Case Studies Demonstrating the Potential Benefits of the NOAA Next-Generation Enterprise Ocean Heat Content Algorithm for Tropical Cyclone Intensification Forecasting in the Gulf of Mexico and Caribbean Sea

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Contact: paige.lavin@noaa.gov
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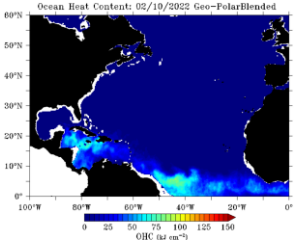
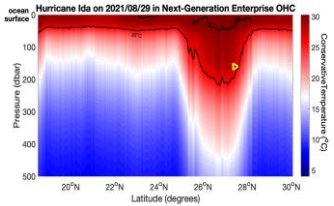
Project Overview

Motivation: Improve tropical cyclone prediction at NOAA
— Particularly rapid intensification and weakening

Objective: Improved estimates of upper Ocean Heat Content (OHC) and structure

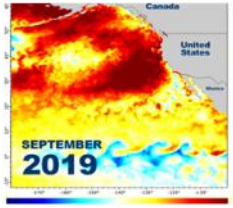


Method: Use a variety of modern techniques including the Geostrophic Empirical Mode (GEM) and AI/ML methods to generate temperature & salinity profiles (and thereby OHC)

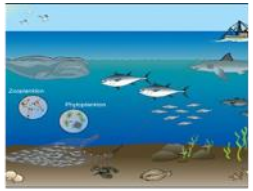


Many applications for Ocean Heat Content across forecasting, monitoring, and planning domains

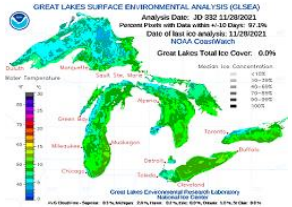
HURRICANE INTENSITY



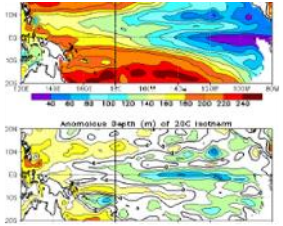
MARINE HEATWAVES



ECOSYSTEM MANAGEMENT (EBFM)



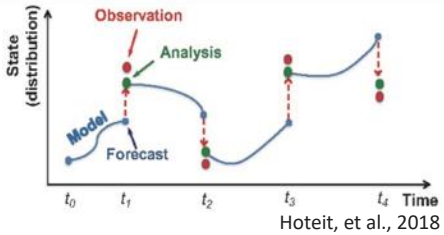
ICE EXTENT FORECASTING



METRICS (A SUBSTITUTE FOR REANALYSES)

PLANNING RESILIENT COASTAL INFRASTRUCTURE

INFORMING RISK ESTIMATES



Hoteit, et al., 2018

DATA ASSIMILATION

"Data Assimilation" image from Hoteit, et al., 2018: Data assimilation in oceanography: Current status and new directions. In "New Frontiers in Operation Oceanography", doi:10.17125/gov2018.ch17.

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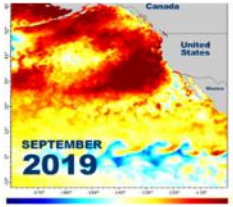

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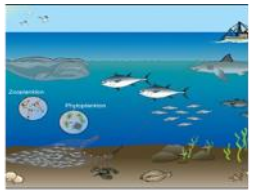

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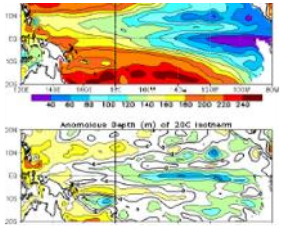

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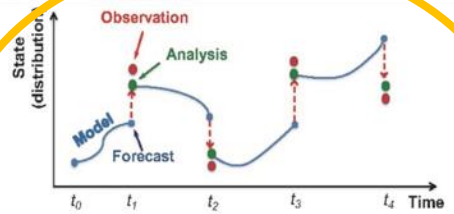

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Roadmap

- NOAA Next-Generation Enterprise Ocean Heat Content (**NGE OHC**) vs. Current NESDIS OHC
- Nuts and bolts of NGE OHC algorithm
- Evaluation of algorithm skill in Gulf of Mexico and NW Caribbean (both in general and in hurricane season)
- Comparison of NGE OHC/Argo/HAFS ocean conditions during 5 hurricanes of interest (from 2020–2022)
- Future directions

What is the **Next Generation Enterprise Ocean Heat Content** (NGE OHC) Product?

A statistically robust, observationally-based estimate of ocean thermohaline conditions (T(z), S(z)), with a focus on high accuracy in the upper ocean.

- **Daily**, 1/4°-gridded and ~10 km along satellite track
- 2 dbar vertical resolution to ~1800 m
- Gulf of Mexico/NW Caribbean testbed product
- North Atlantic pre-operational product
- Adaptable to more extreme ocean conditions, e.g., climate change

Current NESDIS operational product:

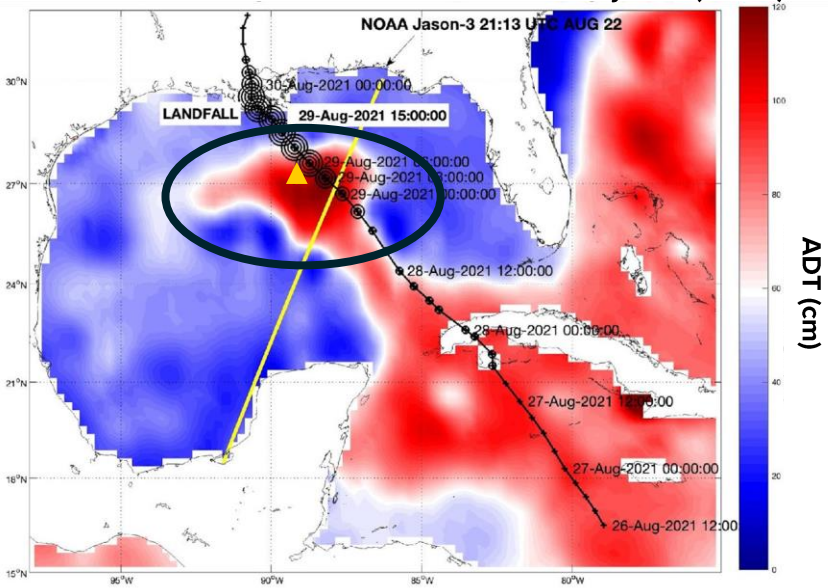
- ***Daily**, 1/4°-gridded (no along satellite track), providing three depths [20°C, 26°C isotherms (Z20, Z26), and simplistic mixed layer depth (MLD)]*
- *Climatologically based*

How does the NGE OHC perform against *in situ* observations and the current NESDIS operational OHC?

Case Study: Hurricane Ida

- 08/29/21: **Rapidly intensified** from category 2 to 4 in only 6 hours over Gulf of Mexico before U.S. landfall that day (slightly underpredicted by HAFS)
- RI is coincident with a warm core anticyclonic eddy in Loop Current
- Jason-3 passed over RI region a few days earlier, allowing us to estimate OHC along that satellite track
- Nearby Argo float profile

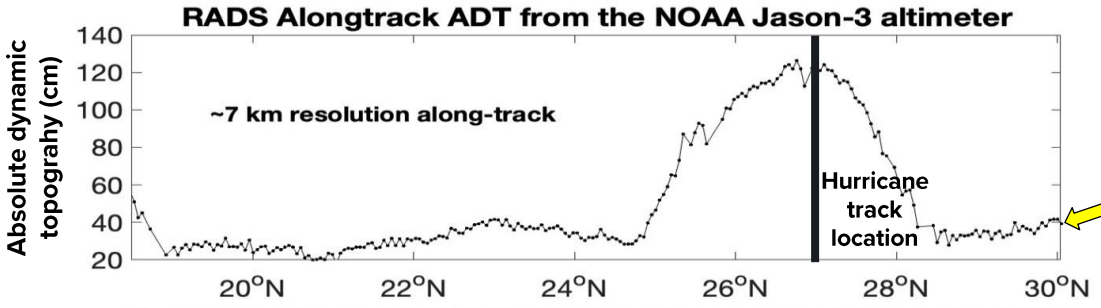
Near real-time absolute dynamic topography (ADT) from the NOAA/EUMETSAT Radar Altimeter Database System (RADS)

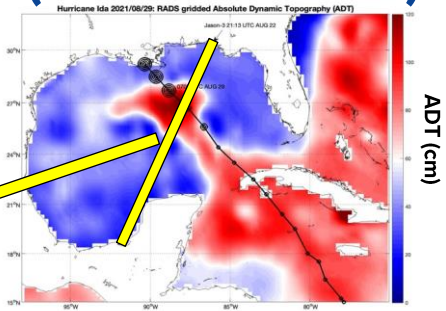


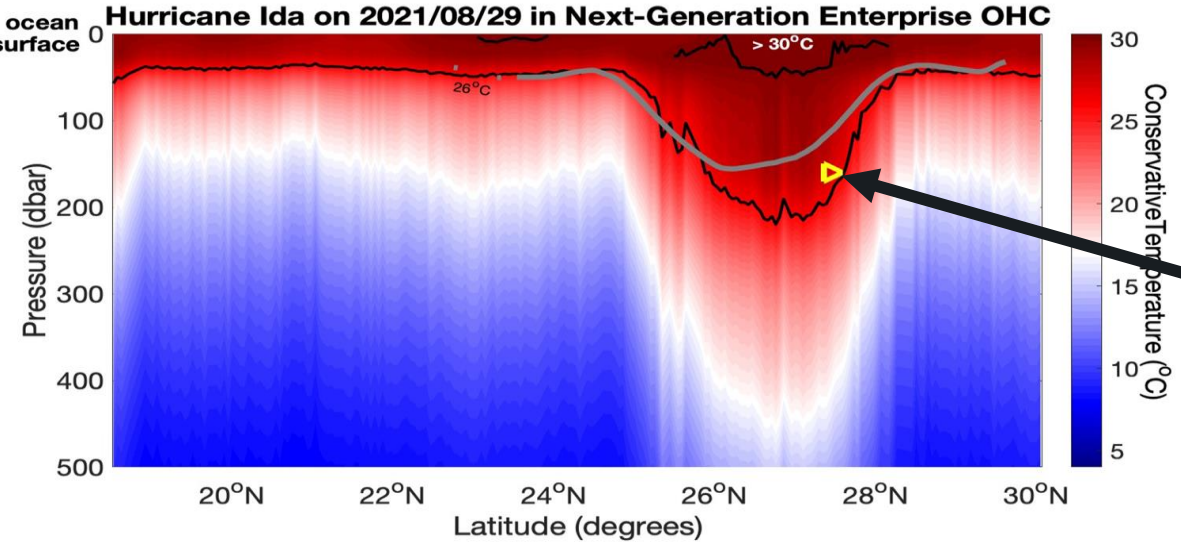
ADT = MDT* + SSH_{anom}

(*mean dynamic topography)

NGE OHC vs. Current operational NESDIS OHC (*Hurricane Ida*)



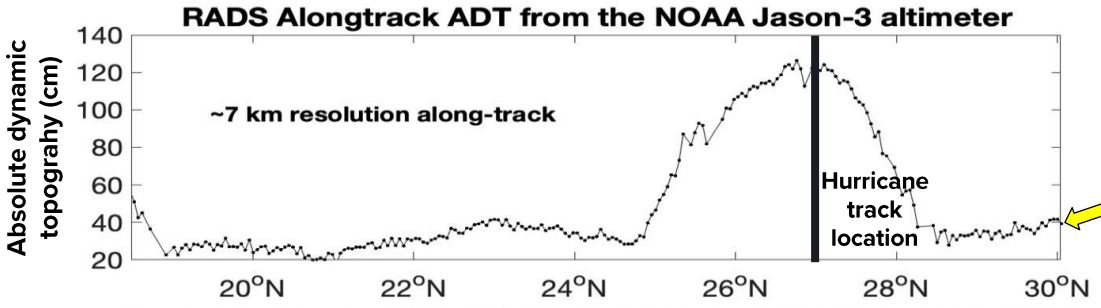


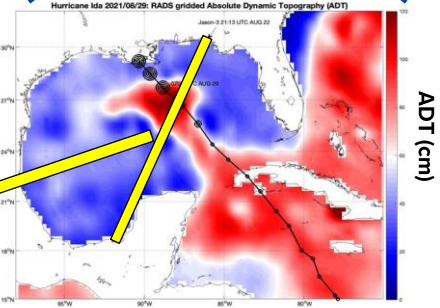


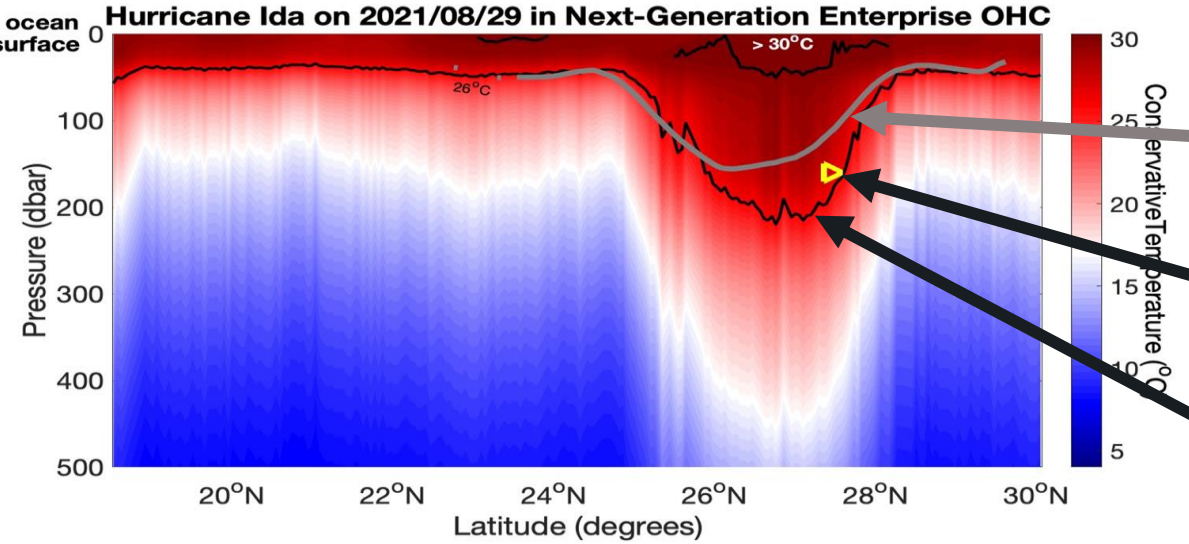
Z26 = Depth of 26°C isotherm

Argo float Z26 measurement (~160 m)

NGE OHC vs. Current operational NESDIS OHC (*Hurricane Ida*)







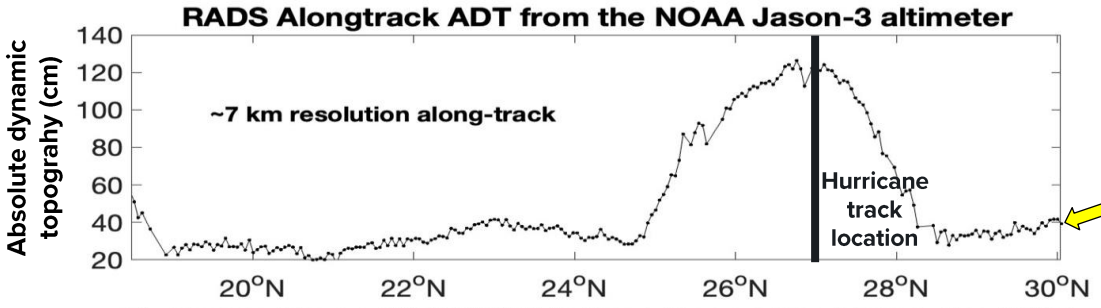
Z26 = Depth of 26°C isotherm

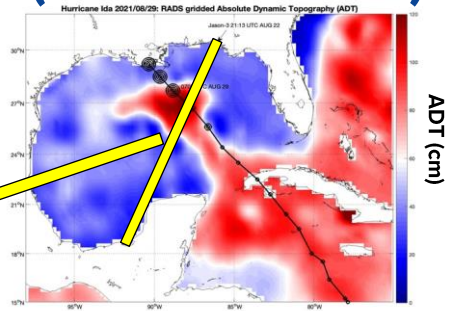
Current operational product Z26 (only contains Z20, Z26, MLD)

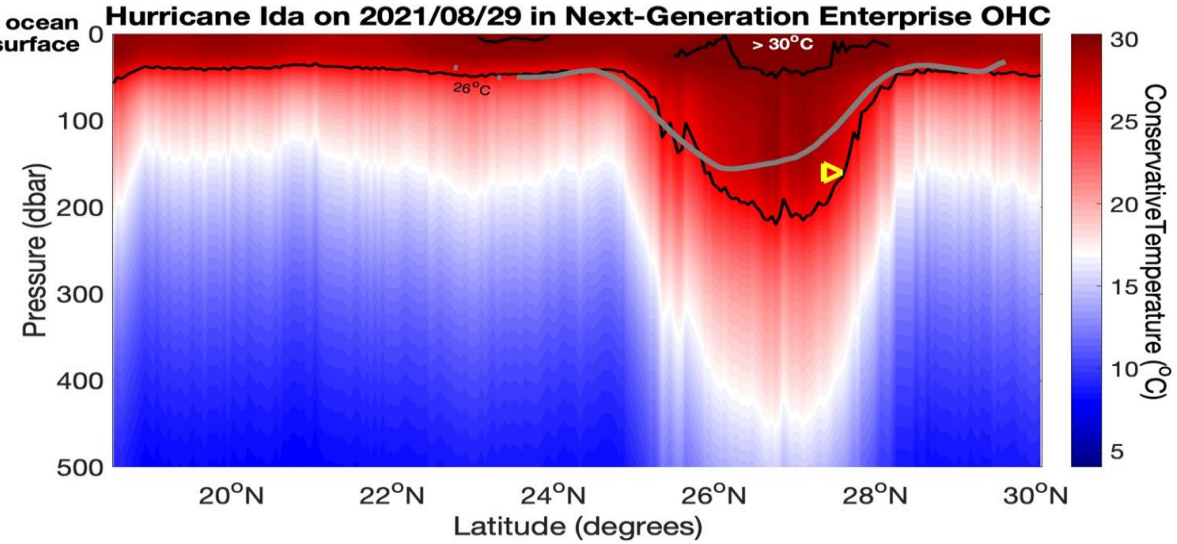
Argo float Z26 measurement

NGE OHC Z26 (derived from the 2 dbar field)

NGE OHC vs. Current operational NESDIS OHC (*Hurricane Ida*)

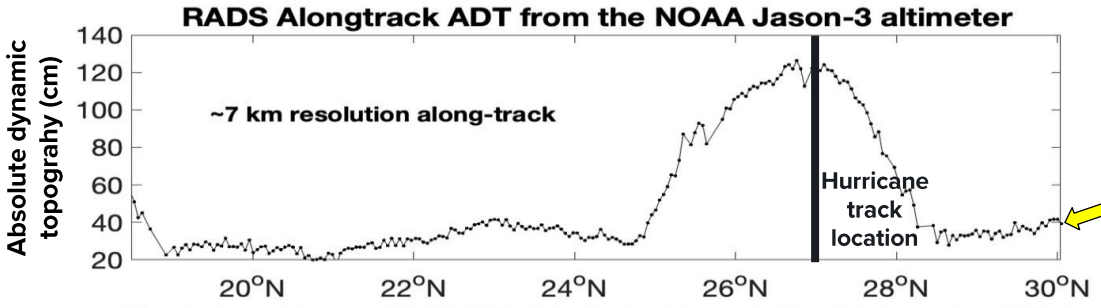


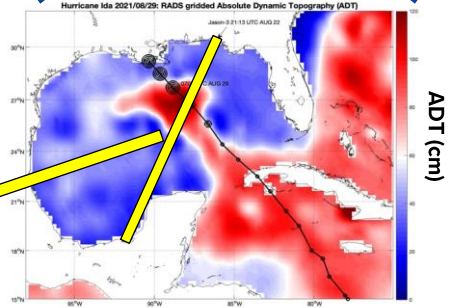


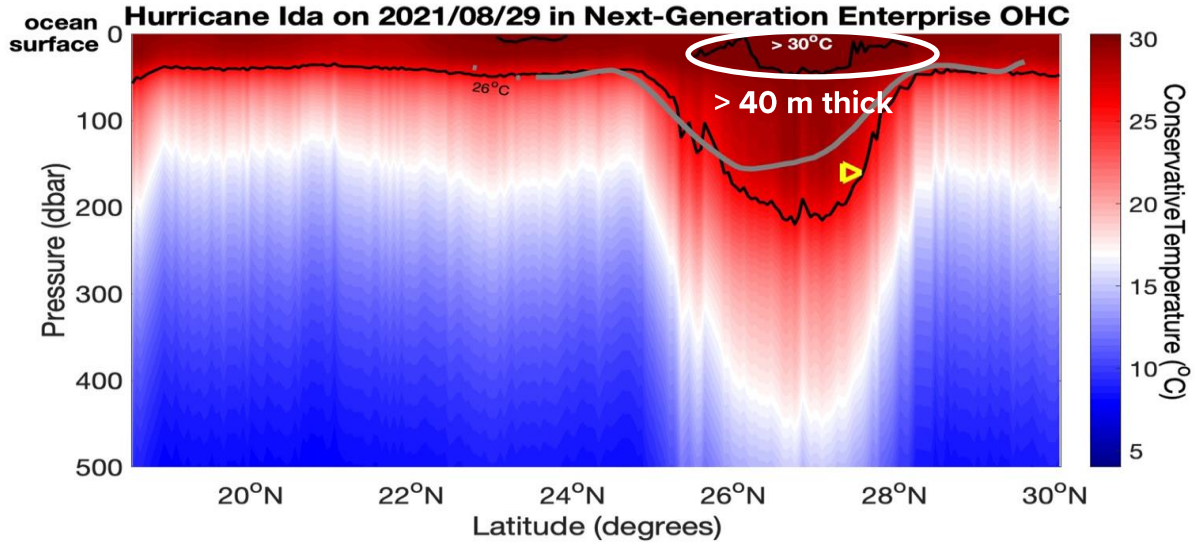


- NE corner of eddy (near hurricane track): **Maximum difference between operational and NGE OHC Z26 is ~80 m**.
- **Z26: NGE OHC better matches Argo** (~3 m error) **than operational OHC** (~32 m shallower). This is an order of magnitude reduction in error.

NGE OHC vs. Current operational NESDIS OHC (*Hurricane Ida*)







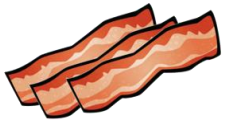
- **Extremely warm pool** (>30°C) **seen in NGE OHC and Argo profile** but not operational OHC.
- **NGE OHC is adaptable to a warming ocean** (good skill even with ADT value outside historically observed range).

How does the NGE OHC work?

Uses the *BLT method!*

Byrne
Lavin
Trossman

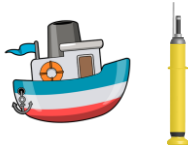
How does the NGE OHC work?



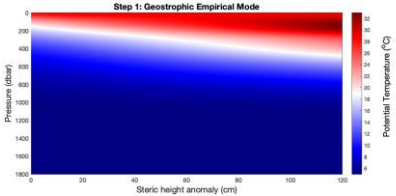
= Geostrophic Empirical Mode (GEM) method to derive look-up tables of SSH vs. T(z), S(z)

Byrne Lavin Trossman

Database of *in situ* ocean profiles

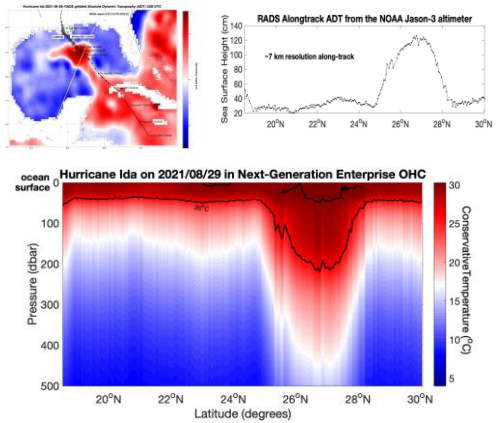


1) Calculate steric height anomaly (SHA) for each profile
2) Use GEM to generate look-up table (SHA vs. T(z), S(z))



Coincident altimeter data (absolute dynamic topography) from RADS

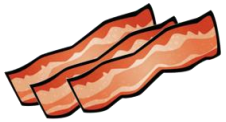
Calculate (typically linear) fit between the satellite-measured ADT and *in situ* steric height anomaly:
m*ADT + b = SHA



Result = Lookup table where every satellite-measured ADT value in the region has a corresponding T(z) and S(z) profile

How does the NGE OHC work?

Byrne
Lavin
Trossman



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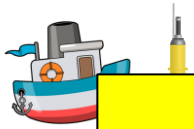
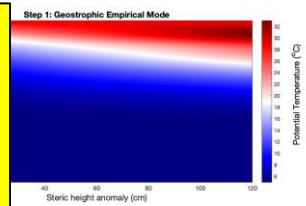


1) Calculate steric height anomaly (SHA) for each profile
2) Use GEM to generate look-up table (SHA vs. T(z), S(z))

+ ML/AI to:
1) QC data
2) Sort profiles into dynamical regimes before GEM



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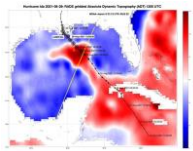

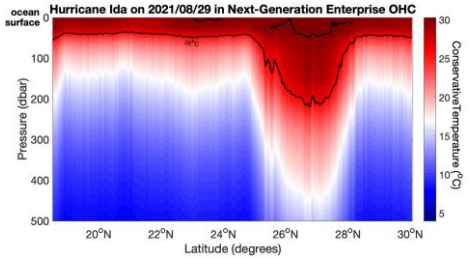

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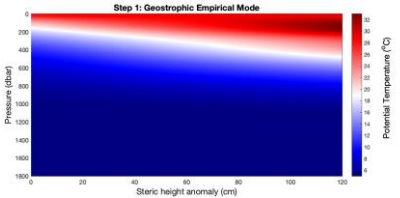
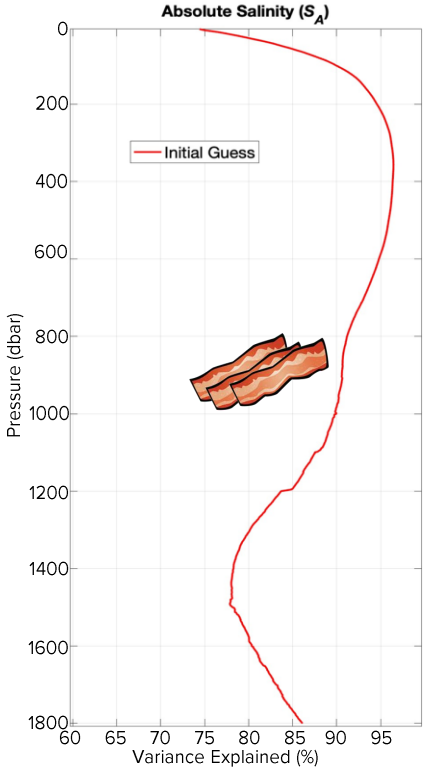
How does the NGE OHC work?

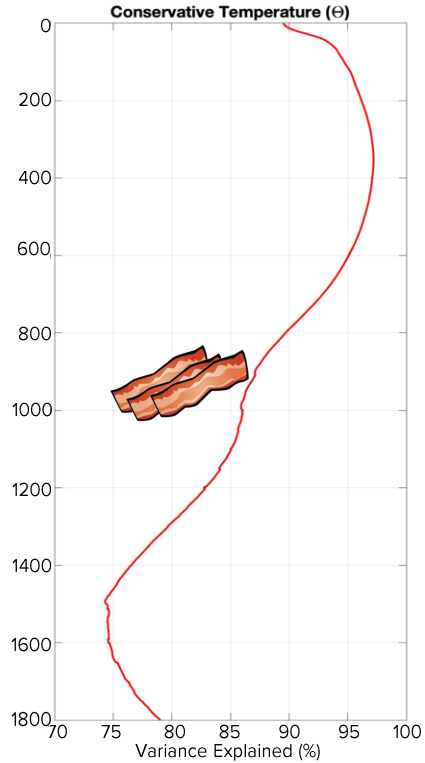
Uses the *BLT method*

(Results shown for N Atlantic pre-operational product)



GEM alone does not capture full temperature and salinity variability, particularly in the mixed layer





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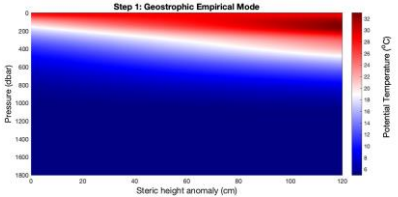


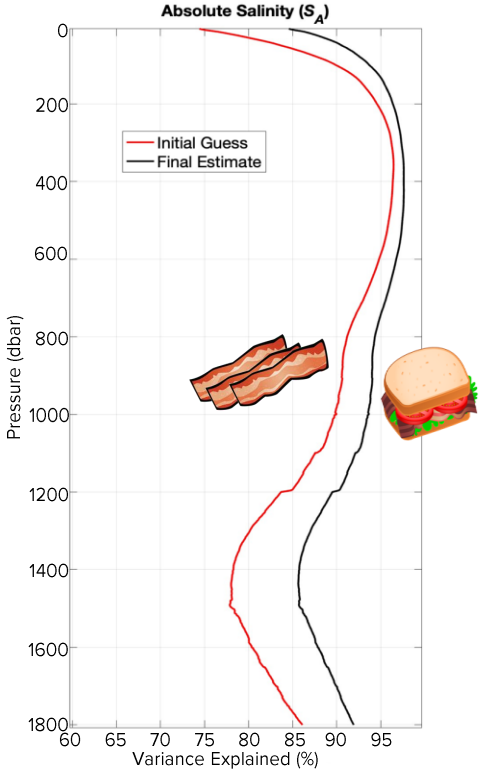
GEM alone does not capture full temperature and salinity variability, particularly in the mixed layer

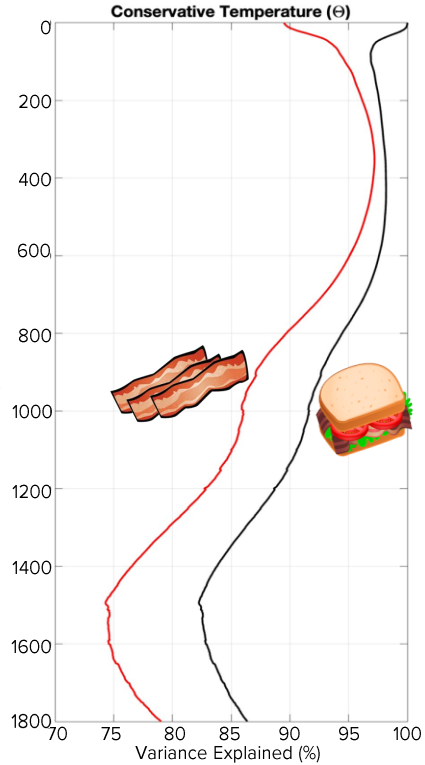
Fit residuals!

(our easy to swap toppings)

Current toppings:
Latitude, yearday, & SST*

*Using NOAA's 5 km GeoPolar blended SST





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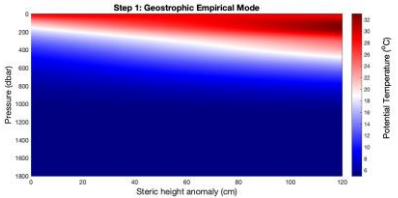

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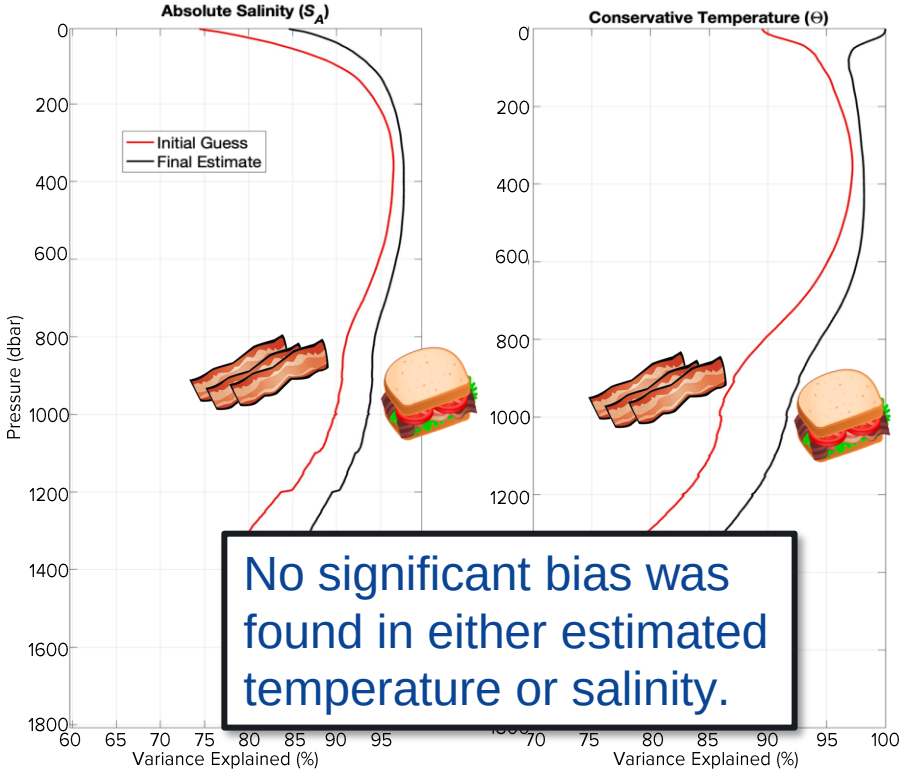
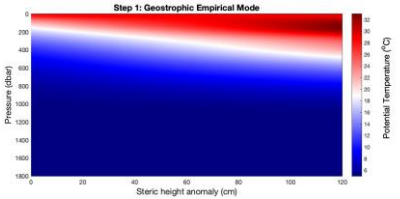


No significant bias was found in either estimated temperature or salinity.

How does the NGE OHC work?

Uses the ~~BLT~~ *method*

(Results shown for N Atlantic pre-operational product)



Formally, we refer to this as the “Empirical Dynamic Topography (EDT)” method

GEM alone does not capture full temperature and salinity variability, particularly in the mixed layer

Fit residuals!

(our easy to swap toppings)

Current toppings:
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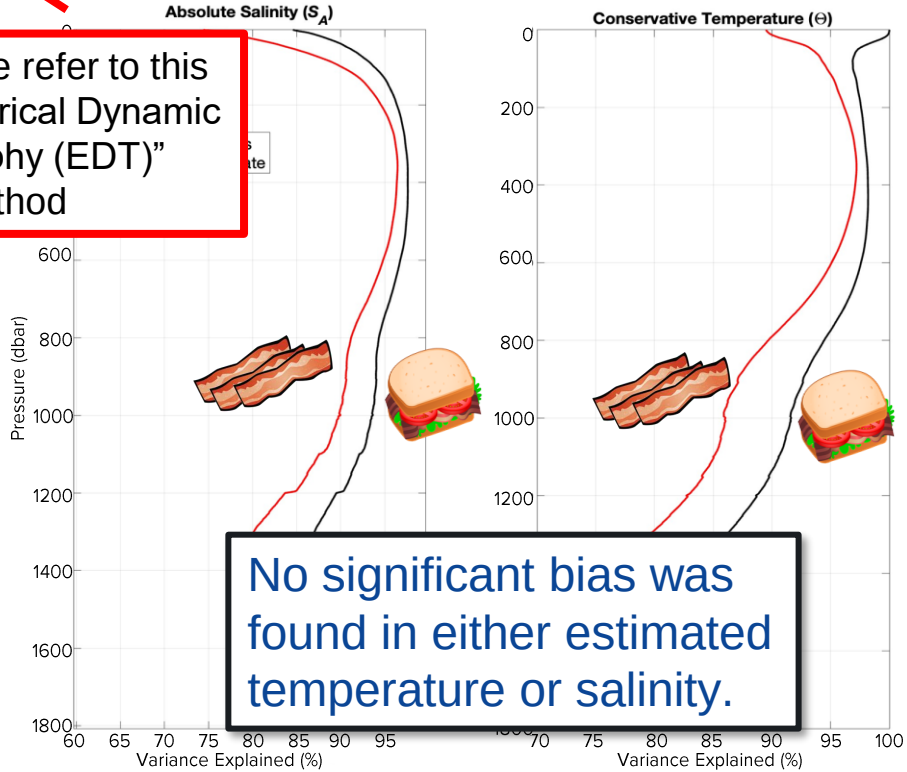

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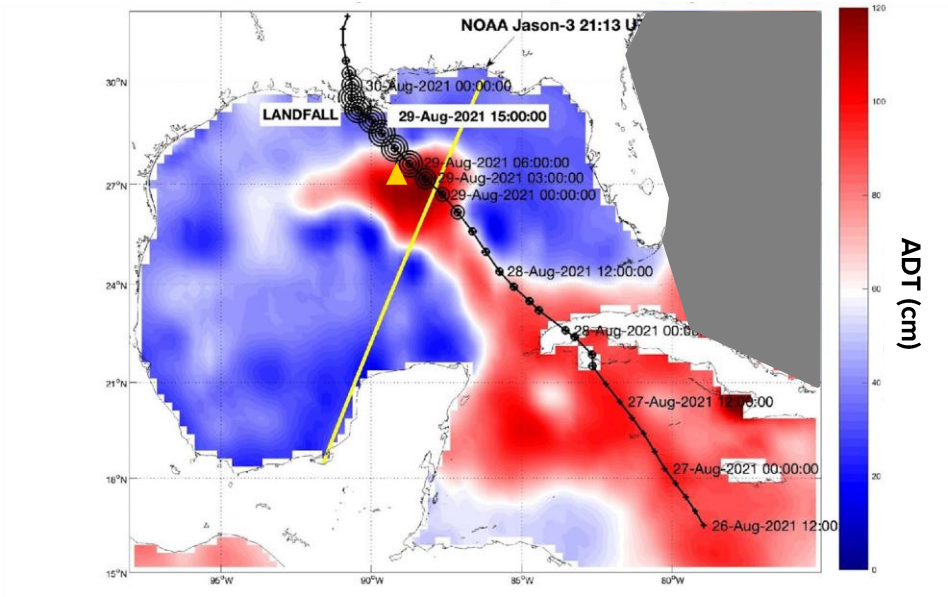
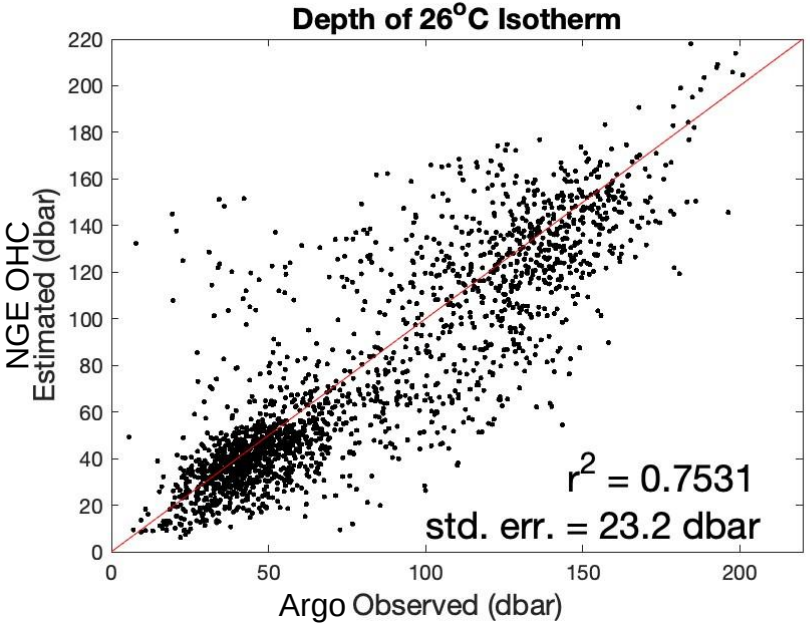
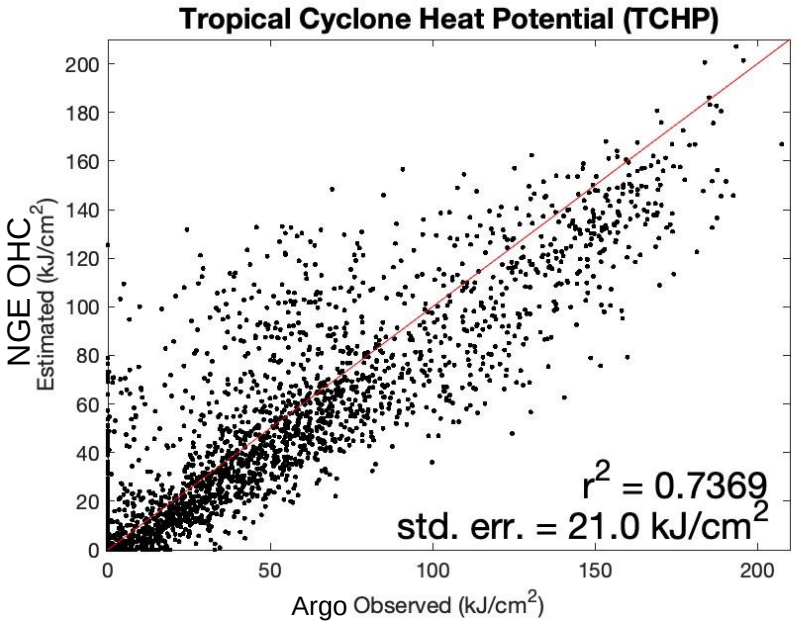
Evaluation of NGE OHC algorithm skill in Gulf of Mexico/Northwest Caribbean



Independent Argo Profile Assessment Indicates High Skill of NGE OHC in Representing Subsurface Parameters of Interest





- **3000 Argo profiles in Gulf of Mexico (2018–2023)**
- **Using EDT trained on ship & Argo CTDs (1985–2019)**

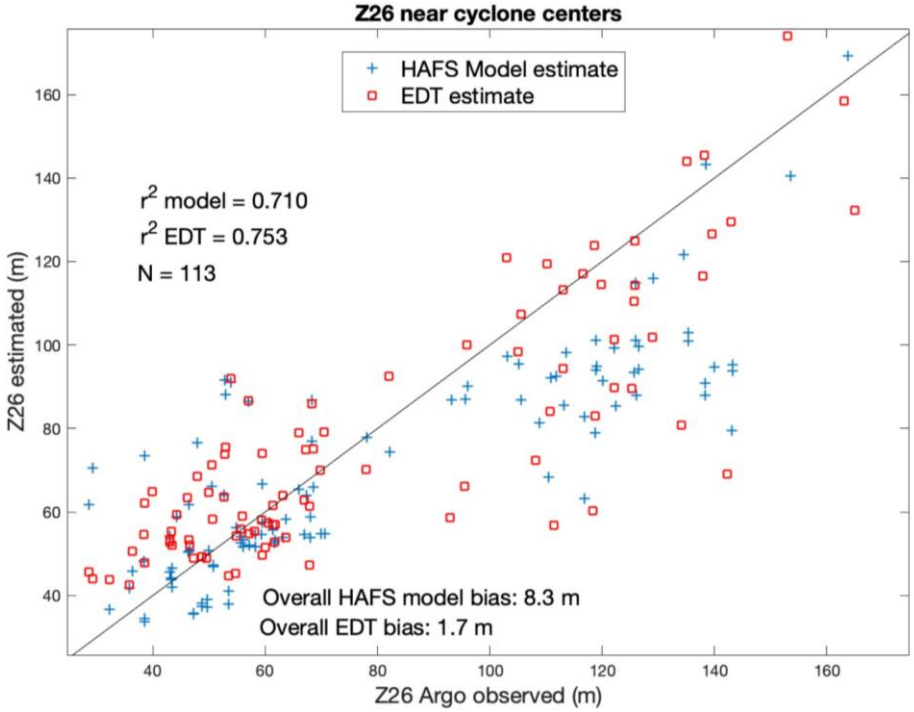
Case Studies: 7 storms of interest to assess NGE OHC skill

- All from 2020, 2021, and 2022 Atlantic hurricane seasons
- 7 storms = 11 (HAFS v1 B) forecasts
- All forecast where ocean seems to have played a role in affecting the model's intensity prediction skill
- 113 Argo profiles nearby (within 4 days of model initialization)

1) **Hanna (08l)**: 20200723Z12
2) **Hanna (08l)**: 20200724Z00
3) **Laura (13l)**: 20200821Z12
4) **Laura 13l)**: 20200822Z00
5) **Delta (26l)**: 20201005Z18
6) **Delta (26l)**: 20201006Z06
7) **Elsa (05l)**: 20210701Z00
8) **Elsa (05l)**: 20210706Z06
9) **Fred (06l)**: 20210814Z18
10) **Ida (09l)**: 20210827Z18
11) **Ian (09l)**: 20220927Z18

Argo floats near 7 storms of interest demonstrate NGE OHC skill in representing true ocean conditions*

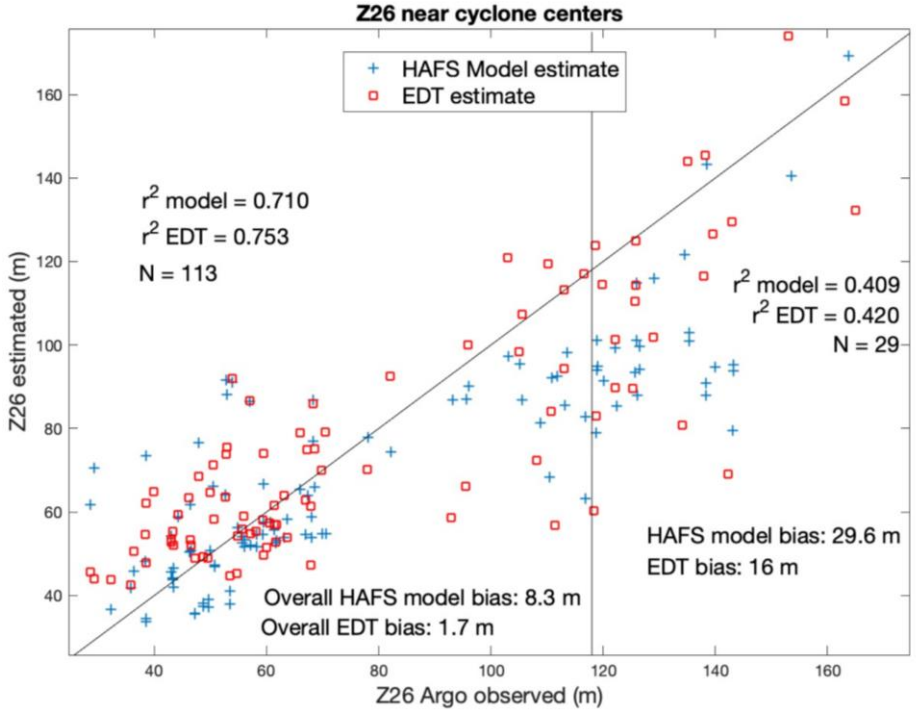
(*Near 26°C isotherm)



- EDT outperforms HAFS in correctly representing the 26°C isotherm depths for our 113 Argo profile locations of interest

Argo floats near 7 storms of interest demonstrate NGE OHC skill in representing true ocean conditions*

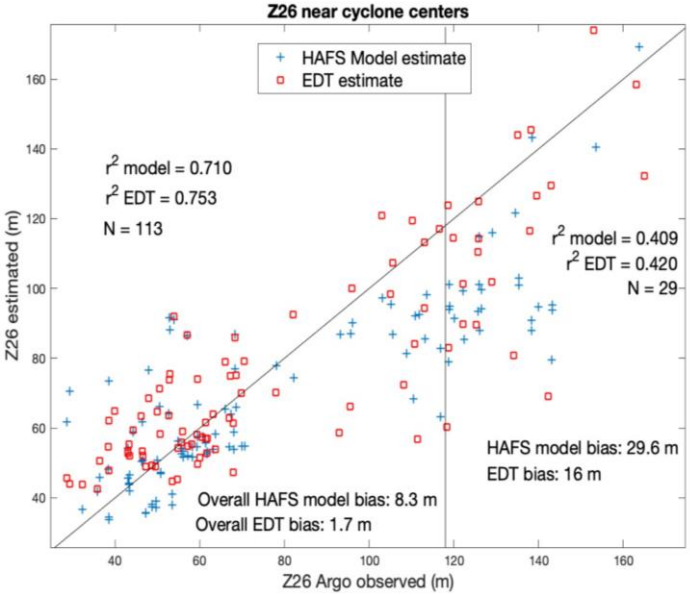
(*Near 26°C isotherm)



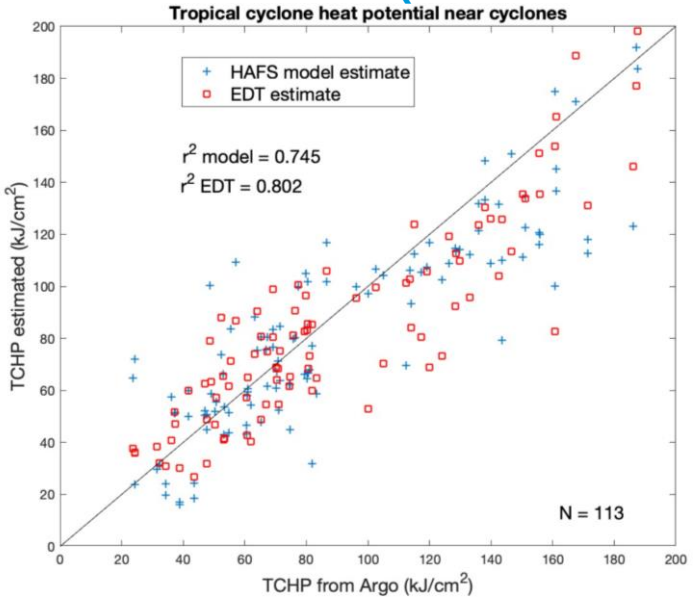
- Both EDT and HAFS perform worse when Z26 is deeper (i.e., larger reservoir of heat near surface) though EDT still outperforms HAFS (note bias values)
- Maybe thermostad >120 m causing the difficulties?

Argo floats near 7 storms of interest demonstrate NGE OHC skill in representing true ocean conditions*

(*Near 26°C isotherm)



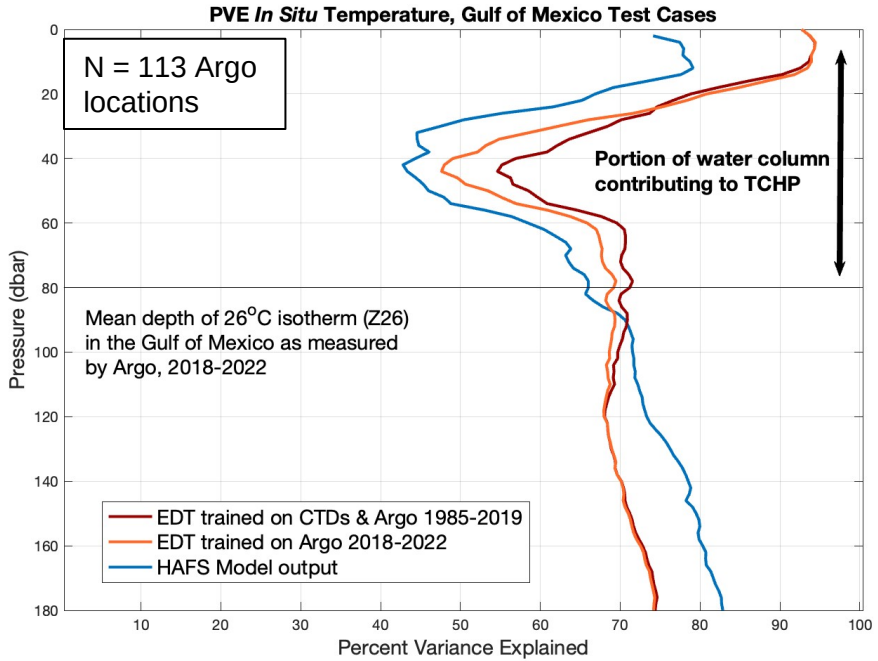
- EDT outperforms HAFS in the 26°C isotherm depths for our 113 Argo profile locations of interest



- EDT Tropical Cyclone Heat Potential (OHC > 26°C) also better matches Argo than HAFS

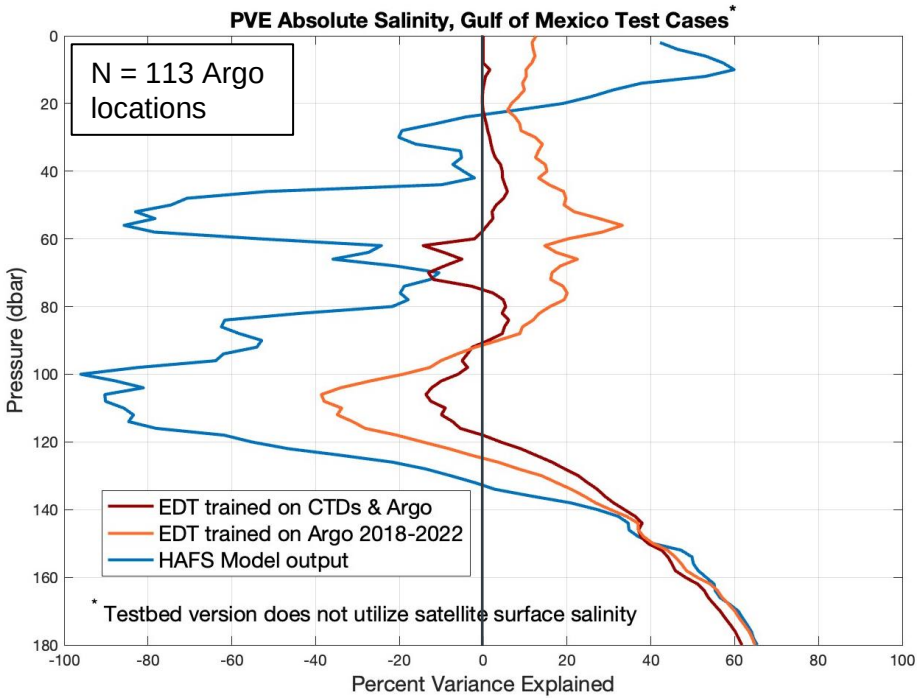
Argo floats near 7 storms of interest demonstrate NGE OHC skill in representing true ocean conditions*

(*In upper 180 meters)



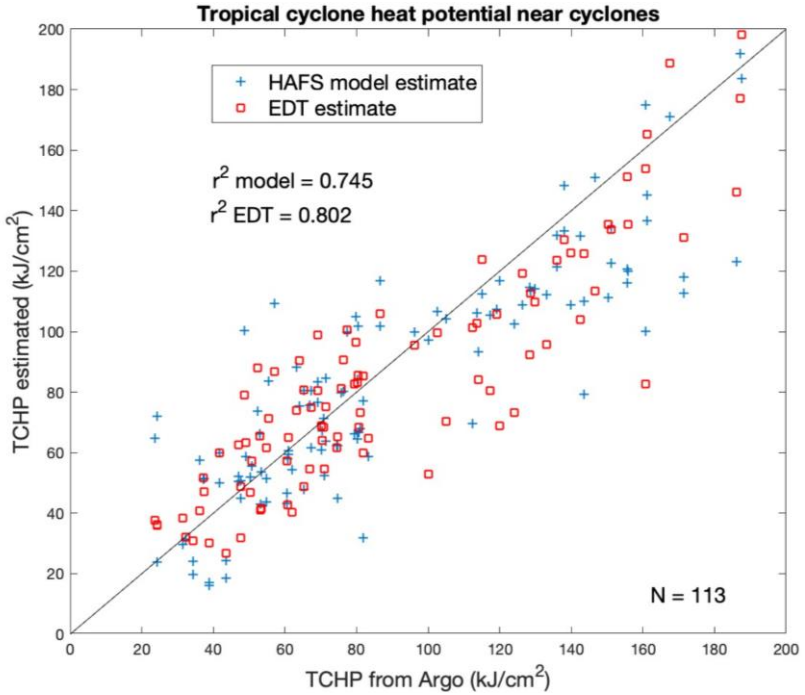
Argo floats near 7 storms of interest demonstrate NGE OHC skill in representing true ocean conditions*

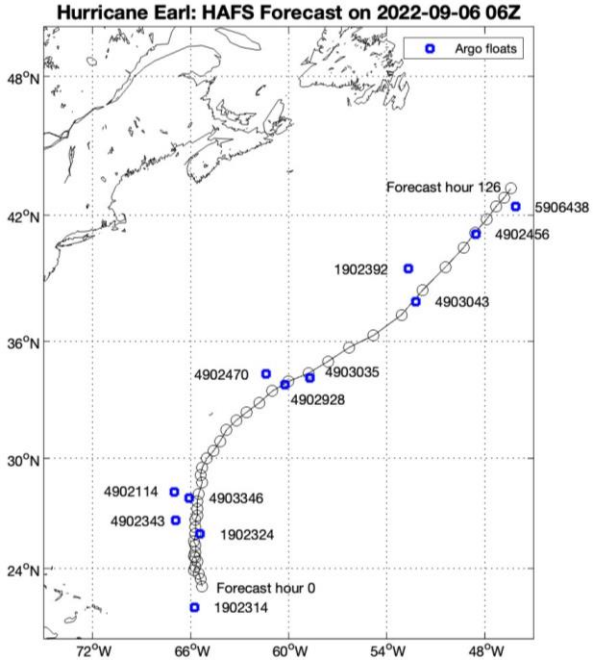
(*In upper 180 meters)



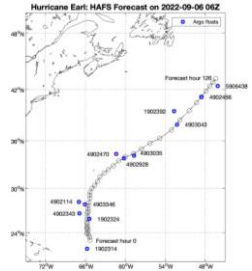
- Clear issues in HAFS salinity
- NGE OHC (EDT) has plenty of room for improvement as well
- SSS improvements in EDT are already in progress

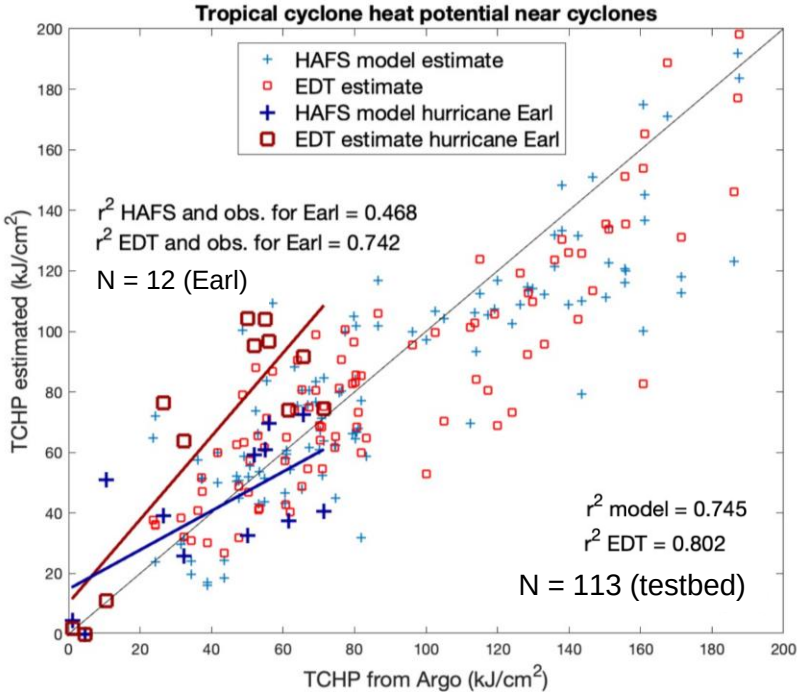
Can our EDT look-up tables (trained in testbed region) be used in the North Atlantic?





Can our EDT look-up tables (trained in testbed region) be used in the N Atlantic?



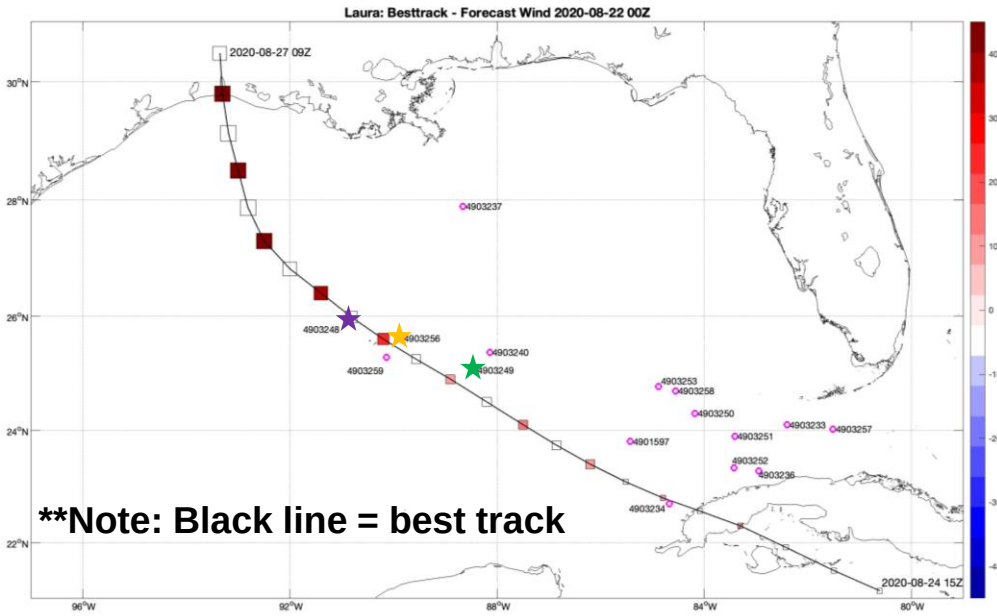


- Looks quite good even though look-up table was trained on Gulf of Mexico data
- Bodes well for North Atlantic EDT product currently in development (that should perform even better!), which will be trained on T(z) & S(z) in situ profile data from this entire basin with additional tuning (e.g., for SSS)

Some Hurricane Case Studies...

Laura (13l) – 2020082200 HAFS v1B

- Intensity bust with many nearby Argo profiles
- Rapid intensification over ocean (08/26/20), landfall as Cat 4 in Louisiana (08/27/20)



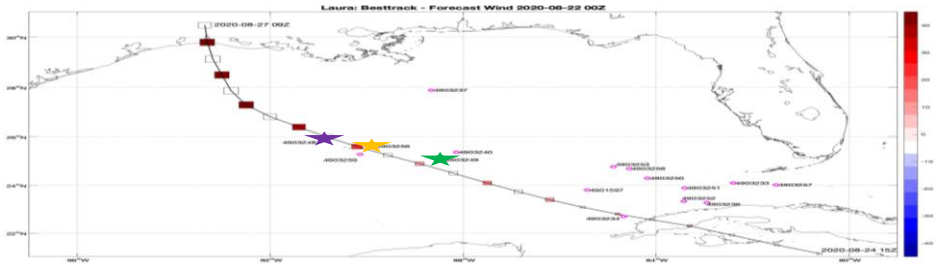
**Note: Black line = best track

Storm stronger than prediction (Model underpredicts intensity)

White = intensities match or no HAFS estimate available

Storm weaker than prediction (Model overpredicts intensity)

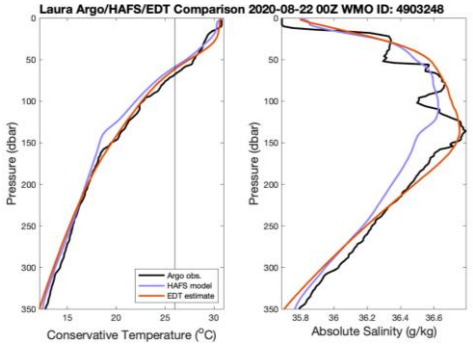
Laura (13l) – 2020082200 HAFS v1B

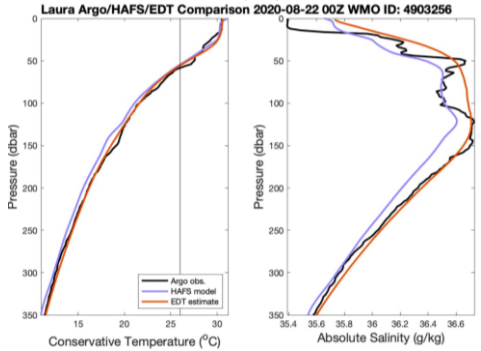


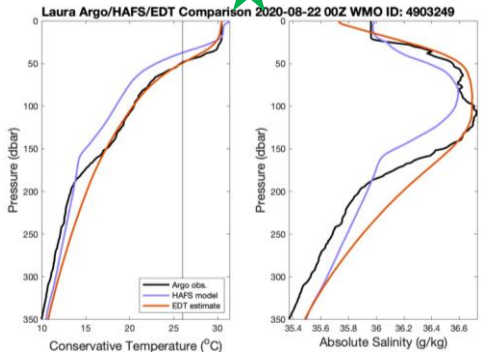
Storm stronger than prediction (Model underpredicts intensity)

Storm weaker than prediction (Model overpredicts intensity)

- HAFS temperature: too cool in mixed layer (ML), good at all depths, or too cool below ML
- HAFS consistently too fresh at depth (i.e., misses subsurface salinity/density gradient and maximum)

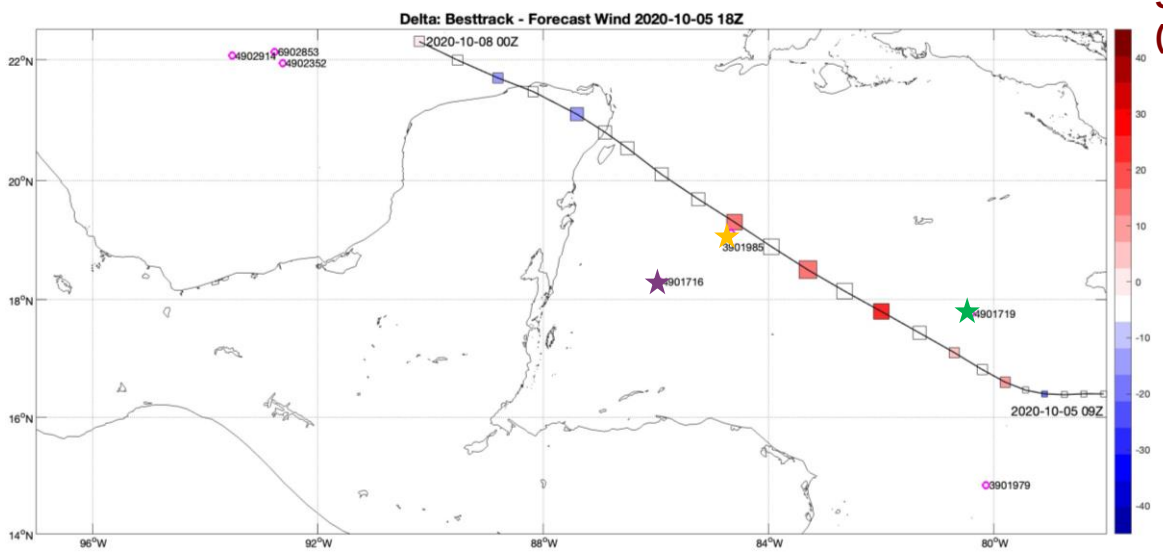






Delta (26l) – 2020100518 HAFS v1B

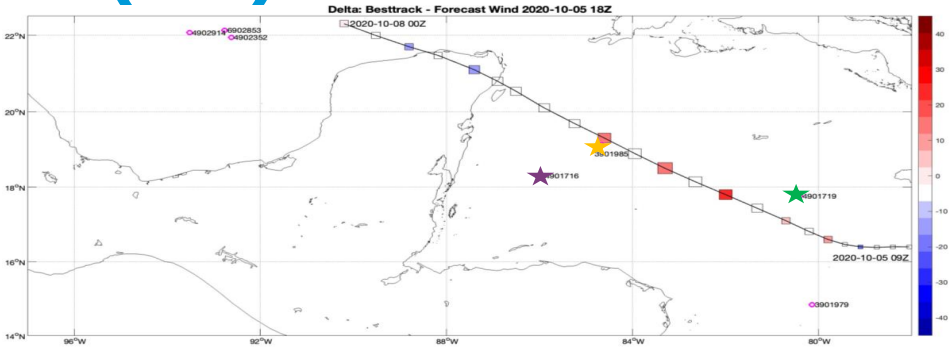
- RI occurred 10/05/2020–10/06/2020 (up to Cat 4) over ocean
- Increase in wind shear and dry air weakened it to Cat 2 before Mexico landfall (still caused substantial property/crop damage); Later damaging U.S. landfall not shown here
- Initial RI underpredicted by HAFS



Storm stronger than prediction (Model underpredicts intensity)

Storm weaker than prediction (Model overpredicts intensity)

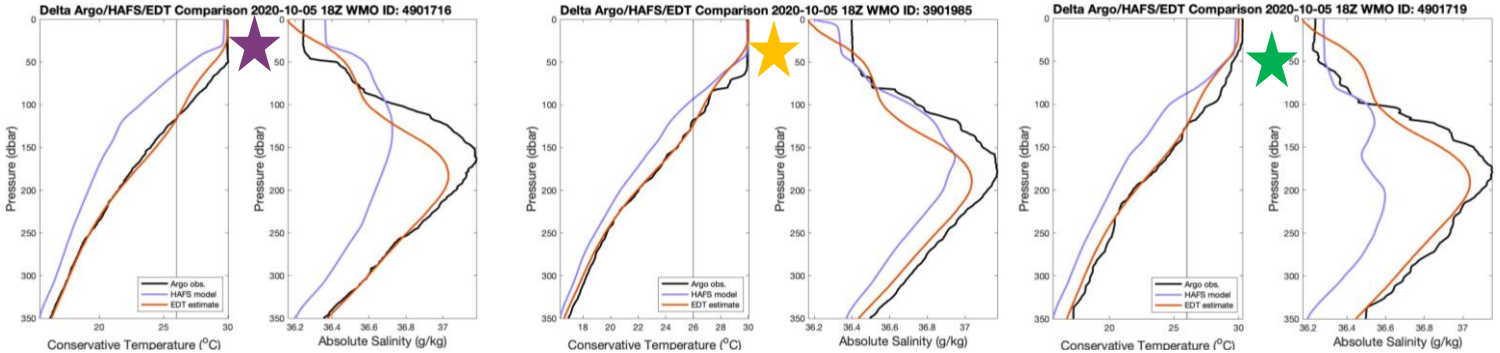
Delta (26l) – 2020100518 HAFS v1B



Storm stronger than prediction (Model underpredicts intensity)

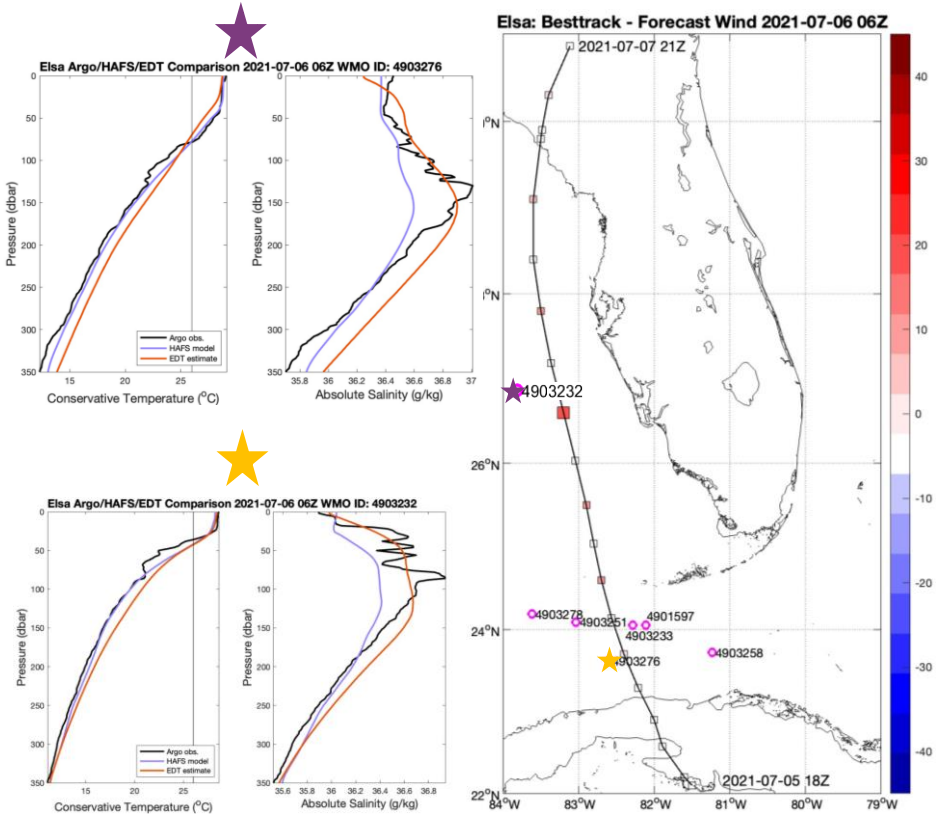
Storm weaker than prediction (Model overpredicts intensity)

- HAFS is missing heat (too cool) both within and below the mixed layer
- HAFS is typically too fresh (i.e., misses subsurface salinity/density gradient and maximum)



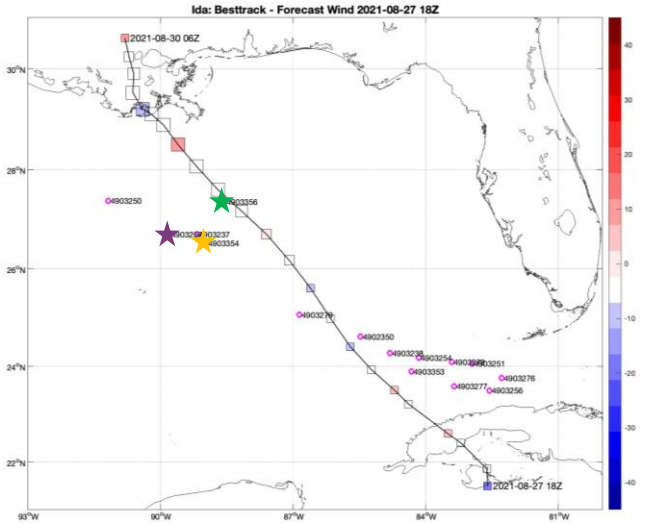
Elsa (05l) – 2021070606 HAFS v1B

- 07/05/21 landfall in Cuba; entered Gulf of Mexico early on 07/06/21
- 07/07/21: Briefly re-intensified to a minimal hurricane just west of Tampa (intensity underrepresented in HAFS), before weakening back to a tropical storm and making landfall later that day in Florida
- NGE OHC, HAFS, and Argo temperature profiles generally in agreement
- HAFS subsurface salinity too fresh (i.e., it missing the subsurface salinity maximum) and therefore model mixing differs from true mixing

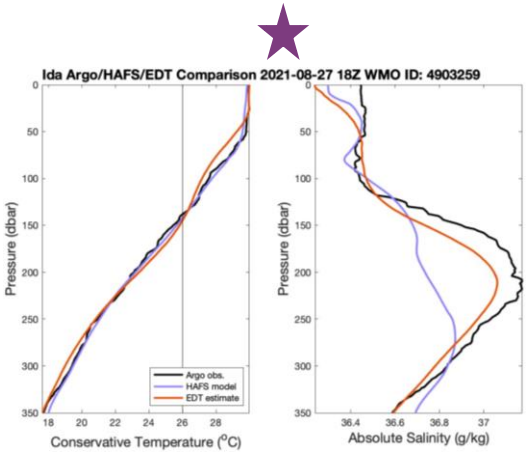


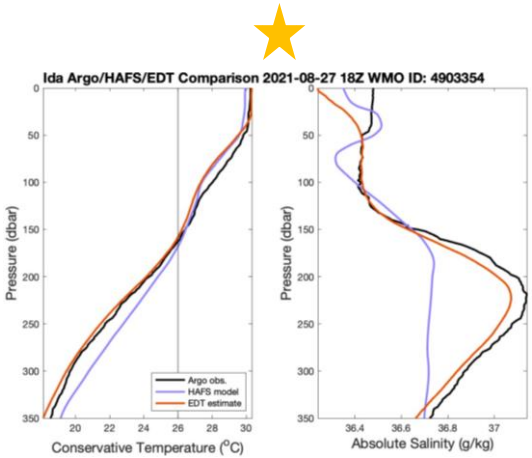
Ida (09l) – 2021082718 HAFS v1B

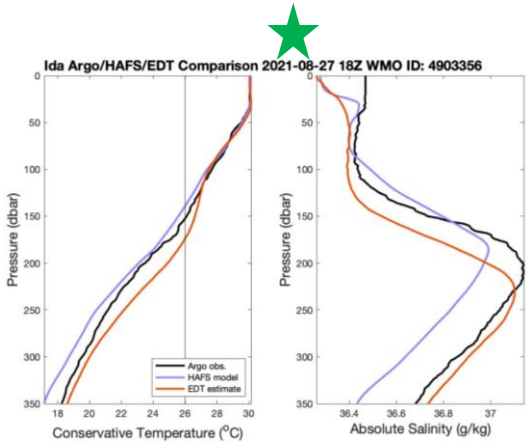
• 08/29/21: **Rapidly intensified** from category 2 to 4 in only 6 hours over Gulf of Mexico before U.S. landfall that day (RI slightly underpredicted by HAFS)



• HAFS is missing subsurface salinity max (i.e., is too fresh) and its mixed layer is too cool

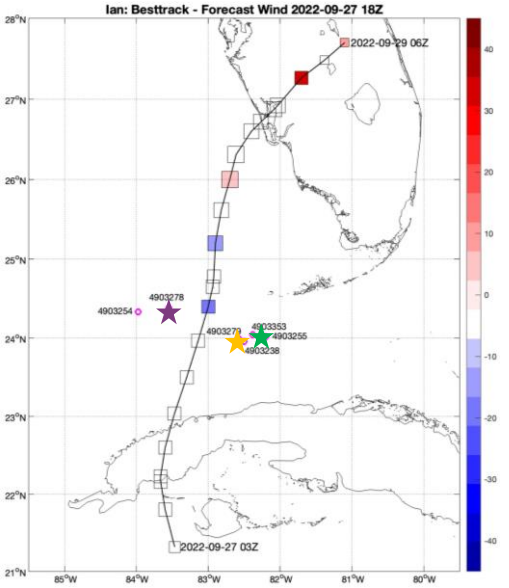


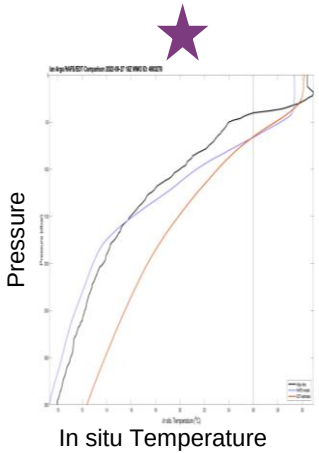


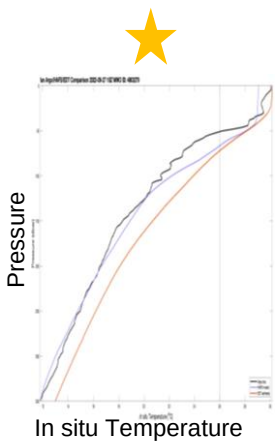


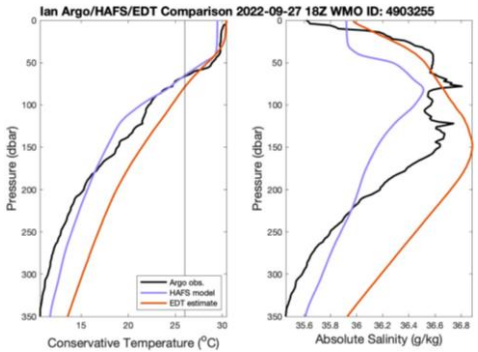
Ian (09l) – 2022092718 HAFS v1B

- Made landfall in Cuba as a Cat 3 then restrengthen over SE GoM before peaking as a Cat 5 on 09/28/23 and making landfall in Florida
- HAFS initially overintensifies over ocean then later is underintensified closer to landfall
- Again, HAFS mixed layer has too little heat; in upper 50 m, HAFS does not capture salinity/density gradient that is present and preventing vertical mixing in reality (and thereby increasing intensity)

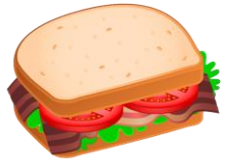








Summary and Conclusions



Adaptable OHC algorithms are needed for a warming world and will be useful for hurricane intensification forecasting

- Dynamically-based NGE OHC better captures extremes than current NOAA product
- Use of ML/AI allows for continuous updating of profile database and annual updates to lookup tables
- High depth resolution in T/S enables OHC (TC heat potential) & MLD estimates, and provides flexibility to derive other metrics* as needed

Coming this Atlantic Hurricane Season

- Real-time evaluation of model forecasts using NGE OHC output

Coming Later in 2023

- Pre-operational, daily, ¼° gridded and ~7km along-track T(z), S(z) fields for the North Atlantic using RADS ADT

Possible Future Directions

- Expansions: Global open ocean; coastal zone (< 1800 dbar)
- Generate error estimates for future DA trials (HAFS/MOM6, RTOFS?)
- Test method on SWOT data to prepare for future, operational wide-swath altimetry

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