Evaluating the Vertical Mixing Schemes in the Ocean Surface Boundary Layer in the Intensification Forecast of Hurricane Fiona (2022)

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Abstract - Turbulent mixing is a process in the ocean surface boundary layer that affects the air-sea interactions, which plays a key role in the intensification of tropical cyclones (TCs). To improve the numerical forecasting of TC intensification, accurately modeling the process of turbulent mixing is essential. However, uncertainties exist in the turbulence parameterization within the vertical mixing schemes, which can cause forecast errors, including both systematic biases and variability mismatches between forecasts and observations. Given the impact of background-error covariances on data assimilation and background ensemble under-dispersion at the air-sea interface, ocean physics errors may contribute to insufficient sampling. As a first step, this study perturbs the critical Richardson number (Ric) in the K-profile parameterization and uses novel observations from Hurricane Fiona (2022) to verify the background ensemble. Using the Hurricane Analysis and Forecast System coupled with Modular Ocean Model v6 (HAFS-MOM6), two sets of 40-member background ensemble without and with perturbing Ric are generated and compared. Verification against the novel observations showed that perturbing Ric increased ensemble spread and diversity in the atmosphere, air-sea interface, and ocean. This indicated an improved forecast uncertainty, and could be beneficial towards coupled data assimilation.

***Keywords*:** Turbulent mixing; vertical mixing schemes; critical Richardson number; KPP; ensemble background and diversity

1 Introduction

Turbulent mixing modulates the exchange of heat and momentum in the ocean surface boundary layer (OSBL), which is the uppermost region of the ocean that interacts with the atmosphere (Li et al. 2019). The air-sea interaction process plays a key role in the intensification of tropical cyclones (TCs) as the air-sea fluxes provide the primary sources of energy (Reichl et al. 2016). For example, the warmer sea surface temperature (SST) for the TC intensification is determined by turbulent mixing in the OSBL. On the other hand, when momentum from the wind is transferred into the ocean, the vertical shear creates turbulence, which drives the deepening of the mixed layer (Balaguru et al. 2015). The near-surface temperature cools as the mixed layer continues to deepen (Balaguru et al. 2015; Reichl et al. 2016), thereby reducing the energy budget and decreasing storm intensity (Balaguru et al. 2015). Therefore, the turbulent mixing process in the OSBL is a main concern for predicting TC intensification.

Because of the fine spatial and temporal scale of the turbulent dynamics, turbulent mixing in the OSBL is unresolved in models (Balaguru et al. 2015; Li et al. 2019). Vertical mixing schemes are used to parameterize the turbulent mixing processes in numerical models. Therefore, an accurate parameterization of turbulent mixing in the OSBL is needed to create robust predictions of TC intensification (Van Rokel et al. 2018). However, many uncertainties exist in parameterizing the OSBL turbulent mixing, which may cause biased TC intensification forecasts (Li et al. 2019; Van Rokel et al. 2018).

As a nonlocal first-order parameterization, the K-profile parameterization (KPP; Large et al. 1994) is widely used to parameterize upper-ocean turbulence mixing in ocean models (Reichl et al. 2016; Van Roekel et al, 2019), including the Modular Ocean Model Version 6 (MOM6; Adcroft et al., 2018) for the operational hurricane implementation. Van Roekel et al. (2018) have illustrated the critical elements of KPP and discussed the potential issues. For example, the eddy diffusivity in KPP heavily relies on the boundary layer depth, which is diagnosed with the critical bulk Richardson number (Ric). The bulk Richardson number is defined as the value of buoyancy over shear. The boundary layer depth is the shallowest depth where the bulk Richardson number equals Ric. Once Ric is reached, the ocean becomes stratified compared to the shear, which sharply decreases the vertical mixing. This is then considered the base of the OSBL. However, the value of Ric varies with different theories and observations due to various ocean conditions (Van Rokel et al. 2018).

Under the Unified Forecasting System (UFS) framework, the Hurricane Analysis and Forecast System (HAFS) is a numerical modeling and data assimilation (DA) system for operational hurricane predictions (e.g., Dong et al. 2020; Wang et al. 2024). The background-error covariances in the DA system are used to spread observational information spatially, temporally, and across variables (Fischer 2003). The estimate of the background-error covariance matrix is based on the state of each ensemble member (Keppene et al. 2014). However, Li et al. (2025) highlighted the necessity of advancing background ensemble sampling at the air-sea interface for the self-cycled HAFS, especially for the under-dispersion of SST.

The background ensemble under-dispersion may be caused by the insufficient sampling of ocean physics errors. The limitation from the turbulent mixing parameterization within the OSBL during TC intensification, such as the uncertainty in model parameters, could be one source of model error. As a first step, KPP is selected as a vertical mixing scheme within the ocean model, and Ric is perturbed to account for the uncertainties in KPP. The goal of this study is to evaluate the background ensemble at the air-sea interface without and with perturbing Ric against observations. Perturbing Ric is expected to improve the ensemble spread and increase the ensemble diversity at the air-sea interface, which are important for the coupled ensemble DA.

2 Methods

The self-cycled HAFS has been developed to implement the eddy-resolving regional MOM6 ocean coupling capability (HAFS-MOM6) by the University of Oklahoma Multi-scale Data Assimilation and Predictability Lab (Yang et al. 2024).

Hurricane Fiona (2022) is chosen as the case study due to the availability of inner-core novel observations from the field campaign. The novel observations over the ocean include saildrones, gliders, dropsondes, and Airborne eXpendable BathyThermographs (AXBTs). Novel observations at the air-sea interface are leveraged to assess the 6-h background ensemble from the HAFS-MOM6 during the intensification stage of the hurricane.

The 40-member cold-start ensemble forecasts are initialized from 0600 UTC 18 September 2022. Two sets of 6-h background ensemble are generated based on the different configuration of Ric. As a reference, the ensemble forecasts that use unperturbed Ric with the standard value of 0.2 are denoted as Ens_Std. Another set of ensemble forecasts that use perturbed Ric ranging from 0.1 to 0.5 (e.g., Barad and Fringer 2010; Sanford et al. 2011; Large et al. 1994) are named Ens_Ptb. Ens_Std and Ens_Ptb are compared and verified against novel observations.

Multiple variables are verified against dropsondes for the atmosphere, saildrones for the air-sea, gliders and AXBTs for the OSBL. These variables include temperature, equivalent potential temperature, and wind speed. The spread and diversity of the ensemble members are evaluated by comparing the differences between Ens_Std and Ens_Ptb.

3 Results

3.1 Comparsion of Model Results

Taking member 1 as an example, the differences in model results between Ens_Ptb and Ens_Std are compared to show the impact of perturbing Ric on the background, focusing on three components of the earth system: the air-sea interface, the atmospheric boundary layer, and the OSBL.

Figure 1 shows the impact of perturbing Ric on the background at the air-sea interface. In Ens_Std, stronger gradients of surface air temperature (SAT) indicate prevalent TC structure (Fig. 1a). For the SST, there is a gradient near the TC center that shows upwelling occurring south of the eye (Fig. 1b). The differences in SAT show both cooling and warming in the area (Fig. 1c). However, the differences in SST indicate a region that is cooled by the perturbed experiment, specifically point A (64.56 ºW, 18.69 ºN) with the largest cooling degree. Perturbing Ric shows that both SAT and SST are heavily location dependent for how much the ensemble spread is impacted. The saildrone site 1031 has low sensitivity, while saildrone site 1040 shows a greater sensitivity to perturbing Ric.

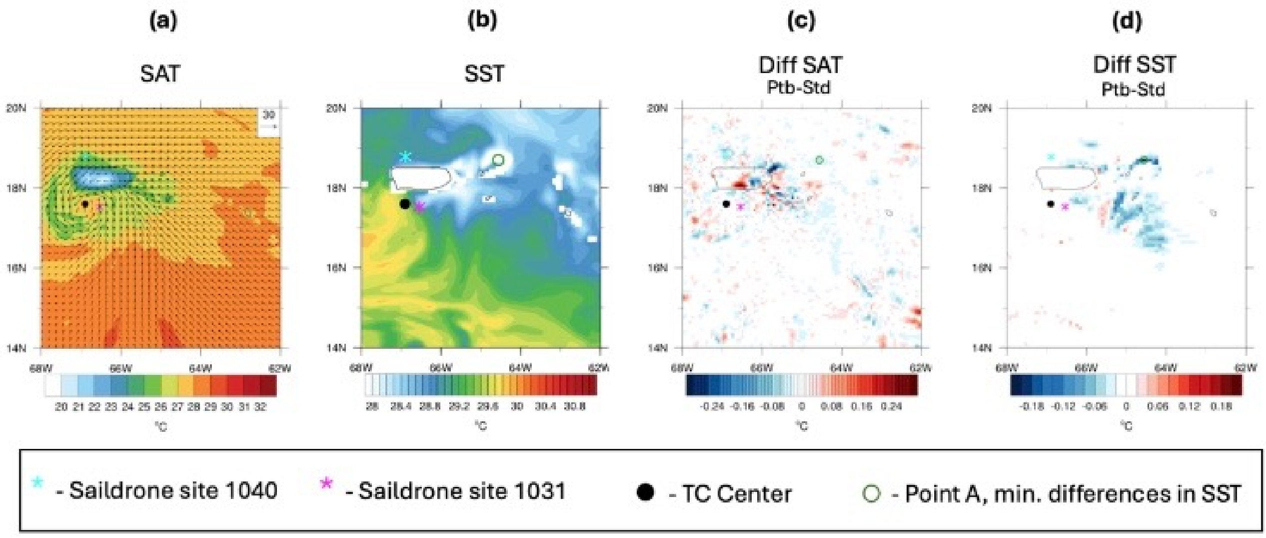

Figure 1: *Forecasts of member 1 for (a) surface air temperature (SAT; ºC) and (b) sea surface temperature (SST; ºC) in Ens_Std. Differences between Ens_Ptb and Ens_Std in (c) SAT and (b) SST for member 1. The stars represent the saildrone locations (cyan for 1040 and magenta for 1031). The black dot indicates the TC center diagnosed from model results. The green circle marks the location with minimum differences in SST.*

Figure 2 shows the cross sections of the TC center to evaluate the wind field and temperature in the atmosphere using the differences between experiments in the atmospheric boundary layer. The temperature gradient in Ens_Std ((Figs. 2a,b) shows an obvious warm-core around 17°N and 66°W in the middle and lower troposphere, peaking around 850 to 750 hPa. The wind vectors show some rotation with stronger winds near the warm-core area. The winds peak around 850 to 800 hPa, and are symmetric around the center of the TC. The temperature differences reach up to ±0.18 K, specifically

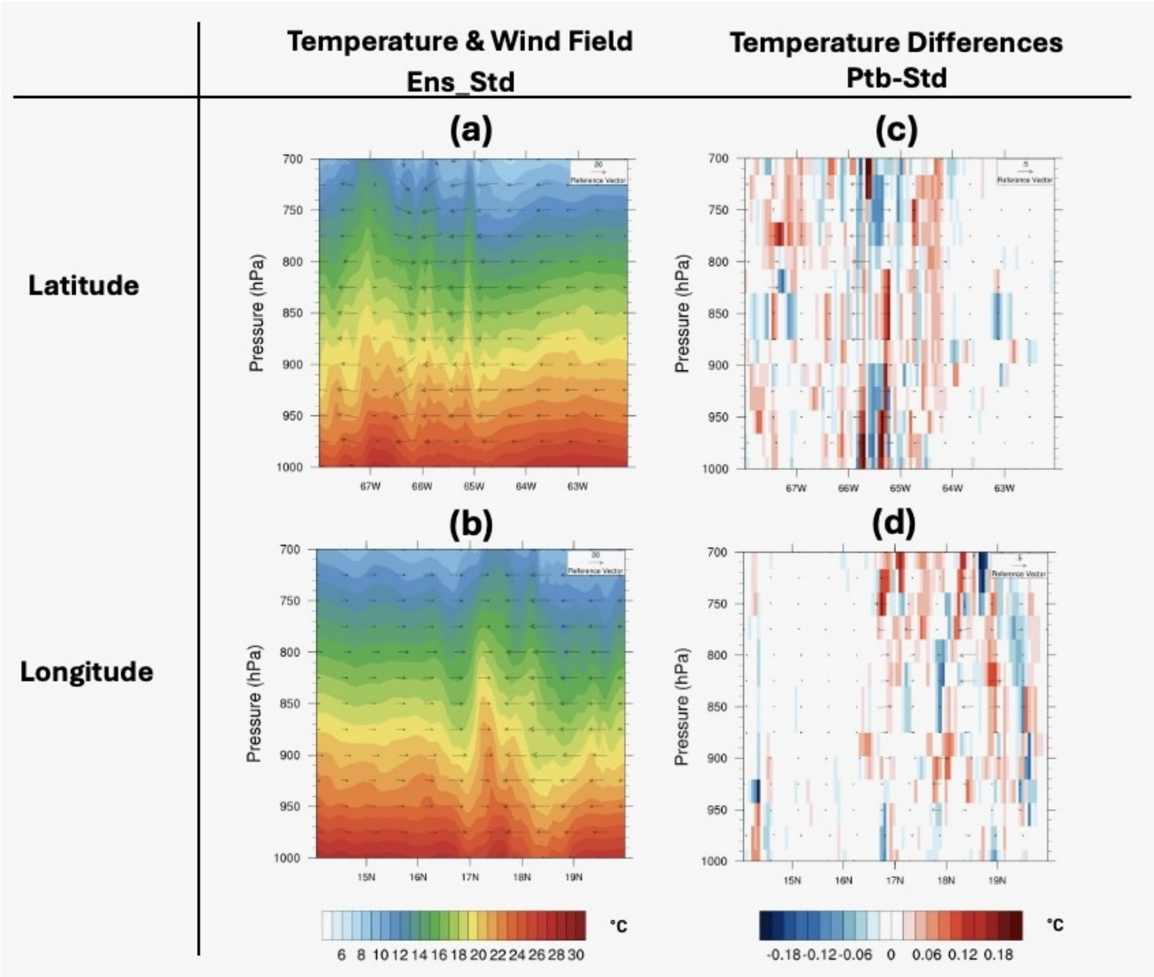

Figure 2: *The vertical cross sections of temperature (°C) and wind (vectors, m s) from Ens_Std in (a) and (b), and temperature differences between Ens_Ptb and Ens_Std in (c) and (d) (Ptb-Std). Plots (a) and (c) show the latitude-pressure slice across the storm center at a fixed longitude of 66.25°W. Plots (b) and (d) show the longitude-pressure slice at a fixed latitude of 17.25°N.*

around 900 and 750 hPa. The differences are not symmetric to the center of the storm, and have larger positive anomalies west of the core, and negative anomalies to the east.

Even though Ric is a process that occurs in the OSBL, we can see that it also highly impacts the low-level atmosphere as well. Ric is dependent on the regional thermodynamics and can affect the TC intensity from thermal wind balance and convection.

Figure 3 shows the glider data evaluation of the wind field and temperature in the atmosphere to examine the impact of pertubring Ric on sea water temperature. Ens_Std shows a warm pool in the western tropical Atlantic, with temperatures exceeding 29°C. The structure of the warm-core is typical for late-summer climatology, and is favorable for TC development. The differences plot shows the impact of perturbing Ric on sea water temperature, with a value of around ±0.1°C.

The sea water temperatures from the model match well with the glider data points, which suggests that the thermal patterns are measured accurately. The differences plot shows that the changes are small but are strongest upstream of the storm track. The differences appear next to regions with high SST gradients. This could be indicative that varying Ric values affect mixing and surface fluxes. This is important since this is the area where air-sea interaction is sensitive and could affect TC development the most. The differences plot shows the oceanic sensitivity to Ric and the differences that could impact TC intensity and structure through air-sea interactions.

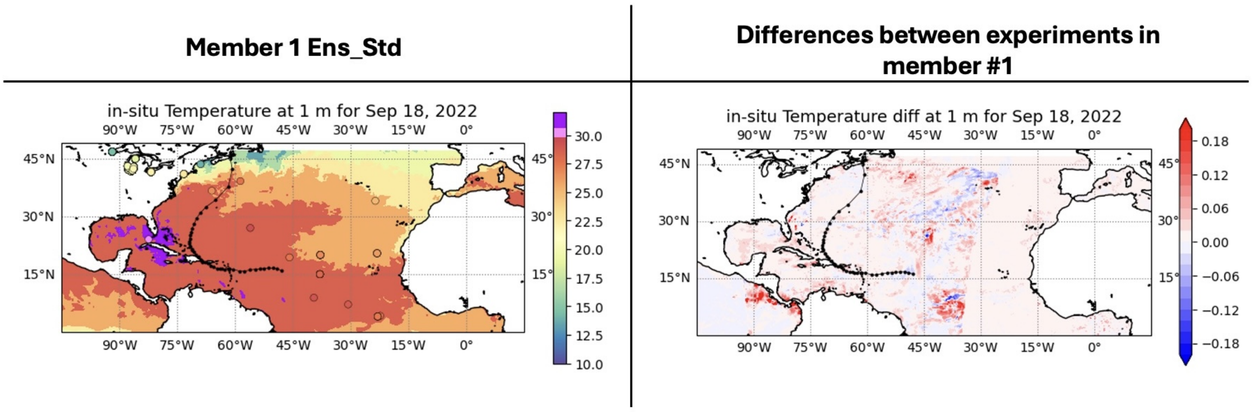

Figure 3: *Sea surface water temperaturess (1m depth) from Ens_Std overlaid with glider observations. The left side of figure 3 shows member 1 from Ens_Std, while the right side of figure 3 shows the differences between Ens_Ptb and Ens_Std for the the same member.*

3.2 Verification against Novel Observations

Figure 4 shows the comparison of the saildrone observations against the performance of the ensemble forecasts for each experiment. Each plot compares SST and SAT for the 40 ensemble members for both Ens_Std and Ens_Ptb. The verifications against novel observations are conducted on three components of the earth system: the air-sea interface, the atmospheric boundary layer, and the OSBL. The spatial distribution of the ensemble members shows the differences between the two experiments for each verification site.

Site 1040 shows some tight clustering, which shows good model agreement and consistent air-sea coupling. For site 1031, there is more spread in the center which suggests a higher sensitivity to Ric perturbation, which could be because of the location relative to the TC, where the air-sea interaction is strong. Also, the ensemble members diverge more than site 1040, which means there is a greater uncertainty in the perturbation.

Point A has no observations to compare against, but is used to measure the differences between the two experiments. It doesn't validate the model but shows how Ric perturbations affect the air-sea relationship at a location. Perturbing Ric increases the ensemble diversity and enlarges the ensemble spread compared to Ens_Std (blue points).

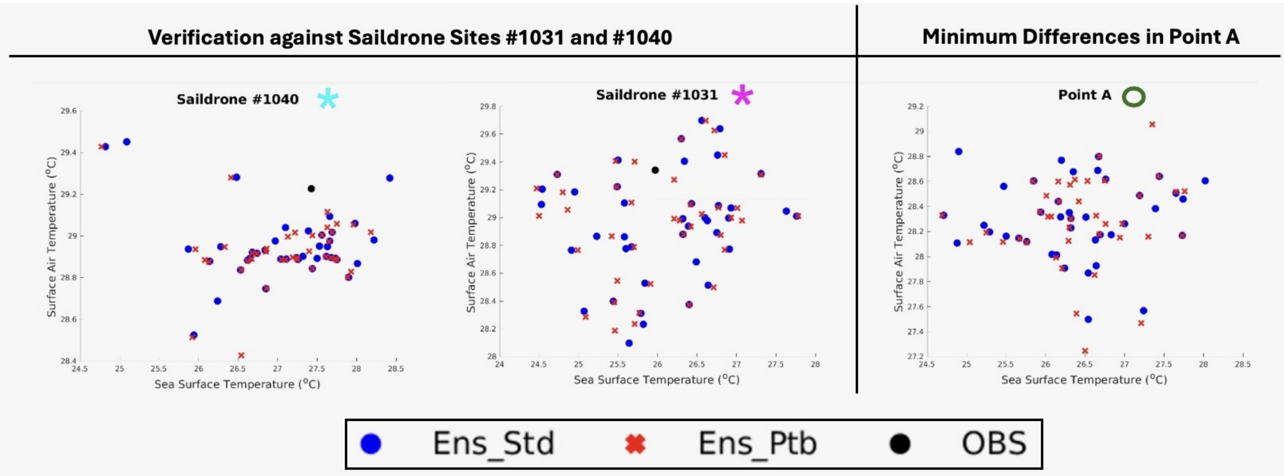

Figure 4: *The saildrone verification for the two observation sites and the one location without observations (point A). The blue and red points each represent an ensemble member, and the black points are the saildrone observations. The blue dots are Ens_Std, the red crosses are Ens_Ptb.*

Figure 5 shows the vertical profile averages from the dropsonde location to evaluate each ensemble experiment for the structure of the atmosphere during the storm. The profiles extend up to 3 km for both experiments and allow for a direct comparison between the modeled profile and the observed conditions to assess the spread and diversity for each variable.

The perturbed ensemble shows a wider spread in the equivalent potential temperature, especially below 1.5 km. However, the wind profiles stay clustered in both experiments. Figure 5 shows that the ensemble lines completely cover the dropsonde observation for all variables shown, which shows a skillful spread, and that it is well calibrated.

Compared to Ens_Std, Ens_Ptb shows more variability, especially in equivalent potential temperature and wind speed, especially in the lower levels of the atmosphere. This is positive considering that Ric is occurring in the OSBL, so changes here are important. The control member in the equivalent potential temperature graph is much colder than both the ensemble members and the observation, which underestimates the energy available for convection within the column. This shows an improvement towards the air-sea coupling because of the Ric adjustment. For the wind variable, many of the ensemble members are closer to the observed measurements within lower levels of the atmosphere. This shows that perturbing Ric better represents the mixing and surface drag in the atmosphere. Both the spread and diversity are increased in this verification, which supports robust model performance, and addresses forecast uncertainties to a certain degree.

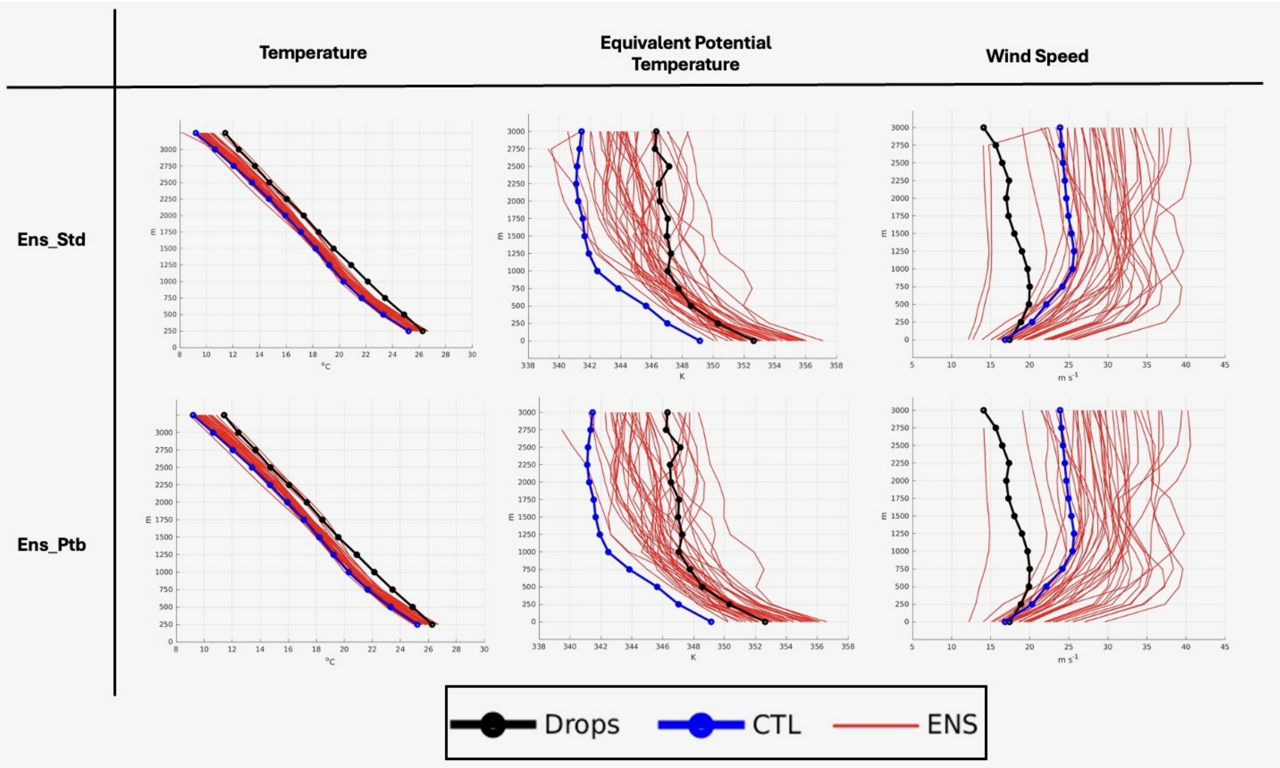

Figure 5: *The dropsonde verification for temperature, equivalent potential temperature, and wind speed. Each red line is an ensemble member from the experiment, the blue line is the control member, and the black line is the dropsonde observation. The top row is Ens_Std, and the second row is Ens_Ptb.*

Figure 6 shows the sea water temperature profiles of the OSBL against the AXBT observations to assess the background ensemble performance. Both experiments show a steep thermocline, with temperatures decreasing rapidly below the mixed layer. The spread is clustered in both experiments, which shows a consistent vertical structure. The standard and perturbed experiments both cover the AXBT observations, which suggests the capability of the ocean model. The top 20 m in Ens_Ptb show that the spread is increased, and also slightly wider than Ens_Std. This result implies that there is an enhanced sensitivity to Ric in the upper ocean. Increased spread within the upper ocean affects the SST forecasts, which is critical for air-sea coupling. The increased diversity shows a positive impact on the uncertainty within the forecast.

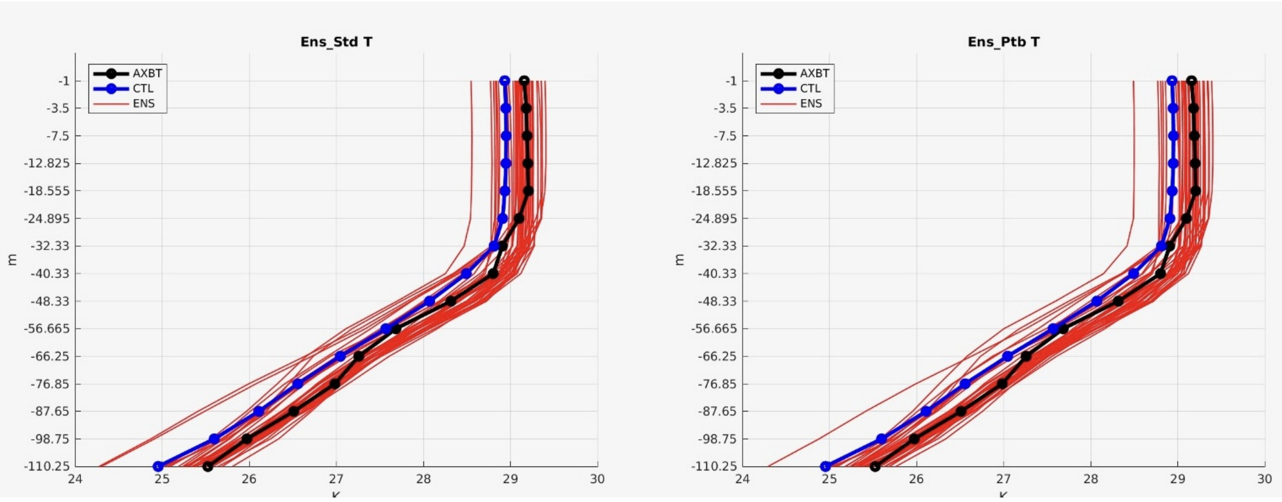

Figure 6: *The sea water temperature profiles of the OSBL against the AXBT observations. The left is the standard experiment (Ens_Std), and the right is the perturbed experiment (Ens_Ptb). The red lines are each ensemble member, the blue line is the control member (CTL), and the black line is the AXBT observation.*

4 Conclusion

To improve tropical cyclone intensification forecasts, it critical to have an accurate representation of the ocean procceses in the upper ocean. The goal of this study is to evaluate the impact of perturbing Ric on the background ensemble using novel observations, i.e., saildrones, dropsondes, gliders, and AXBTs, for Hurricane Fiona (2022). So, two sets of 6-h 40-member background ensembles from the HAFS-MOM6 were compared through the standard (Ens_Std) and perturbed Ric (Ens_Ptb) experiments. In comparisons of model results between Ens_Std and Ens_Ptb, the distribution of differences for member 1 is significant in space. However, the differences are limited at the observation sites when verifying against the observations. Such sensitivity to Ric is highly location-dependent. Perturbing Ric influences the earth system, ranging from the upper ocean, air-sea interface, and atmospheric boundary layer. Evaluations using novel observations show that introducing the perturbed Ric into the background ensemble leads to increased spread and diversity, which is encouraging towards ensemble DA. In future work, we will apply the background ensemble with perturbed Ric in DA experiments and explore the impact on DA. While the differences as of now are small, the impact of perturbing Ric on the background ensemble in the atmosphere will be accumulated through the self-cycled coupled DA system. Perturbing more physical parameters to increase the background ensemble diversity is warranted for the future.

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