Report for 2022-2023 DTC Visitor Program

Evaluating Improvements in PBL and Cumulus Schemes in HAFS for Forecasts of TC Structure and Large-Scale Steering

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1. Background

The Hurricane Analysis and Forecast System (HAFS) is the tropical cyclone (TC) application of NOAA's Unified Forecast System (UFS). Two versions of HAFS are scheduled to be implemented operationally in July 2023 and eventually replace the Hurricane Weather Research and Forecasting (HWRF) and Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic Model (HMON). Prior to this operational implementation, HAFS has been tested extensively with real-time runs during the 2019-2022 Atlantic and East Pacific hurricane seasons (e.g. Dong et al. 2020, Hazelton et al 2021, 2022), through the support of the Hurricane Forecast Improvement Program (HFIP, Gopalakrishnan et al. 2021). HAFS has demonstrated promising skill in forecasts of TC track, intensity, and structure.

A key area of research in HAFS has been evaluation and improvement of the planetary boundary layer (PBL) physics. HAFS currently uses the eddy-diffusivity mass flux with prognostic turbulent kinetic energy (EDMF-TKE) PBL scheme (Han and Bretherton 2019). Some TC-specific modifications, including changes to the mixing length, mass flux, and surface layer formulations, have been made to the scheme, based on a combination of observations (Gopalakrishnan et al. 2021, Hazelton et al. 2022) and large eddy simulation (LES) data (Chen et al. 2021). These observational/LES-based PBL physics modifications have been extensively tested in TC settings in HAFS simulations, both case studies (Chen et al. 2022) and a large number of quasi-real-time HAFS forecasts during the 2021 Atlantic hurricane season (Chen et al. 2023). The PBL physics modifications demonstrated promise in improving HAFS forecasts of TC structure and intensity change, particularly rapid intensification.

Despite the notable improvement in TC-scale structure evolution with the PBL physics modifications, it was not readily apparent how, if at all, the PBL physics modifications impacted the large-scale environment surrounding the TC. This is an important question to address, both for prediction of TC steering and also unification of model physics across multiple applications of the UFS. Ideally, a scheme can be used with options or modifications that allow for more skillful prediction of not just TCs but other large-scale and small-scale atmospheric phenomena. Thus, it is important to evaluate model physics and modifications to the physics across a variety of scales and applications, and this is the main goal of this project. In addition, other physics schemes, such as the cumulus parameterization, have not been optimized for HAFS and their impacts are not as well understood. HAFS uses the Scale-Aware Simplified Arakawa-Schubert (SA-SAS) convective scheme (Han et al. 2017), which is the same as that used in the operational GFS model. However, SA-SAS has not been thoroughly evaluated in how the scale-aware aspects impact TC forecasts. This will also be a subject of investigation.

2. Experiments

a. Hurricane Laura Physics and Scale Sensitivity Tests

One of the initial tests we performed was to examine how HAFS, with and without the modified PBL physics, performed compared to other UFS applications across a variety of resolutions for a TC forecast. For this test, we selected a forecast of Hurricane Laura (2020), which made landfall in Southwest Louisiana as a Category 4 hurricane. The test compared two versions of HAFS that were run in real-time during the 2022 Atlantic hurricane season, HAFS-A (HF3A) and HAFS-S (HF3S). HF3A and HF3S used different PBL physics (HF3S incorporated the TC-specific PBL modifications discussed above) and different microphysics. HF3S used the Thompson Microphysics (Thompson et al. 2004), while HF3A used the GFDL 6-class microphysics (Zhou et al. 2022). These versions of HAFS were both run at 2-km grid spacing. These forecasts were compared with the operational HWRF and HMON models, as well as 4 different versions of the UFS Short-Range Weather (SRW) application. Two of these used the current GFS physics suite (including the GFDL microphysics), while 2 used an experimental suite that included the Thompson microphysics (the P8 suite). Thus, this provided a good opportunity to compare the GFS and HAFS runs with Thompson microphysics. The UFS SRW forecasts were run at 3-km and 13-km grid spacing, which provided an initial opportunity to test the UFS physics across scales. Table 1 summarizes the forecasts that were compared and the grid spacings that they used. All forecasts used the operational GFS for initial and boundary conditions. HAFS also used its data assimilation system to assimilate observations near the storm.

Model	4-Letter ATCF Abbreviation	Grid Spacing (Finest)
2020 Operational HWRF	HWRF	1.5-km
2020 Operational HMON	HMON	2-km
2022 Experimental HAFS-A	HF3A	2-km
2022 Experimental HAFS-S	HF3S	2-km
2022 UFS SRW Application With GFSv16 Physics, 3-km	SV03	3-km
2022 UFS SRW Application With p8 Physics, 3-km	SP03	3-km
2022 UFS SRW Application With GFSv16 Physics, 13-km	SV13	13-km
2022 UFS SRW Application With p8 Physics, 13-km	SP13	13-km

Table 1: Description of the experiments compared in the Hurricane Laura test.

Figure 1 compares the track forecasts of the various experiments for Hurricane Laura, initialized at 00 UTC August 25, 2020, while Laura was near the Western tip of Cuba. The two HAFS forecasts both had a notable left-of-track bias for this case, while the operational hurricane models (HWRF and HMON) had more accurate track forecasts. Interestingly, the leftward bias was shared by the 3-km versions of the SRW, which showed the storm making landfall near Houston. The 13-km versions of the SRW were accurate, however. The fact that the two HAFS versions were similar to each other, the two 3-km SRW versions were similar to each other, and the two 13-km SRW versions were similar to each other seems to indicate that it was not a particular physics scheme (especially the microphysics) leading to the track bias in this case, but likely instead how the physics behaved at different scales (for example, the lower resolution SRW having a more accurate forecast).

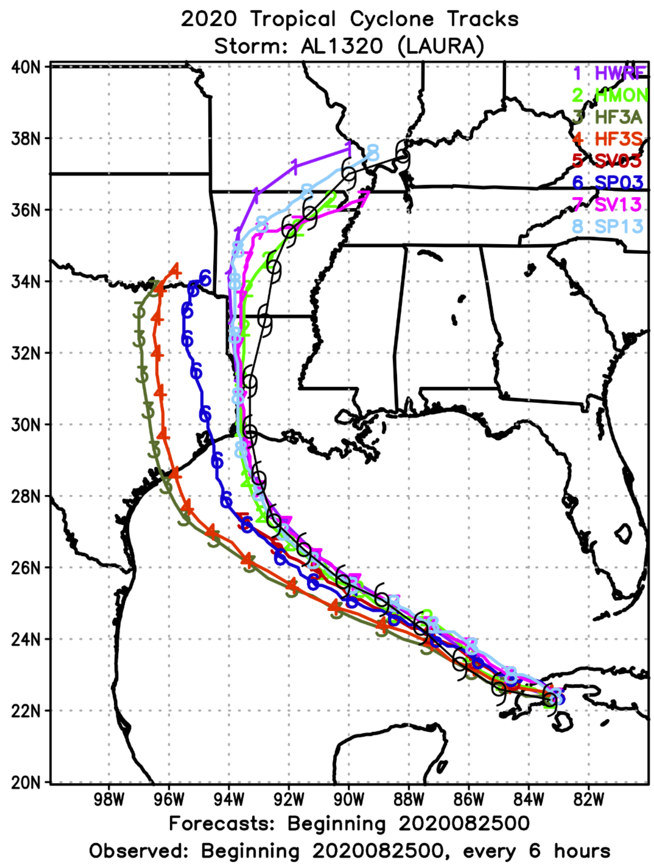


Figure 1: Track forecasts for Hurricane Laura initialized at 00 UTC August 25, 2020 from HF3A (dark green), HF3S (orange), HWRF (purple), HMON (light green), SP03 (dark blue), SV03 (red), SP13 (light blue), and SV13 (magenta). The observed track "Best Track" is shown in black.

In order to determine the reason for the differences in track in a relatively short-term forecast, Figure 2 shows the 500-hPa geopotential height forecasts from HWRF and the two HAFS runs (not all forecasts were shown to keep the plot from being too crowded), as well as the analyses from the GFS and ERA5 (to give two independent verifications). Note that the subtropical ridge over the NE Gulf was too weak in both HAFS forecasts (and HWRF), which is a common bias with GFS-based hurricane models (e.g. Hazelton et al. 2022). Usually, we would expect that this kind of subtropical ridge bias would potentially lead to a right-of-observed track bias. However, the HAFS forecasts were too far west in spite of this. The track bias appears to be due to a misrepresentation of the upper-level trough moving into the southern plains, which was deeper in reality than any of the forecasts represented. HWRF did a better job representing this feature than either of the HAFS forecasts.

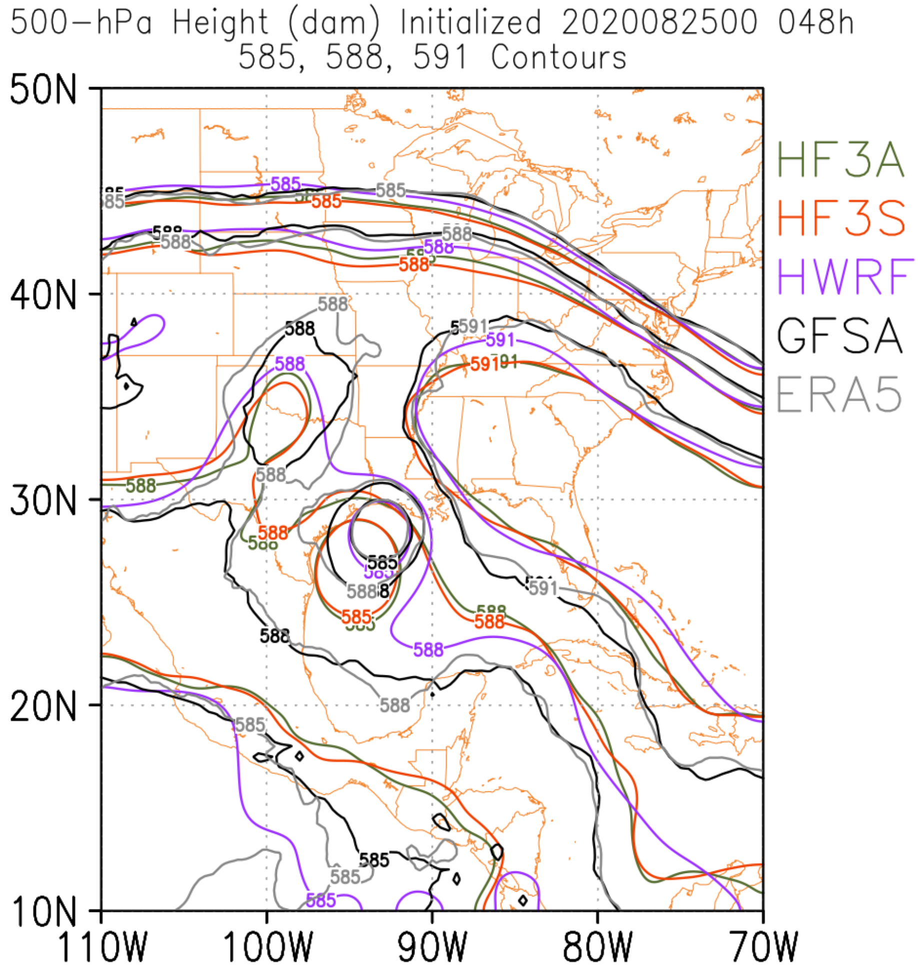


Figure 2: 500-hPa geopotential height forecasts (dam) from the HWRF (purple), HF3A (green), and HF3S orange, initialized at 00 UTC August 25, 2020, and valid at 48h. The GFS analysis is shown in black and the ERA5 reanalysis is shown in gray.

This example shows how, even without direct TC biases induced by the physics, biases in large-scale forecasts can lead to forecast issues. The next section examines more directly the scale-aware aspects of the physics in another TC example.

b. Hurricane Ian Scale-awareness Tests

In order to address some of the scale questions raised in the previous section, we next test HAFS forecasts using a new implementation of the scale-awareness of the SAS convective scheme implemented by Bengsston et al. (2022). This modification is expected to have some impact on TC forecasts in HAFS since the convective scheme is enabled on both the 6-km outer domain and the 2-km moving nest. This new prognostic closure is called “prognostic sigma” or “progsigma” for short. We tested both HAFS-A and HAFS-B (the two newly operational versions of HAFS) with “progsigma” for Hurricane Ian (2022), across all cycles from 06 UTC September 23, 2022 to 06 UTC October 1, 2022.

Figure 3 shows the track forecast errors and skill (relative to the default) for HAFS-A (HFSA) and HAFS-B (HFSB) along with their corresponding “progsigma” tests (HFAP and HFBP). Also included in the figure is the consistency metric developed by Ditchek et al. (2023) to determine if forecast improvement/degradation is consistent (consistency is a measure of the robustness of the results, somewhat similar to a measure of statistical significance). The results show that for both HAFS-A and HAFS-B, there is marginally consistent improvement at longer lead times for the Ian cases. For HAFS-B, this mostly comes from improvement in early cycles where the default retrospective configuration had a left bias. For HAFS-A, the signal is slightly less clear, and there is also some marginally to fully consistent degradation at earlier leads.

Figure 4 shows the intensity forecasts errors and skill for the default and “progsigma” tests for HAFS-A and HAFS-B. In general, the results are overall mostly neutral. There was slight, marginally consistent improvement for HFAP over HAFS-A, but no notable changes in the bias. For HFBP compared to HFSB, there were some changes in the bias. In particular, HFBP had more of a positive bias, especially for several early cycles, than HFSB, which led to some marginally consistent degradation. However, there was marginally consistent improvement at longer leads, so the results were again mostly neutral. It is not immediately clear why “progsigma” would lead to different bias characteristics for HAFS-B but not for HAFS-A, although it may be due to the fact that the development of this closure was optimized in a physics suite using the Thompson microphysics. An example using HAFS-B will be explored somewhat further.

It is possible that the PBL changes introduced in HAFS-B are having a larger effect when coupled with the mass flux changes in the convective scheme.

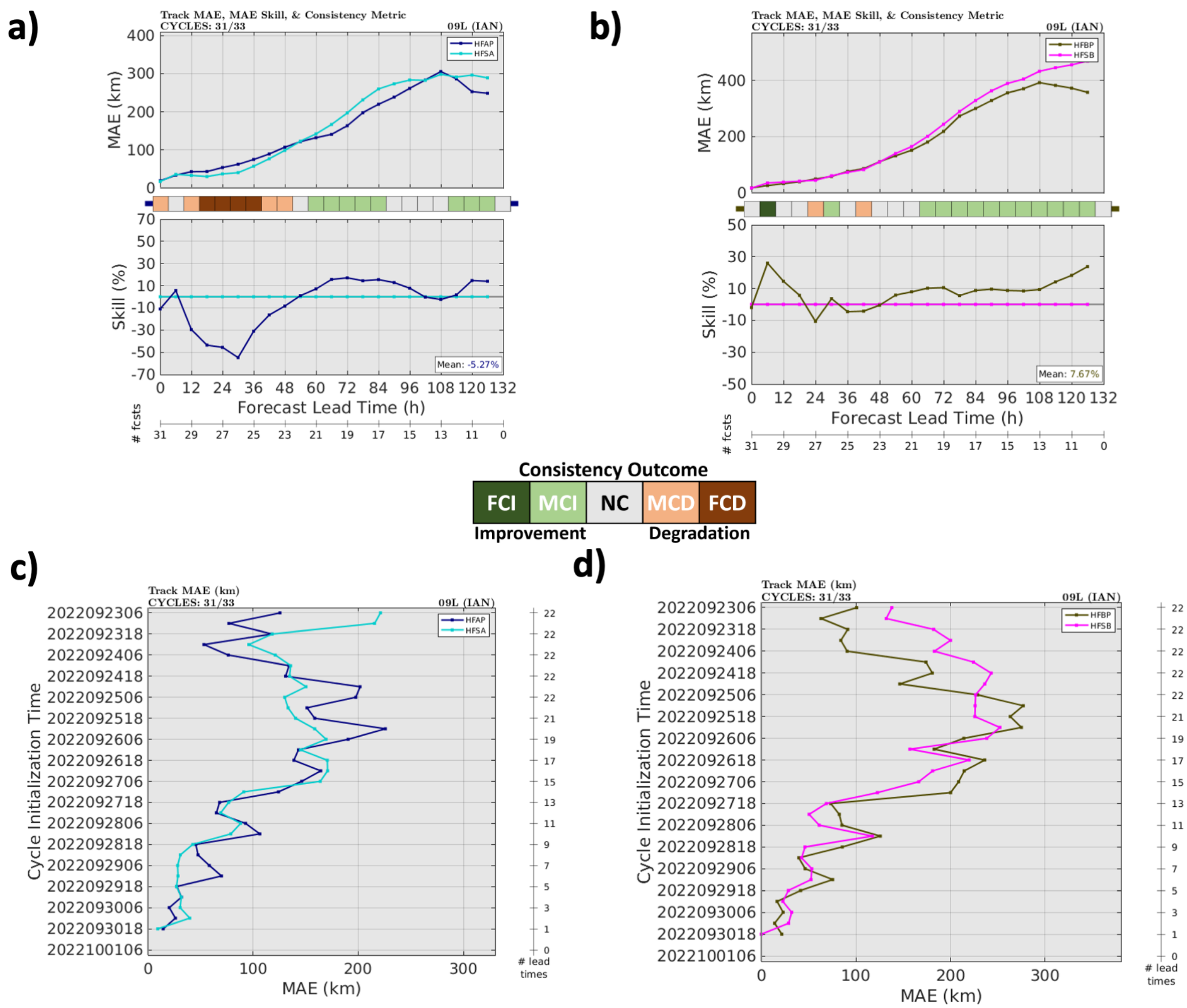


Figure 3: a) Track forecast mean absolute error (MAE, km) for HFSA and HFAP in the top panel. The skill relative to HFSA is also shown in the bottom panel. The middle bar shows the consistency metric from Ditchek et al. (2023) for these forecasts. b) As in a), but for HFSB/HFBP. c) Cycle-by-cycle mean track error (km) for HFSA and HFAP. d) As in c), but for HFSB/HFBP.

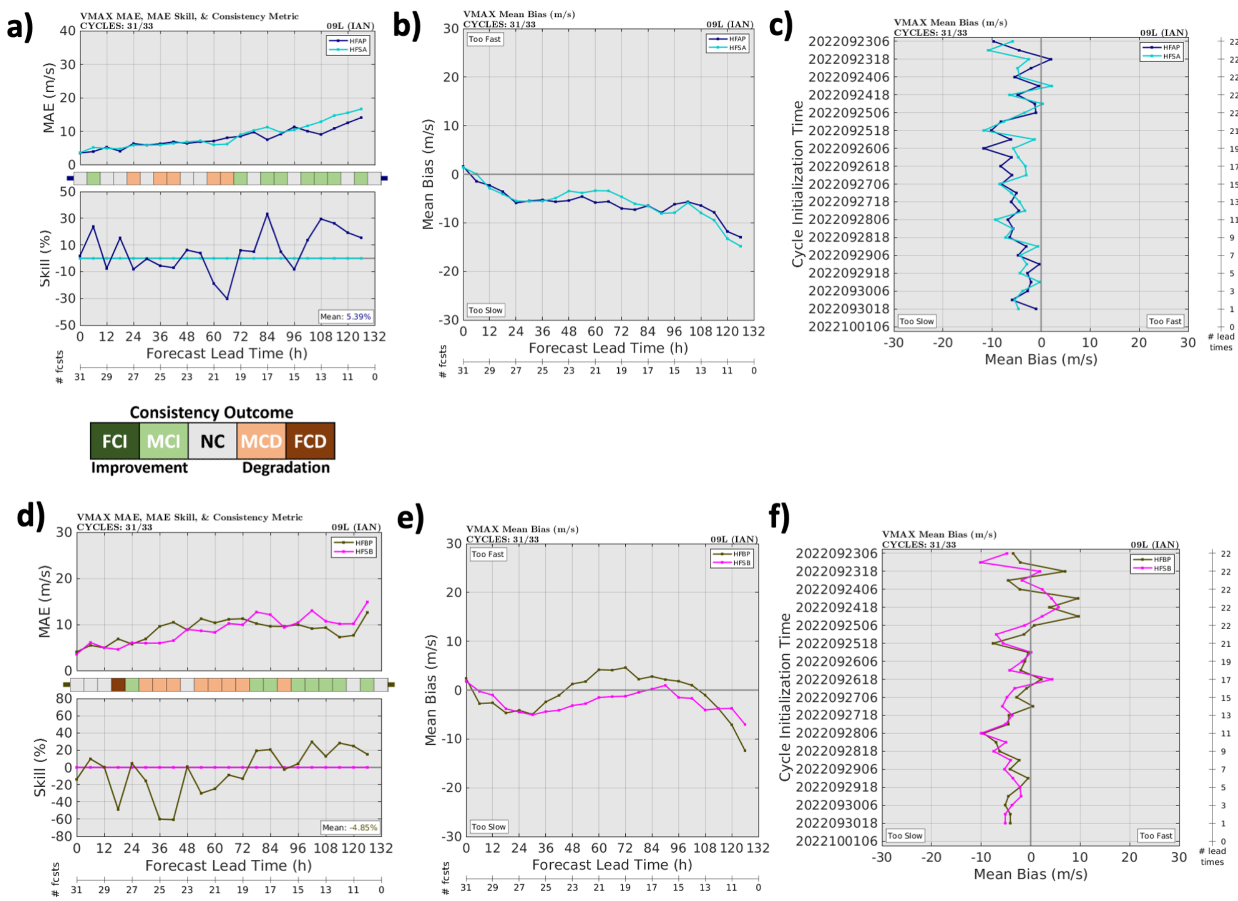


Figure 4: a) Intensity forecast error (m s^{-1}) for HFSA and HFAP. The skill relative to HFSA is also shown, along with the consistency metric from Ditchek et al. (2023). b) As in a), but for intensity bias. c) Cycle-by-cycle mean intensity bias (ms^{-1}) for HFSA and HFAP. The number of forecast lead times for each cycle is shown along the right hand side. d) As in a), but for HFSB/HFBP. e) As in b), but for HFSB/HFBP. f) As in c), but for HFSB/HFBP.

To examine some of the reasons for the intensity forecast differences in HAFS-B with and without progsigma, we focus on a case study of one early cycle, specifically the cycle initialized at 18 UTC September 23, 2022. Figure 5 shows the track, maximum wind speed, and minimum pressure forecasts from default HAFS-B (HFSB) and HAFS-B with progsigma (HFBP) for this cycle. The tracks are initially very similar, but diverge as the TC approaches Cuba, with HFBP showing a more realistic curve to the north and then northeast towards the West Coast of Florida, while HFSB moved more slowly north and then kept the TC out over the northern Gulf of Mexico. For the intensity evolution, the forecasts are again very similar for the first two days, but diverge significantly around Days 2-3, with default HAFS-B intensifying at a rate close to observed for most of the forecast, but HAFS-B with progsigma showing an excessive rate of intensification. To diagnose the reasons for this excessive intensification, we compared the two HAFS forecasts with observations from the NOAA P3 radar, specifically the tail Doppler radar (TDR) observations, during the period of intensity divergence. Figure 7 shows the comparison of reflectivity and wind structure from the model and observations valid for the 66-hour forecast, while Figure 8 shows the comparison twelve hours later, valid for the 78-hour forecast. While the overall structure of the TC is generally similar to observations, and similar between the two forecasts, there are some notable differences that explain the intensity differences. For example, both the wind field and precipitation field are more compact in HAFS-B with progsigma than with default HAFS-B. This favors greater rates of intensification, as convection inside the radius of maximum winds (RMW) has been shown to be more conducive for TC intensification (e.g. Rogers et al. 2013, Hazelton et al. 2017), favoring enhanced inflow inside the RMW leading to greater spin up of the TC vortex (e.g. Smith and Montgomery 2015). In the 78-h forecast, the precipitation and wind fields are also much more symmetric in HAFS-B with progsigma. In general, it appears that the HAFS-B physics with progsigma leads to a more compact, symmetric vortex that has a much greater positive feedback rate once intensification begins, leading to greater and, for some cycles, excessive intensification of the TC. It should be noted that this analysis used the “default” version of progsigma, so it is possible that with modified tuning, the excessive parameterized convection will be lessened and the results will be more accurate.

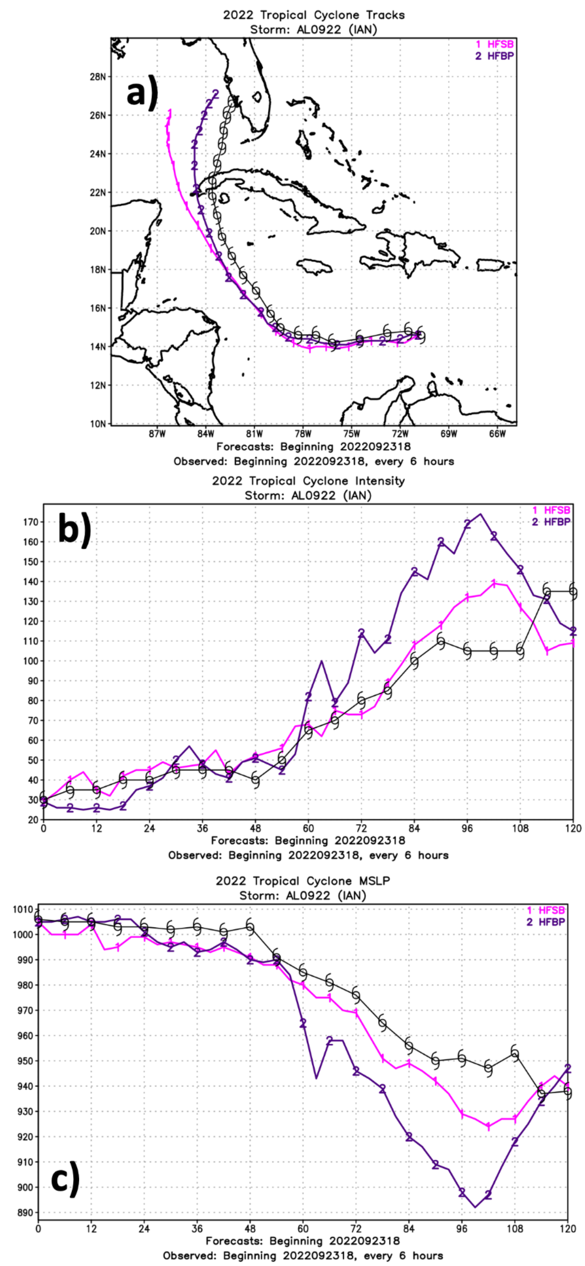


Figure 5: a) Track forecasts from default HAFS-B (magenta) and HAFS-B with progsigma (purple) initialized at 18 UTC September 23, 2022. b) As in a), but for forecasts of maximum wind speed. c) As in a), but for forecasts of minimum central pressure.

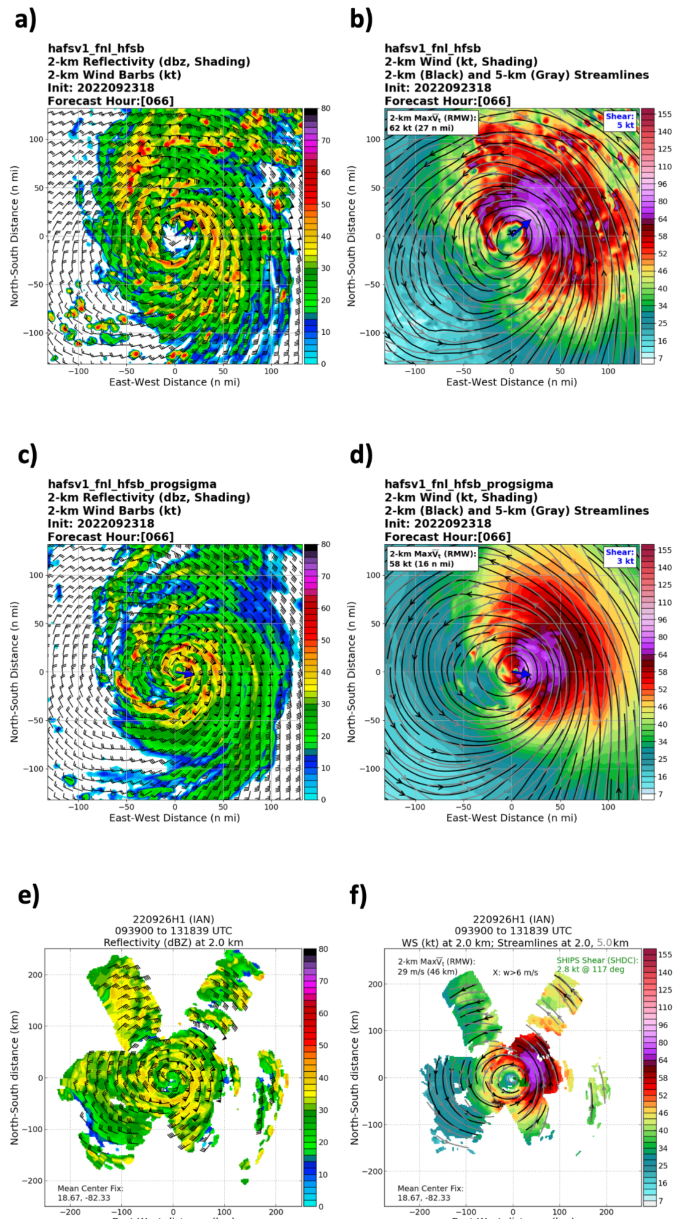


Figure 6: a) 66-h forecast 2-km reflectivity (shaded) and wind barbs from HAFS-B initialized 18 UTC September 23, 2022. b) 66-h forecast 2-km wind speed (shaded) and 2-km/5-km streamlines from HAFS-B. c) As in a), but for HAFS-B with progsigma. d) As

in b), but for HAFS-B with progsigma. e) TDR observed 2-km reflectivity (shaded) and wind barbs valid at ~12 UTC September 26, 2022. f) TDR observed 2-km wind speed (shaded) and 2-km/5-km streamlines valid at ~12 UTC September 26, 2022.

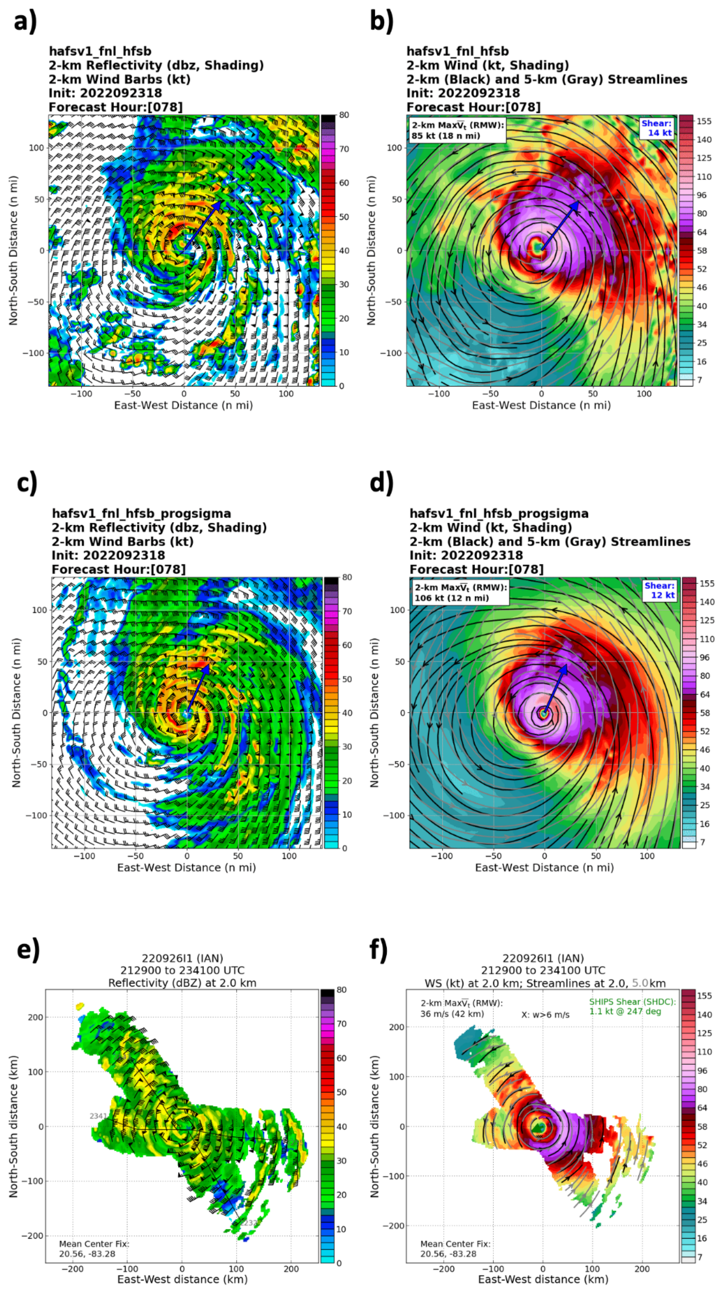


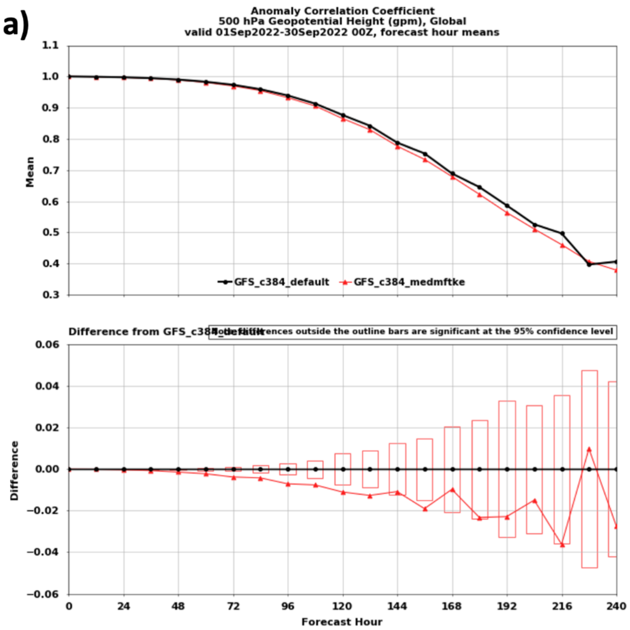
Figure 7: As in Figure 6, but for the 78-h forecast and observations valid at ~00 UTC September 27, 2022.

c. Hurricane PBL Physics in GFS

The results presented so far illustrate that model physics can have a notable impact on TC structure across different scales. To further examine how TC-specific PBL physics impact large-scale predictability, experiments are conducted with the Global Forecast System (GFS). This experiment also allows for testing that looks towards the goal of unified physics across scales and applications within the UFS. For these tests, we used a 25-km version of the GFS, to be able to run a large number of cases. Specifically, we ran 10-day forecasts every 6 hours for the entire month of September 2022. We used two configurations of the GFS - the first was the default GFSv16 (at C384 or 25-km grid spacing), and the second configuration included the version of the EDMF-TKE PBL scheme modified for TCs using LES data and observations (Chen et al. 2022, 2023). We evaluated both the large-scale forecast skill and also the global TC skill, to get a better understanding of how the PBL changes impact UFS predictability at global scales.

The first evaluation was the global anomaly correlation of 500-hPa height (Figure 8). There were no major differences between the two experiments for the first 2-3 days, but with increasing lead time there was a small but notable decrease in anomaly correlation with the modified PBL physics. There was a small increase in skill relative to GFS around Day 9, but the small sample size (from only one month of forecasts) makes it hard to interpret this result. Other global verification metrics (including at 250 hPa) showed similar results (not shown). These findings indicate that, although the PBL modifications lead to improvements in the intensity and structure forecasts for the hurricane application, they are currently not optimal for the finely-tuned global skill (at least for the relatively small sample of cases examined here), and resolving this discrepancy would be a valuable avenue of future research.

a)



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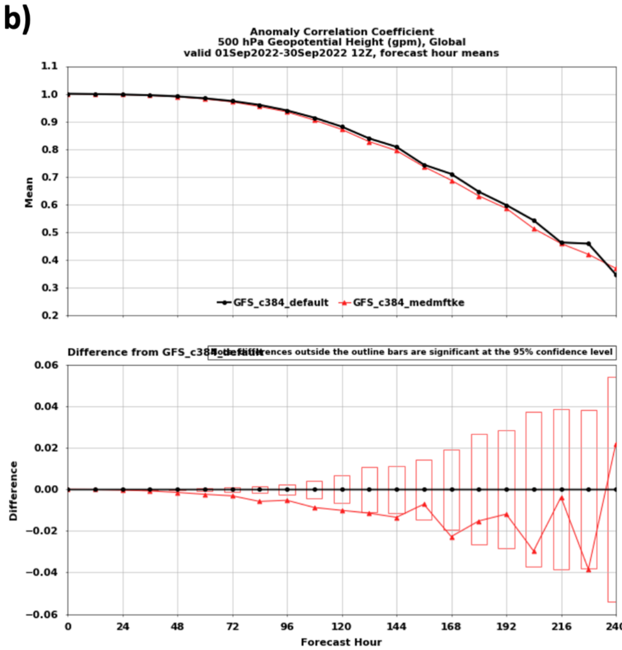

Figure 8: a) Top: Global 500-hPa height anomaly correlation from the default GFS (black) and GFS with modified PBL physics (red) for all 00Z runs. Bottom: Difference between the default and modified GFS. b) As in a), but for all 12Z runs.

Despite the fact that the GFS large-scale anomaly correlation at mid/upper levels showed slight degradation from the modified PBL physics, there were other metrics where the modifications did prove useful to improving the large-scale skill. For example, Figure 9 shows the global PBL height for the default and modified GFS runs, and also the dewpoint temperature bias (compared with observations) over the Eastern United States. Not surprisingly, since the PBL modifications tend to reduce mixing, the PBL height is lower in the modified version of the GFS. Also as a result of reduced mixing, the dewpoint bias (a negative or dry bias) is reduced over the Eastern U.S. This result shows how complex the interplay between different verification metrics can be, with TC-specific results, large-scale upper-level metrics, and surface verification metrics all painting slightly different pictures.

Finally, since the PBL changes were originally designed for TC forecast improvement, we evaluated the global TC track forecast skill in the 25-km GFS with the original and modified PBL physics. Figure 10 shows the track forecast error and skill for the Atlantic, East Pacific, and West Pacific, all of which had TC activity during September 2022. The figures also show the consistency metric from Ditchek et al. (2023), which shows how robust and reliable the results are. Once again, the skill is a mixed bag. For the Atlantic, there is some slight (5-10%) but consistent track degradation with the modified PBL physics. The East Pacific results are mostly neutral. For the West Pacific, there is marginally to fully consistent improvement in longer-lead track forecasts (Days 5-7), but the sample size is fairly small at this lead. In general, these findings are mostly consistent with the mixed large-scale verification results, and indicate that more work needs to be done to develop modifications to the PBL physics that lead to large-scale forecast improvements as well as TC forecast improvements across a wide range of scales.

a)

b)

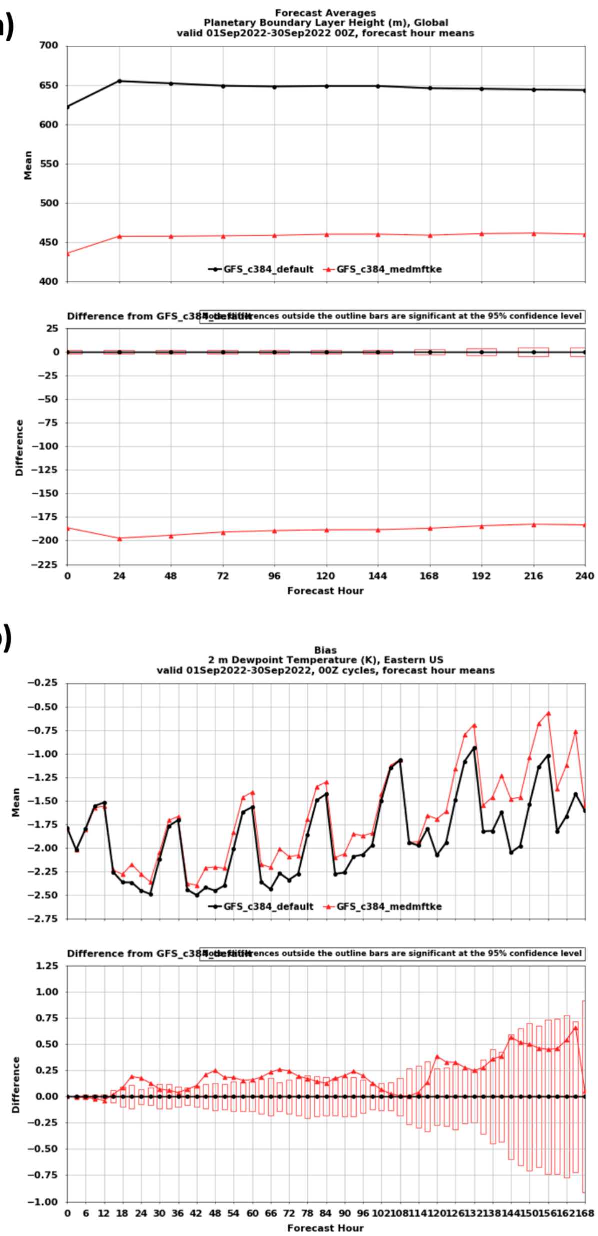

Figure 9: a) Top: PBL height for 00Z runs of the default (black) and modified (red) GFS. Bottom: Difference in PBL height between the default and modified GFS. b) Top: 2-m dewpoint temperature bias over the Eastern U.S. for 00Z runs of the default (black) and modified (red) GFS. Bottom: Difference in dewpoint temperature bias between the default and modified GFS.

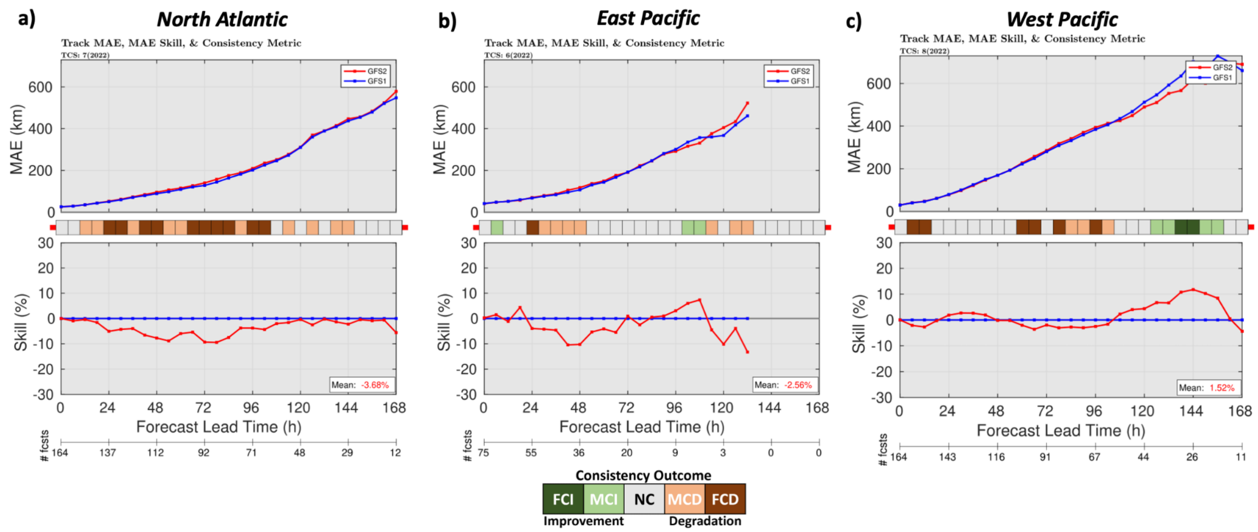

Figure 10: a) Atlantic TC track forecast error (top) for default (blue) and modified (red) GFS, with the skill relative to default shown on the bottom. The consistency metric from Ditcheck et al. (2023) is also shown in the middle. b) As in a), but for the East Pacific. c) As in a), but for the West Pacific.

3. Discussion, Conclusions, and Future Work

In this project, we performed a variety of TC-focused evaluations of UFS physics across a variety of different applications and scales. This was done in order to evaluate the different physics suites and schemes, particularly the PBL physics and its interactions with other physics components (such as the cumulus physics) in these different applications, with the long-term goal of unification of physics. In the Hurricane Laura runs with HAFS and the UFS SRW application, we saw how biases in the large-scale flow could lead to significant track biases (in this case, a leftward track bias). In this case, the bias did not appear to be driven by the PBL physics or microphysics, as suites with both the Thompson MP and GFDL MP, and default and modified EDMF-TKE, all showed similar leftward bias. On the other hand, there did appear to be impacts from changing the resolution. The 13-km SRW runs actually had a better forecast track than the 3-km SRW runs (for both physics suites), indicating that the behavior of the physics (in particular, the cumulus physics) at different scales (i.e. the scale-awareness) is not yet optimal, motivating further examination of the scale-aware aspects of the physics.

To more thoroughly explore these scale-awareness considerations in a hurricane application, we ran several forecasts of Hurricane Ian using the “progsigma” updated closure scheme in the scale-aware SAS convective scheme in HAFS. For HAFS-A, the differences were marginal. For HAFS-B (which includes the Thompson microphysics and tc-pbl options), using progsigma resulted in a more realistic track forecast (less leftward bias) but excessive deepening of the cyclone. Work is ongoing to tune and optimize the progsigma approach in HAFS-B.

Finally, the last test built on these large-scale impacts of the physics, to go even beyond the TC skill and examine how physics modifications impact the global forecast skill in the GFS for the month of September 2022. Our evaluation of the default and modified EDMF-TKE schemes revealed some degradation of global anomaly correlation from the PBL physics modifications, but improvement in other metrics, including a dewpoint bias over the Eastern U.S., likely due to less mixing in the PBL. The TC track results from this experiment were overall neutral at long range despite the large-scale forecast degradation. This experiment points to the need for unification of physics for both TC and large-scale applications.

These results point to several areas for future and ongoing research. One such avenue is unification of the convective and PBL physics to perform well for both small-scale applications (like the HAFS moving nest) and large-scale applications (like the GFS). Even for finer-scale applications, we are exploring ways to improve the physics to simulate both convective-scale processes and the large-scale flow responsible for TC steering. Another key area of future exploration is how different schemes interact (such as the PBL and cumulus physics together) to alter TC structure. Finally, utilizing the uncertainties in the model physics to explore ensemble prediction is another avenue that we think could prove fruitful.

Acknowledgements

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