlantic TCANE – All Forecast Times

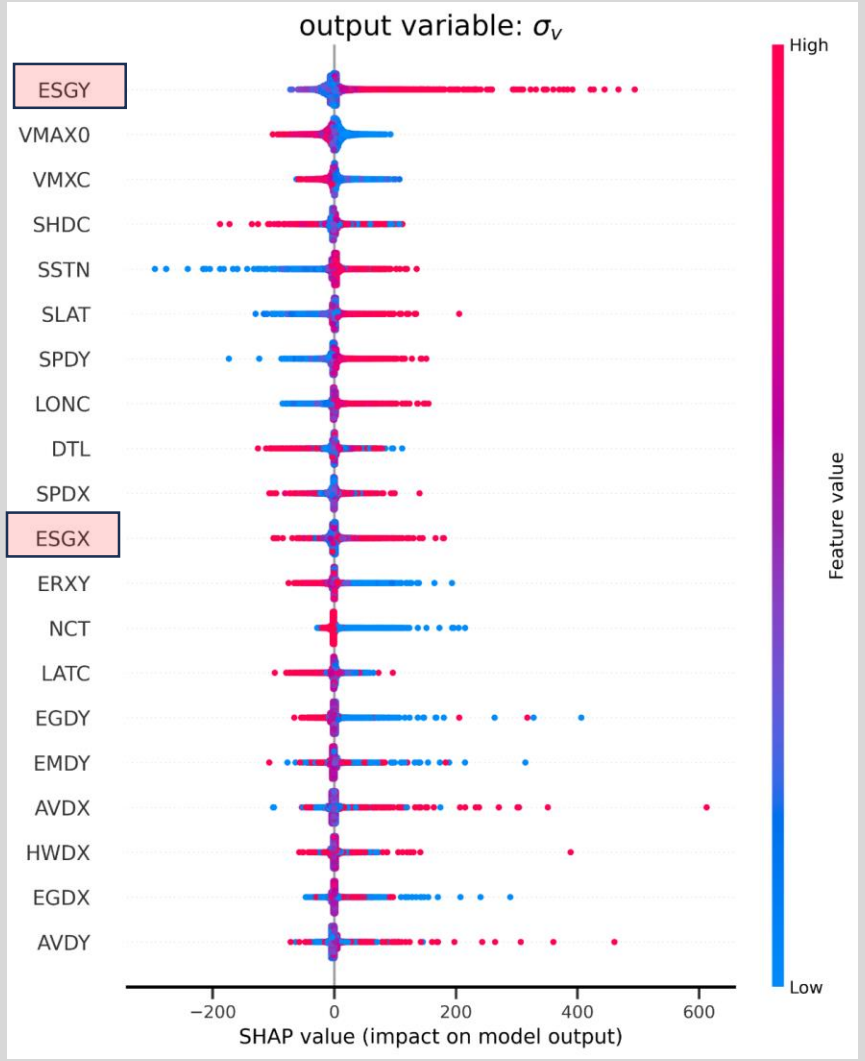


SHAP "Waterfall" Plot for Intensity Spread σ
12 h forecast Hurricane Otis 25 Oct 2023 00 UTC
(Just before RI period)

SAGE Plots for Atlantic track TCANE with GEFS Ensemble Spread Predictors



E-W Track Forecast Uncertainty



N-S Track Forecast Uncertainty