Evaluating Sub-Grid Cloud Variability Enhancements in HAFS Tropical Cyclone Predictions

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Final Project Report

Developmental Testbed Center (DTC) Visitor Program 2022-2024

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1. Overview

The main objective of this project for the Developmental Testbed Center Visitor Program was to evaluate several cloud overlap options in the 2023 Hurricane Analysis and Forecast System (HAFS-A_v1) hurricane model using the RRTMG radiation code (*Iacono et al.,* 2008) in support of selecting the optimal configuration for NOAA operations. ***Based in part on this research, the NOAA Environmental Modeling Center (EMC) plans to perform more comprehensive testing to establish the optimal cloud overlap configuration for the 2025 operational HAFS***. This outcome was supported through testing of the physics change in multiple tropical cyclone (TC) hindcast predictions using several cloud overlap configurations that were performed by AER and by DTC during this project. These experiments showed sufficient sensitivity in TC track and intensity forecasts to cloud overlap to justify further investigation. This project reinforces the results of our prior DTC projects in documenting the influence that sub-grid cloud overlap can have on the prediction of tropical cyclone track and intensity (*Iacono and Henderson*, 2021; *Iacono and Henderson*, 2019). Finally, results from this project were communicated through a conference presentation, and a new publication on this research, to be submitted in 2024, is in preparation.

Recommendations: The exponential (EXP) and exponential-random (ER) cloud overlap methods were each tested in HAFS-A along with the 2023 default maximum-random (MR) operational setting using different methods for specifying the required decorrelation length as a spatially varying quantity. Although the modest scale of testing and validation that was accomplished during this visitor project was not extensive enough for us to draw definitive conclusions about which overlap configuration has the most potential to improve hurricane forecast skill with HAFS-A, we can make the following recommendations:

1) From a physics perspective, EMC should consider the ER overlap method as the higher priority for future HAFS operational use than either the AER-developed or the NOAA-developed EXP approaches or the older MR method,
2) Either of the EXP overlap methods should be considered a second priority for HAFS operational use rather the MR method from the perspective of consistency with the global GFS model (v16), which uses the NOAA-developed EXP method operationally,
3) EMC should perform further testing of the new *Oreopoulos et al (2022)* decorrelation method for the operational HAFS (EMC has expressed interest in taking this action).

2. Background

2.1 Cloud Fraction Overlap

The representation of the sub-grid scale properties of clouds in dynamical models remains a significant source of uncertainty in weather forecasts and climate projections. This uncertainty is due in part to the vertical correlation or overlap of clouds and its strong impact on cloud radiative processes, and improving our understanding of these effects is critical to simulations of the atmosphere (*Nam et al.,* 2012; *Wu and Liang*, 2005).

Of importance to the project tasks is the application within RRTMG of the Monte-Carlo Independent Column Approximation (McICA; *Barker et al*., 2008; *Pincus et al.*, 2003), which is a statistical technique for representing the sub-grid variability of clouds within the radiative transfer calculations. At present, McICA is used to represent the cloud fraction and vertical correlation of clouds. Cloud overlap assumptions in RRTMG include random (no correlation between disassociated, separated cloud layers), maximum (fully overlapping in the vertical within adjacent, multiple cloud layers), and a blend of these two called maximum-random (maximum overlap in adjacent cloud layers and random overlap among separated groups of cloud layers) first described by *Geleyn and Hollingsworth* (1979). During our previous DTC/VP efforts, RRTMG was modified to use the exponential and exponential-random (*Hogan and Illingworth*, 2000; *Shonk, et al.,* 2010a) cloud overlap methods, which presume that the vertical correlation within a group of adjacent cloud layers transitions inverse exponentially from maximum to random with increasing distance. The exponential (EXP) and exponential-random (ER) methods are in effect a compromise between the more extreme random and maximum-random (MR) assumptions. The EXP and ER approaches define the exponential transition, α, of cloud overlap from maximum to random within continuous cloud layers as a function of upward vertical distance through the cloud, Δz, and a decorrelation length, Z_c:

$$\alpha = e^{-(\Delta z / Z_c)} \; . \qquad [1]$$

High decorrelation lengths ($\alpha \rightarrow 1$) infer a greater tendency toward maximum overlap, and low decorrelation lengths ($\alpha \rightarrow 0$) infer a greater tendency toward random overlap. Finely spaced vertical layering implies smaller values of Δz, higher α, and maximum overlap, while coarser vertical spacing corresponds to higher values of Δz, lower α, and more random vertical correlation. Through multiple adjacent cloudy layers, the vertical correlation trends toward random overlap as the exponential transition is applied at each layer. The difference between EXP and ER is subtle but potentially radiatively significant. In EXP overlap, the exponential transition and the specification of α occurs through all layers regardless of the cloud configuration. In ER overlap, the presence of at least one clear layer between cloudy layers introduces a degree of randomization in that the exponential transition within non-adjacent blocks of cloudy layers are correlated randomly, which is specified by setting α to zero within any clear layers between cloudy layers. As discussed by *Hogan and Bozzo* (2018), the EXP approach (which they refer to as EXP-EXP) generally underestimates total cloud cover relative to ER, and in some configurations EXP can even underestimate total cloud cover relative to MR overlap.

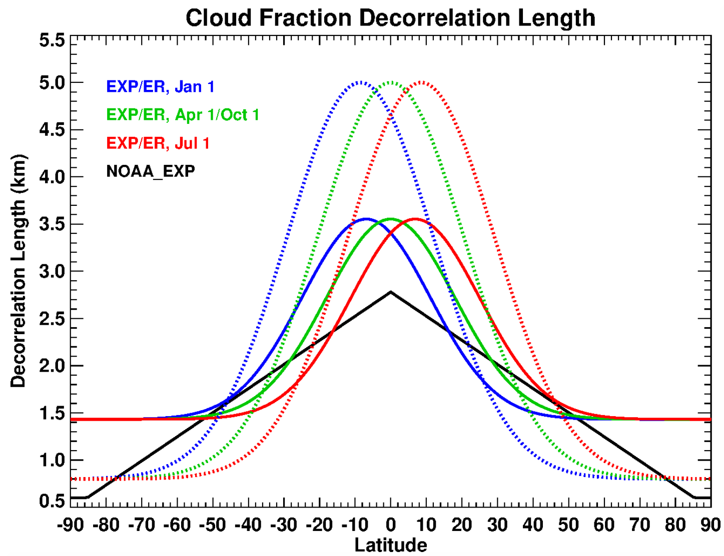

Figure 1. Decorrelation length as a function of latitude for the spatially varying and day of year varying method of *Oreopoulos et al.* (2012) plotted for January 1 (blue, solid), July 1 (red, solid), April 1 and October 1 (green, solid) and for *Oreopoulos et al.* (2022) plotted for the same dates (dotted). Also shown is the latitude varying decorrelation length method of *Hogan and Bozzo* (2018) implemented by NOAA (black).

Considerable uncertainty remains regarding the optimal specification of Z_c in dynamical models. In our HAFS experiments for this project, we used ER overlap with a method for specifying decorrelation length that varies by latitude and day of the year (*Oreopoulos et al.,* 2012). An update to this method was released more recently (*Oreopoulos et al.*, 2022), which we installed in HAFS and used in one test for this project. The earlier approach applies lower decorrelation length values (~1.5 km) at high latitude where cloud vertical correlation is more random and higher values (~3.5 km) at low latitude where cloud vertical correlation tends more toward maximum in deep convection. Decorrelation length values as specified by this method are illustrated in Figure 1 at three-month intervals during the year. The update to this method, based on more recent satellite observations, specifies Z_c over a much wider range of values. Also shown in Figure 1 (labeled "NOAA_EXP") is the latitude varying decorrelation length method of *Hogan and Bozzo* (2018), which does not vary by day of year and covers a lower range of values for Z_c. The latter method was implemented by NOAA EMC as the decorrelation length method for use with NOAA_EXP cloud overlap in the global forecast system (GFS), and this configuration is currently operational with RRTMG in GFSv16 and in the 2024 operational HAFS.

2.2 HAFS-A Configuration

During this project, the HAFS model used for all TC experiments was the near-operational version of HAFS-A_v1 available to DTC during early to mid-2023. All HAFS code was obtained from the develop branch of the HAFS GitHub code repository[1]. All HAFS experiments used the

[1] https://github.com/hafs-community/HAFS

standard high-resolution (~1.3 km) nested grid within a larger synoptic grid covering the Atlantic or Eastern Pacific basins. Since initial condition input files appropriate for this model were only available to DTC for the years 2021-2023, the cases selected for this project were limited to these seasons. All forecast cycles were performed with HAFS-A for the six TC cases described in the next section, and the details of these experiments are listed in Table 1. Generally, individual forecast cycles were run in "cold start" mode in which the TC environment is not propagated from prior cycles. AER completed some of the TC experiments on the NOAA computing system "Jet", but due to computer allocation and resource limitations, DTC supported this project by performing several of the hurricane forecast cycle experiments on the MSU supercomputer "Orion".

2.3 Tropical Cyclone Cases

This project assessed the sensitivity of hurricane forecasts to radiative cloud overlap on the evolution of several recent strong or high-impact TC cases including Hurricanes Ida, Ian, Franklin, Idalia, Lee, and Otis. Hurricane Ida was a Gulf of Mexico TC that was active from 26 August to 1 September 2021 (*Beven et al.*, 2022). This storm reached Category 4 intensity before making landfall in Louisiana with maximum sustained winds near 130 kts. Hurricane Ian was a high-impact storm that was active from 23-30 September 2022 in the western Caribbean and the eastern Gulf of Mexico and reached Category 5 intensity as it recurved toward the north and northeast (*Bucci et al.*, 2023). Ian weakened slightly before making landfall in western Florida, but it caused catastrophic storm surge and devastation in the vicinity of Fort Myers. Hurricane Franklin was active from 20 August to 1 September 2023, and it followed an unusual path as a tropical storm with several changes in direction as it passed through the Caribbean, crossed Hispaniola, and recurved into the northwestern Atlantic basin before intensifying and reaching Category 4 intensity (*Beven*, 2024). Franklin remained over the open Atlantic as it passed within 75 km northwest of Bermuda as it recurved to the northeast. Hurricane Idalia was another significant cyclone in the eastern Gulf of Mexico that was active from 26-31 August 2023 and was generally well forecast by HAFS and other models in real-time. Idalia reached Category 4 intensity before weakening to Category 3 at landfall in a rural part of the Big Bend area of Florida (*Cangialosi and Alaka*, 2024). Hurricane Lee, which was active from 5-16 September 2023, formed in the central Atlantic where it reached a peak intensity of Category 5 before briefly threatening the U.S. East Coast (*Blake and Nepaul*, 2024). Lee remained offshore and moved northward as it weakened, and after passing east of New England it made landfall as a strong post-tropical cyclone in southwestern Nova Scotia. Hurricane Otis was only active for a few days from 22-25 October 2023, but its track and extremely rapid intensification of 90 kts in less than 24 hours to Category 5 were initially very poorly forecast by all models just 48 hours prior to landfall at Acapulco, Mexico (*Reinhart and Reinhart*, 2024). Otis produced catastrophic storm surge, flooding, and widespread damage, and the cyclone was one of the strongest landfalling hurricanes on record over western Mexico.

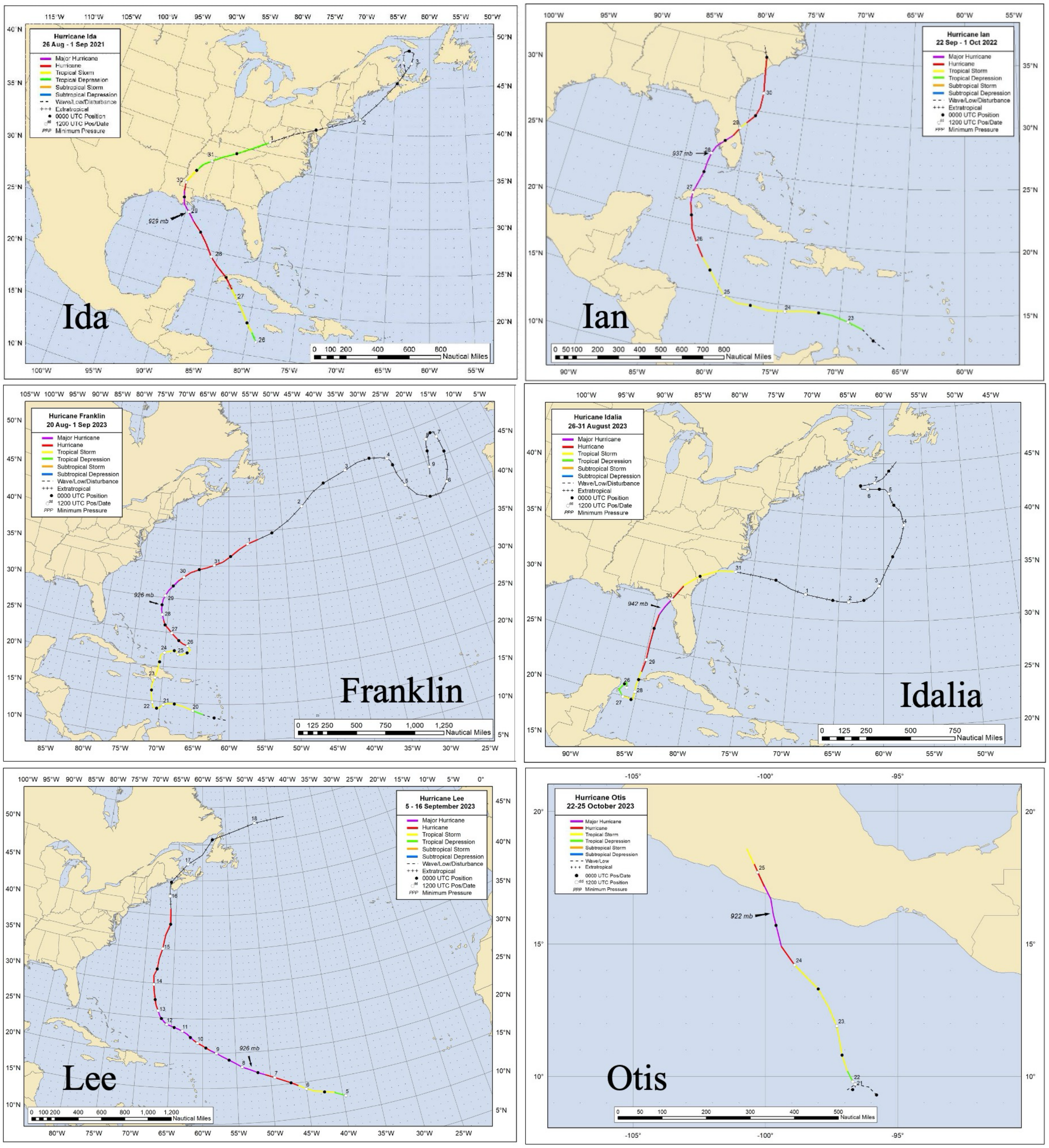

Figure 2. Observed "best-track" positions of Hurricane Ida through the Gulf of Mexico from 26 August to 1 September 2021 (top left), Hurricane Ian across Cuba to landfall in Florida from 23-30 September 2022 (top right), Hurricane Franklin across the northwest Atlantic basin from 20 August to 1 September 2023 (center left), Hurricane Idalia through the eastern Gulf of Mexico through landfall in Florida from 26-31 August 2023 (center right), Hurricane Lee through the western Atlantic basin from 5-16 September 2023 (bottom left), and Hurricane Otis in the Eastern Pacific basin to landfall in western Mexico from 22-25 October 2023 (bottom right). Best-track graphics provided by the NOAA National Hurricane Center.

3. HAFS-A Predictions and Discussion

Hurricane Ida (AL092021)

Our initial TC experiment using HAFS-A was a single forecast cycle of Hurricane Ida that was initialized at 12 UTC on 26 August 2021. For this test case and for all that follow, a set of three predictions was completed that differed only in the cloud overlap method used, where the three approaches were MR (the operational default for HAFS at the time of these experiments in 2023), NOAA_EXP (the default setting used in GFS), and ER. Figure 3 shows the track predictions for MR (in blue), NOAA_EXP (in green), and ER (in red). Also shown is the observed "best-track" position of Ida (in black). This case showed very little track sensitivity to cloud overlap with all three predictions closely matching the observed track except for a small initial eastward bias and a slight westward bias after landfall.

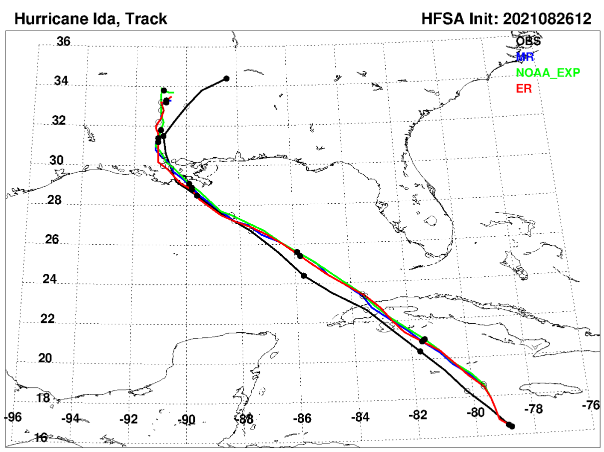

Figure 3. Hurricane Ida track predictions for a forecast cycle initialized at 12 UTC on 26 August 2021 simulated by HAFS-A using three cloud overlap methods including MR (blue), NOAA_EXP (green), and ER (red). Also shown is the observed "best-track" position of Ida (black).

Predicted central pressure (in hPa) and maximum wind speed (in knots) for the same forecast cycle of Ida are shown in Figure 4 along with the "best-track" observed values. Both pressure and wind speed show some sensitivity to cloud overlap overall for this case with ER generating a slightly more intense storm than the other approaches, which is in better agreement with the observed intensity during the period of lowest pressure prior to landfall in Louisiana on 29 August 2021.

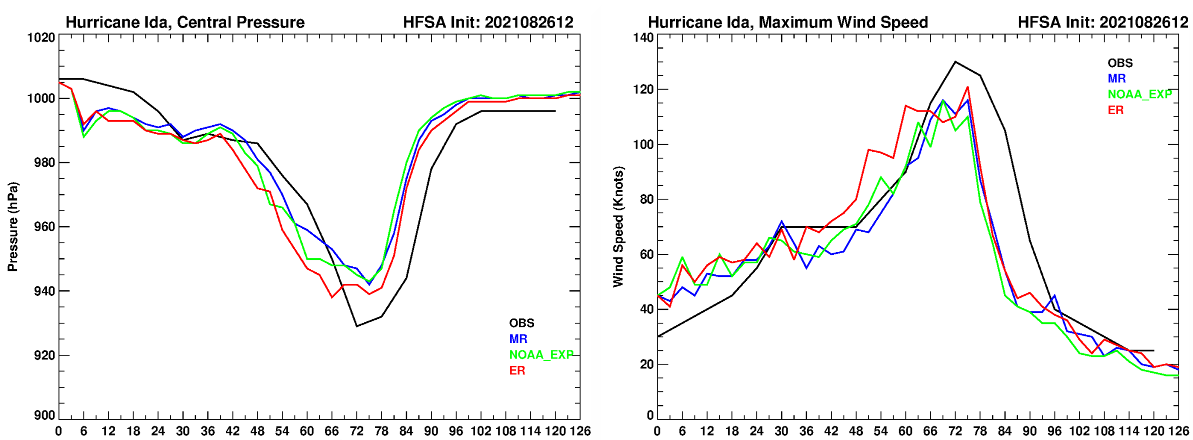

Figure 4. Hurricane Ida central pressure (left) and maximum wind speed (right) predictions for a forecast cycle initialized at 12 UTC on 26 August 2021 as simulated by HAFS-A using three cloud overlap methods including MR (blue), NOAA_EXP (green), and ER (red). Also shown is the observed "best-track" pressure and wind speed data for Ida (black) during this period.

TC Name	TC Code	Forecast Cycle Experiment Initialization Times			
Ida	AL092021	20210826_1200			
Ian	AL092022	20220924_0000	20220925_1200	20220926_1200	20220927_0000
Franklin	AL082023	20230824_1200	20230827_0000		
Idalia	AL102023	20230827_1200	20230828_0000		
Lee	AL132023	20230911_1200			
Otis	EP182023	20231022_1200	20231023_0000		

Table 1. HAFS-A tropical cyclone experiments and 126-hour forecast cycle initialization times for each hurricane examined in this study. For each forecast cycle listed, a set of three forecasts were completed that represented the three cloud overlap methods used for the predictions.

Hurricane Ian (AL092022)

Four forecast cycle experiments using HAFS-A were completed for Hurricane Ian as listed in Table 1, and track predictions are shown in Figure 5 for runs that were initialized at 00 UTC on 24 September 2022 (left panel) and 12 UTC on 25 September 2022 (right panel). Also included in both panels of Figure 5 are the real-time predictions for Hurricane Ian from the operational HWRF model (in gray) and from an experimental, pre-operational version of HAFS (in yellow) as it existed in 2022. Both cycles show only modest sensitivity to cloud overlap, though the tendency for all predictions in these cycles was for landfalls too far north and west of the observed landfall location. It is notable that in the latter cycle all three predictions with the 2023 version of HAFS showed more track skill than the operational HWRF and the older version of HAFS, though it should be noted that this improvement may be due to other model changes in HAFS between the 2022 and 2023 configurations.

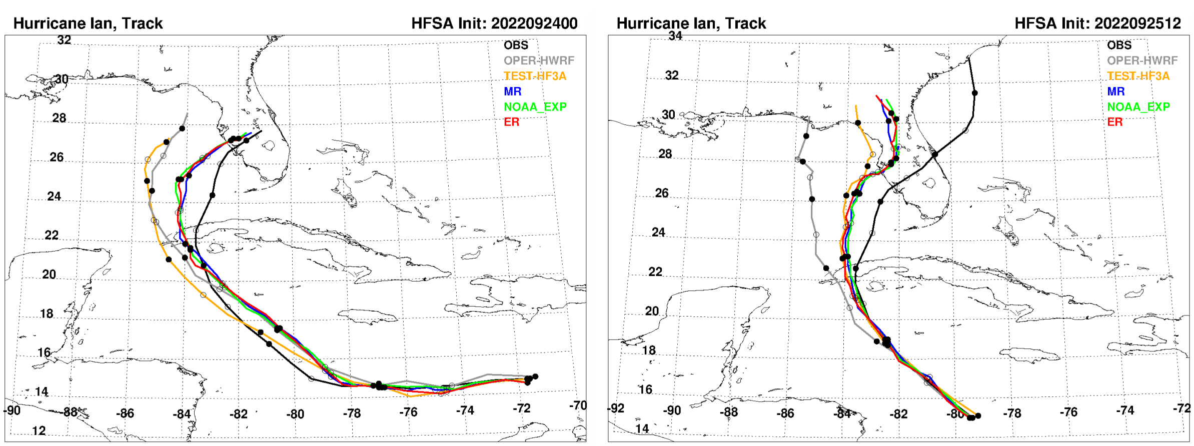

Figure 5. Hurricane Ian track predictions for forecast cycles initialized at 00 UTC on 24 September 2022 (left) and at 12 UTC on 25 September 2022 (right) as simulated by HAFS-A using three cloud overlap methods including MR (blue), NOAA_EXP (green), and ER (red). Also shown are the observed “best-track” position of Ian (black) during this period and the tracks as predicted in real-time by the operational HWRF (gray) and by an experimental pre-release version of HAFS (yellow).

Figure 6 shows the predicted surface central pressure (top panels; in hPa) and maximum sustained wind speed (bottom panels; in knots) for the same two forecast cycles of Hurricane Ian along with the "best-track" observed values and the real-time HWRF predictions for each cycle. Intensity represented by pressure shows more sensitivity to cloud overlap in the earlier cycle than the latter cycle with NOAA_EXP and ER generating a slightly more intense cyclone near Ian's maximum strength in better agreement with the observed intensity than MR cloud overlap. In the latter cycle, the lowest central pressure in the HAFS-A runs all cluster several hours later than the observed minimum pressure, which occurred a few hours before landfall (at Cayo Costa, Florida on 28 September 2022), due to the slightly later landfalls in the HAFS-A runs. The operational HWRF is a close match to the observed intensity, but for the wrong reason, since HWRF kept the storm much further west and out over open water longer than the observed track in this cycle, which allowed its continued intensification. For wind speed, both cycles indicate sensitivity to cloud overlap though all three cases show a weaker storm than observed with both exponential overlap methods doing somewhat better than MR in the earlier forecast cycle.

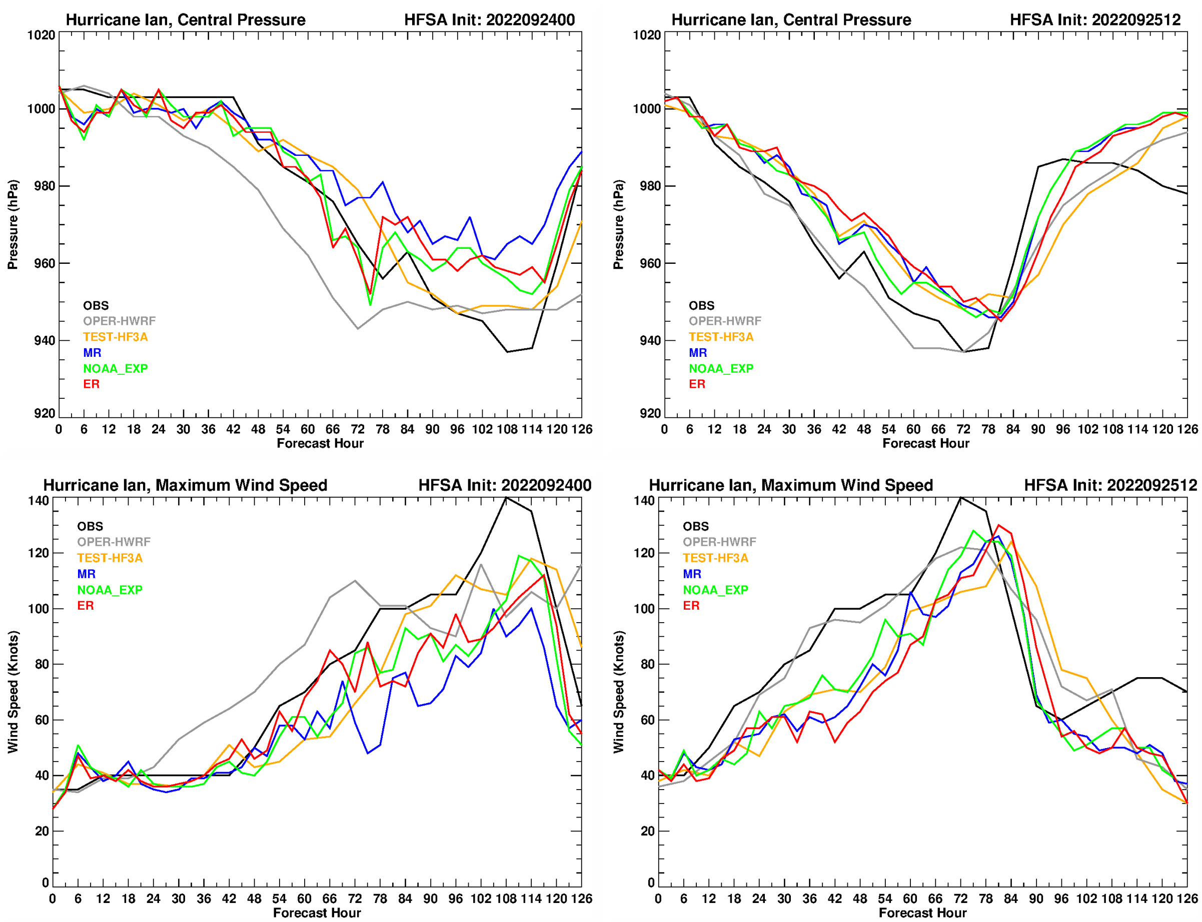

Figure 6. As in Figure 5 for Hurricane Ian central pressure predictions (top panels, hPa) and for maximum wind speed (bottom panels, knots) for the same forecast cycles.

Hurricane Franklin (AL082023)

Two cloud overlap sensitivity experiments were completed for Hurricane Franklin using HAFS-A for forecast cycles initialized at 12 UTC 24 August 2023 and at 00 UTC on 27 August 2023, and track predictions from these experiments are shown in Figure 7. Franklin's unusual track north of the Caribbean due to its interactions with a passing mid- to upper-level trough to its north and a sub-tropical ridge that replaced it presented modeling and forecast challenges in real-time during this period. In the earlier forecast cycle (left panel) for the experiments completed for this project, track skill shows some sensitivity to cloud overlap method and some improved performance during forecasts days 3-4 relative to the operational HAFS-A run (in yellow). Less track sensitivity to cloud overlap is seen in the later forecast cycle for Franklin (right panel), though some improvement is seen relative to the operational run during forecast days 2-4 when MR, NOAA_EXP and ER all show a further westward track closer to the observed track.

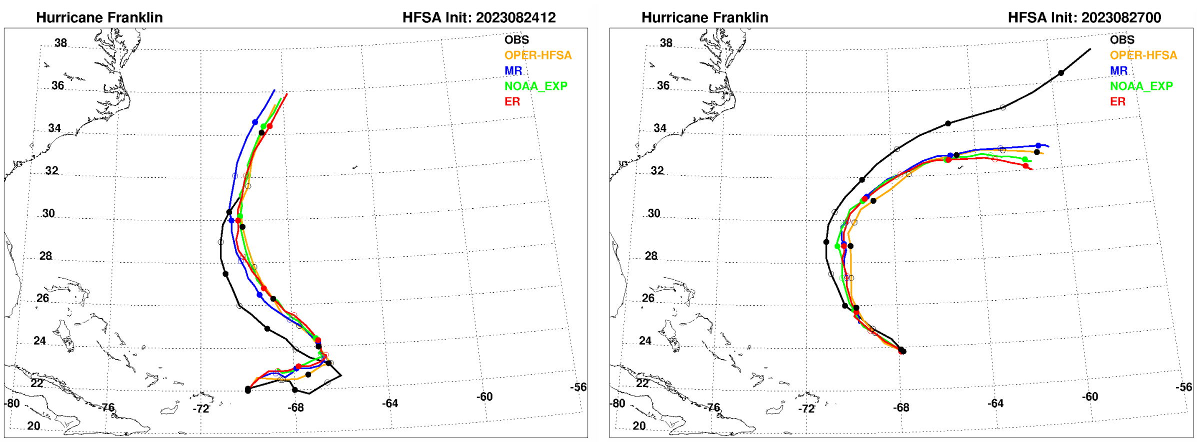

Figure 7. Hurricane Franklin track predictions for forecast cycles initialized at 12 UTC on 24 August 2023 (left) and at 00 UTC on 27 August 2023 (right) as simulated by HAFS-A using three cloud overlap methods including MR (blue), NOAA_EXP (green), and ER (red). Also shown are the observed "best-track" position of Franklin (black) during this period and the tracks as predicted in real-time by the operational HAFS-A (yellow).

Predicted surface central pressure (top panels; in hPa) and maximum sustained wind speed (bottom panels; in knots) for the same two forecast cycles of Hurricane Franklin are shown in Figure 8 along with the "best-track" observed values and the operational HAFS-A forecast. In the earlier cycle, all models predicted a cyclone that was too strong relative to the observed storm, due at least in part to an underestimation of the impact of shear on the cyclone in this period (*Beven*, 2024). During the later cycle, the model predictions are a closer match to the observed intensity for both pressure and wind speed, though some sensitivity to cloud overlap is noted throughout the cycle. Predicted 34-knot wind radii for Franklin are shown in Figure 9 for each directional quadrant from the earlier forecast cycle. Wind radii respond to the over-intensification seen in the models in this cycle and illustrate a larger wind field relative to the "best-track" statistics beyond forecast hour 72, especially in the northwest and southeast quadrants.

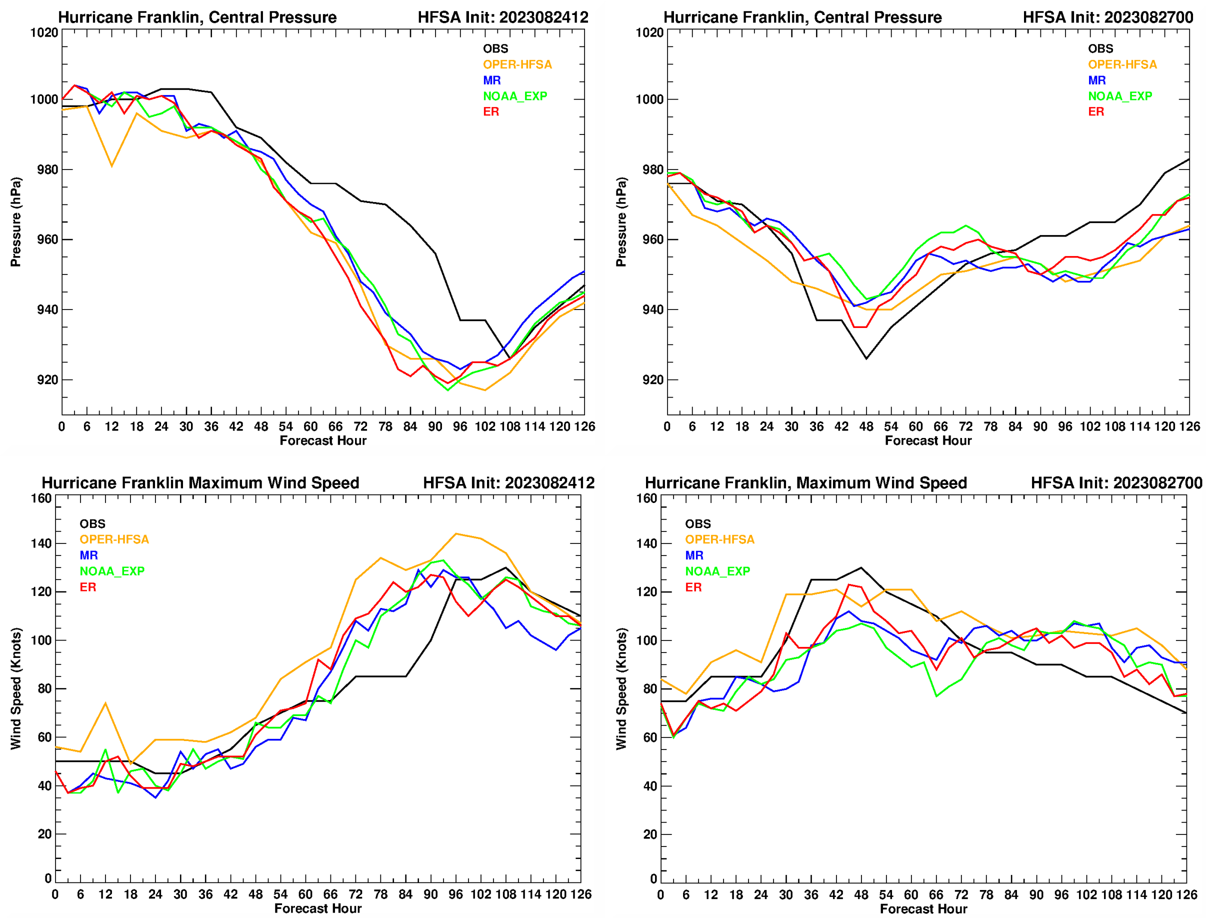

Figure 8. As in Figure 7 for Hurricane Franklin central pressure predictions (top panels, hPa) and for maximum wind speed (bottom panels, knots) for the same forecast cycles.

It is also of interest to identify the degree to which the cloud overlap method impacts the synoptic scale features that can influence TC track and intensity. This topic was explored by examining domain-wide statistics including anomaly correlations ("AC"), mean errors ("ME"), and root mean square errors ("RMSE") for several parameters including 500 hPa geopotential height, 850 hPa temperature, and 850 hPa zonal and meridional wind components. These synoptic statistics analysis plots were generated for this project using procedures from Version 11.1 of the Model Evaluation Tools (MET) package, maintained and distributed by DTC, applied to merged output grib2 files for the storm and parent model domains, which were generated every six hours. Figure 10 shows RMSE forecast errors from the Franklin parent domain for 500 hPa geopotential height (left) and for 850 hPa temperature (right). The results are color-coded by latitude band for the tropics (red; < 30 N), for the mid-latitudes (green), for polar (blue; > 60 N), and for the full domain (black) for the three cloud overlap methods including MR (solid line), NOAA_EXP (dash-dot line), and ER (dashed line). These statistics show modest sensitivity of both parameters to cloud overlap approach at the synoptic scale, especially beyond 48 hours, when averaged over latitude bands that are present within the parent domain.

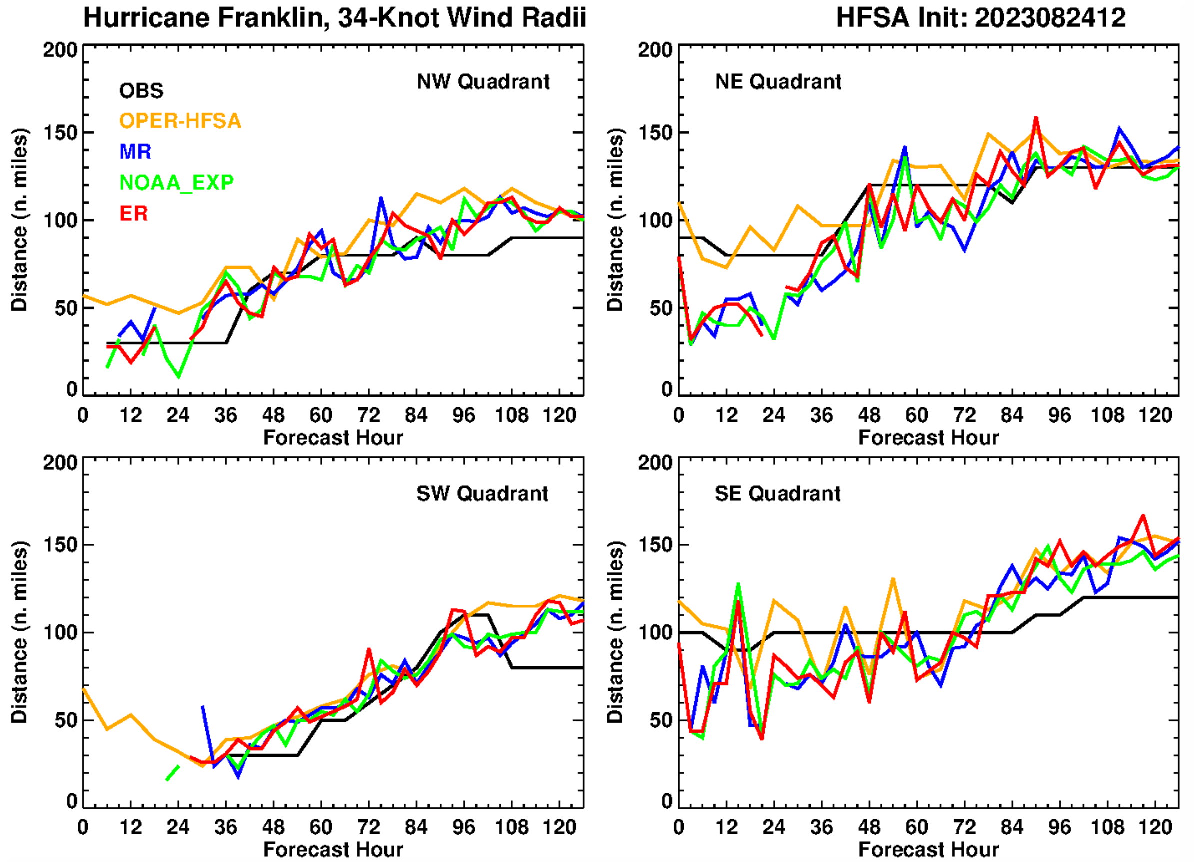

Figure 9. HAFS-A predicted 34-knot wind radii (nautical miles) for Hurricane Franklin in the four directional quadrants for a forecast cycle initialized at 12 UTC on 24 August 2023 for three cloud overlap methods, for the observed "best-track" values, and for the real-time operational HAFS-A prediction.

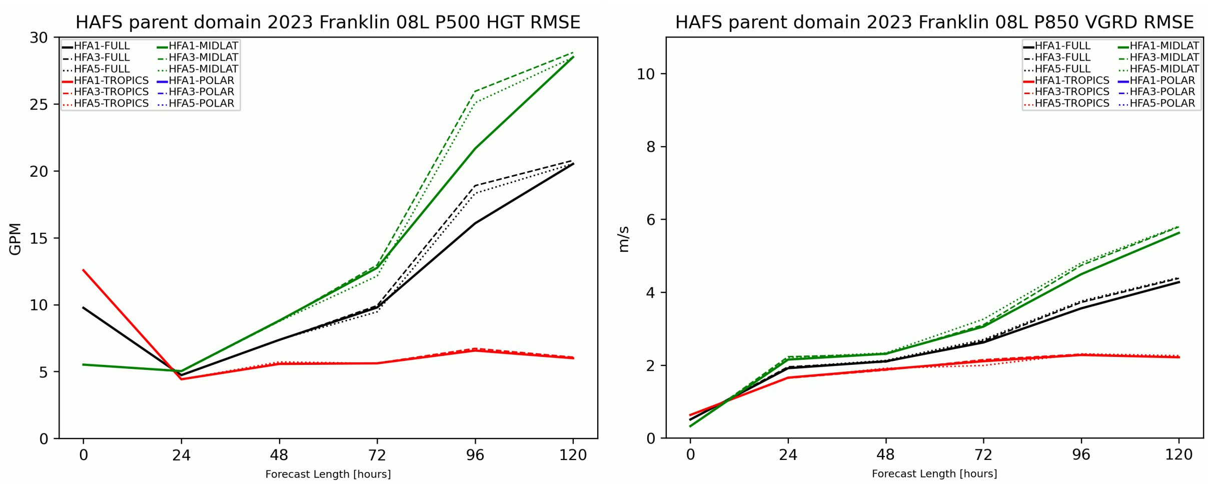

Figure 10. Synoptic-scale sample RMSE forecast errors (HAFS-A forecast minus GFS analysis) over the Hurricane Franklin parent domain for 500 hPa geopotential height (left) and for 850 hPa meridional wind component derived as a composite over both forecast cycles completed for this storm. Results are color-coded by latitude band for the tropics (red; < 30 N), for the mid-latitudes (green), for polar (blue; > 60 N), and for the full domain (black) for three cloud overlap methods including MR (solid line), NOAA_EXP (dash-dot line), and ER (dashed line).

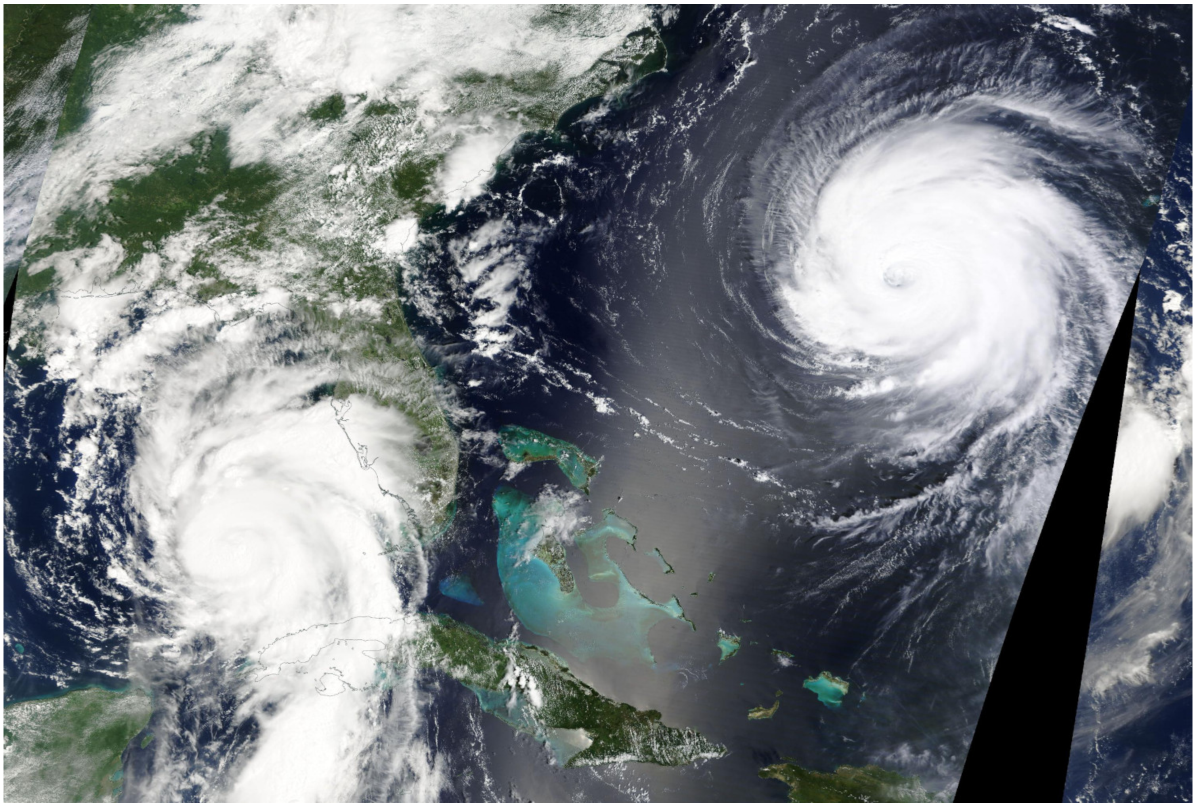

Figure 11. Terra/MODIS corrected reflectance "true-color" satellite imagery of Category 4 Hurricane Franklin (right) weakening as it approaches Bermuda and Category 1 Hurricane Idalia (left) strengthening as it approaches Florida at 15 UTC on 29 August 2023. Image provided by NASA Worldview.

Hurricane Idalia (AL102023)

Two HAFS-A cloud overlap sensitivity experiments were completed for Hurricane Idalia for forecast cycles initialized at 12 UTC 27 August 2023 and at 00 UTC on 28 August 2023. It should be noted Idalia and Franklin were active at the same time during these forecast cycles, though they were separated by approximately 1500 km as seen in Figure 11. The outflow from Idalia contributed to the wind shear that began to weaken Franklin as it passed Bermuda while Idalia intensified as it approached the west coast of Florida (*Beven*, 2024). HAFS-A track predictions for these two forecast cycles are shown in Figure 12. Official NHC forecast track errors for Idalia were generally very low (*Beven*, 2024), and Idalia track is mostly insensitive to cloud overlap in both forecast cycle experiments except for day 4 and beyond, when departures from the observed track were larger. Central pressure and maximum wind speed predictions for Idalia are shown in Figure 13. In general, more sensitivity to cloud overlap is seen, especially in the earlier forecast cycle where the MR overlap method shows the lowest skill in reproducing the observed values during the period of peak intensity. Predicted 34-knot wind radii for Idalia are shown in Figure 14 for each directional quadrant from the earlier forecast cycle. Wind radii reflect the intensification seen in days 4 and 5 in this cycle, especially in the northwest, northeast, and southwest quadrants.

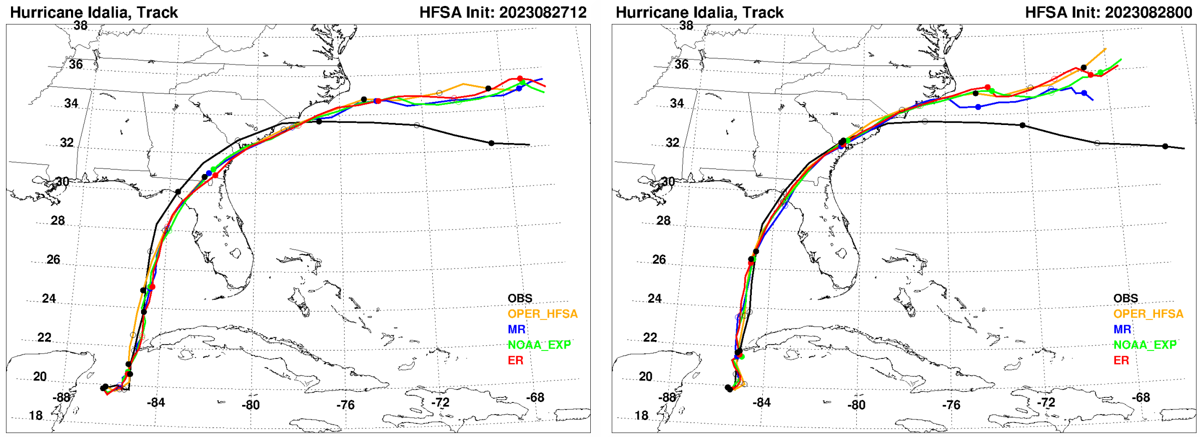

Figure 12. Hurricane Idalia track predictions for forecast cycles initialized at 12 UTC on 27 August 2023 (left) and at 00 UTC on 28 August 2023 (right) as simulated by HAFS-A using three cloud overlap methods including MR (blue), NOAA_EXP (green), and ER (red). Also shown are the observed "best-track" position of Idalia (black) during this period and the tracks as predicted in real-time by the operational HAFS-A (yellow).

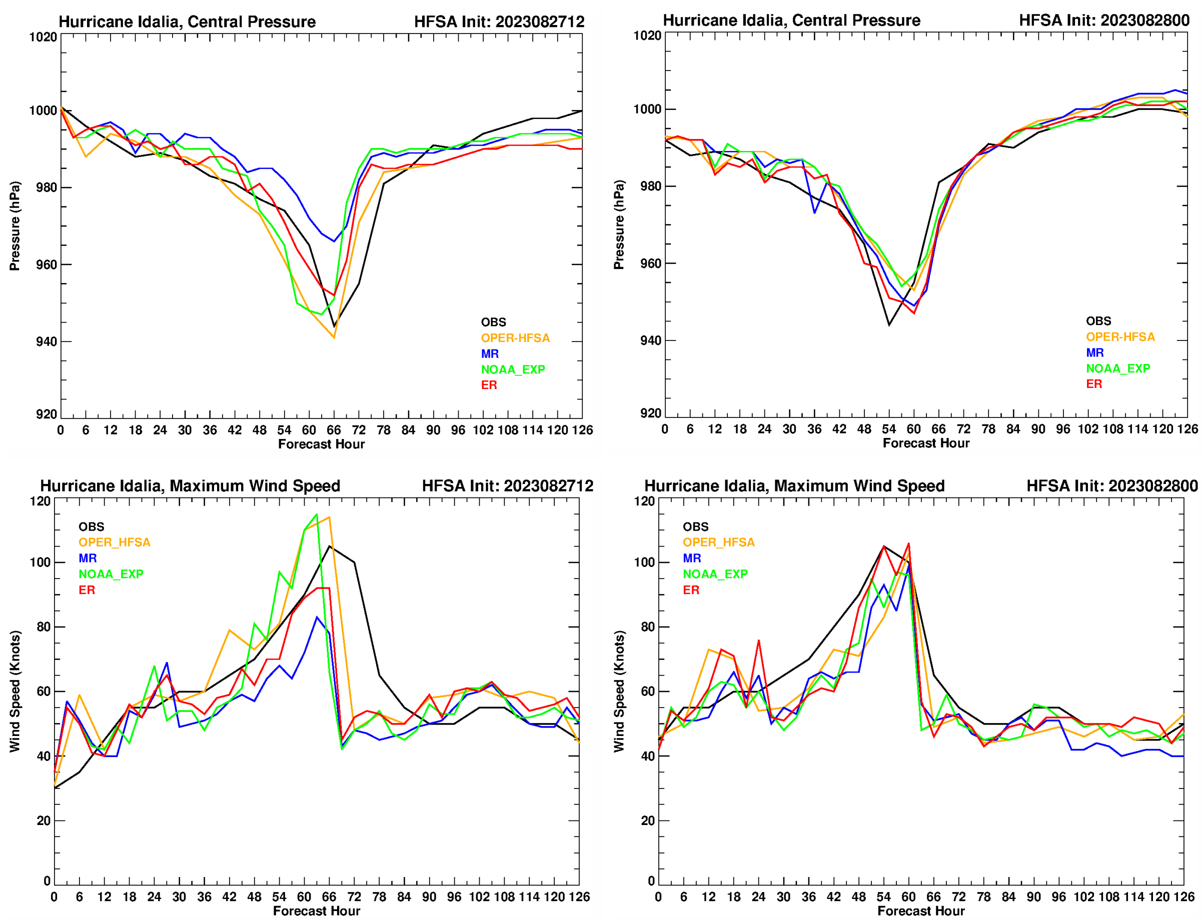

Figure 13. As in Figure 12 for Hurricane Idalia central pressure predictions (top panels, hPa) and for maximum wind speed (bottom panels, knots) for the same forecast cycles.

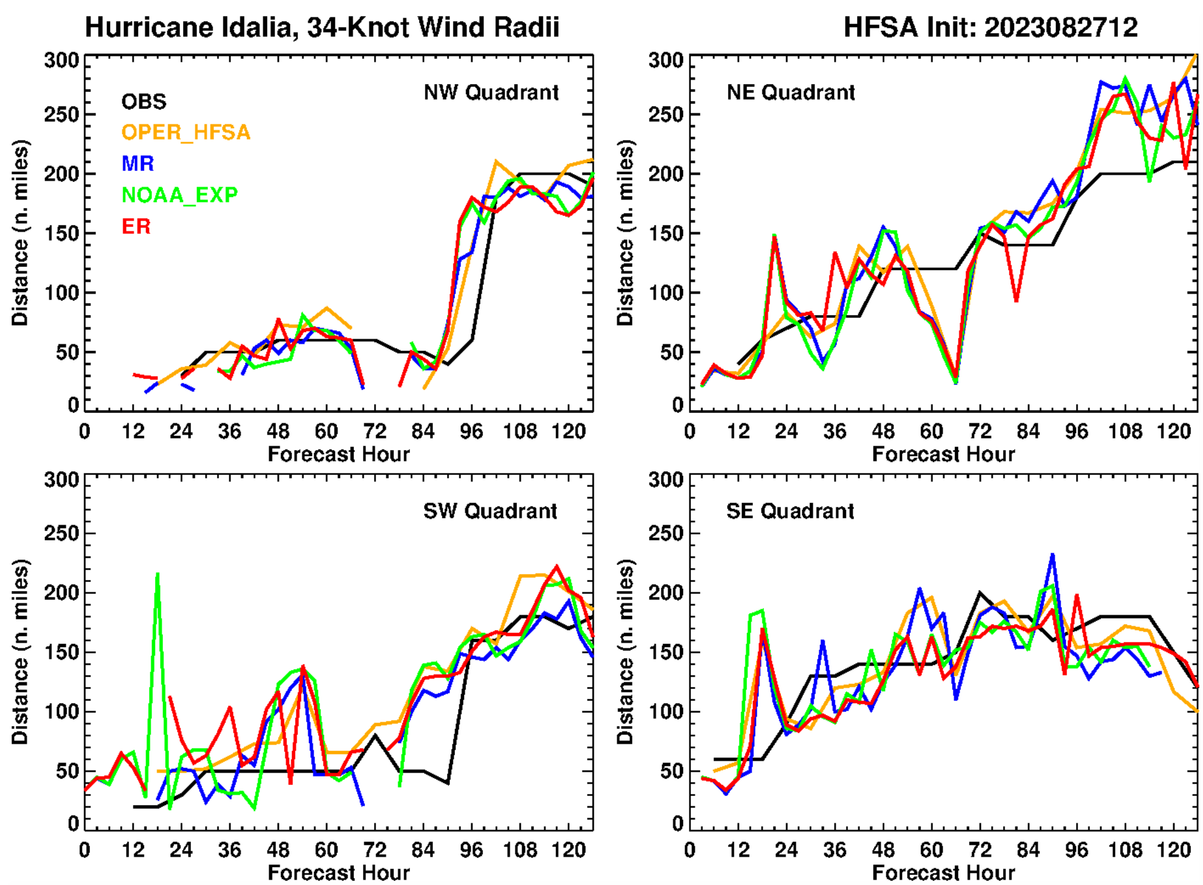

Figure 14. HAFS-A predicted 34-knot wind radii (nautical miles) for Hurricane Idalia in the four directional quadrants for a forecast cycle initialized at 12 UTC on 27 August 2023 for three cloud overlap methods, for the observed "best-track" values, and for the real-time operational HAFS-A prediction.

Storm domain averaged statistics composited over both Idalia HAFS forecast cycles are presented in Figure 15 following the format of Figure 10. Shown are 500 hPa geopotential height (GPH) anomaly correlation (top left) and RMSE (top right), 850 hPa zonal wind component RMSE (bottom left), and 850 hPa meridional wind component RMSE (bottom right). Note that in all panels in Figure 15, the moving inner storm domain shifts out of the tropical zone defined for these statistics as Idalia moves northward, which terminates the tropical statistics at forecast hour 48. Both anomaly correlation and RMSE errors for GPH show considerable sensitivity to cloud overlap in the mid-latitude zone (green) with a general degradation through the forecast period. RMSE wind errors are less sensitive to cloud overlap and increase quickly with forecast hour for all configurations.

Hurricane Lee (AL132023)

One HAFS-A cloud overlap sensitivity experiment was completed for Hurricane Lee for a forecast cycle initialized at 12 UTC 11 September 2023, which was selected to capture the period of Lee's turn toward the north, its passage offshore of the U.S. East Coast, and its landfall in Nova Scotia. This interval was well after the storm reached its maximum intensity on 8 September 2023. Official NHC forecast track errors were generally very low for Lee due to a robust steering flow, though some models, including the operational HAFS, overestimated the Lee's intensity after it reached peak strength (*Blake and Nepaul*, 2024). The sensitivity to cloud overlap for the completed cycle with HAFS-A is shown in Figure 16 for track (left panel) and maximum wind speed intensity (right panel). Track shows little cloud overlap sensitivity, and although the turn toward the north was predicted somewhat late, the northward path was close to the official forecast in all runs until the last six hours, when the HAFS-A runs deviated to the northwest. For intensity, all three runs show a stronger storm than observed in days 2-4, though cloud overlap sensitivity increases in days 4-5 with ER performing somewhat better at several forecast hours.

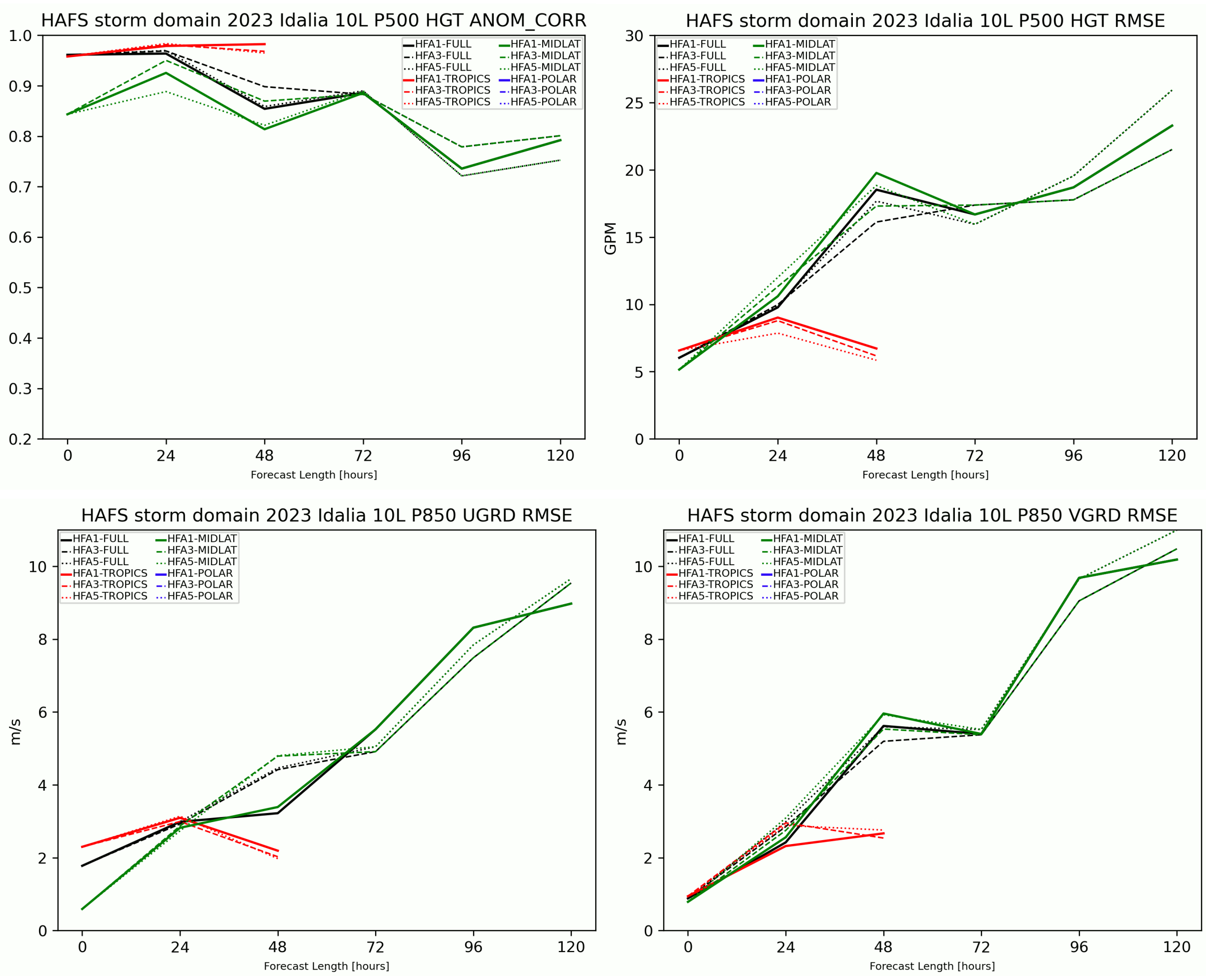

Figure 15. Storm-scale 500 hPa geopotential height anomaly correlation (top left) and RMSE forecast errors (HAFS-A forecast minus GFS analysis) of 500 hPa geopotential height (top right), 850 hPa zonal wind component (bottom left) and 850 hPa meridional wind component (bottom right) over the Hurricane Idalia storm domain derived as a composite over both forecast cycles completed for this storm. Results are shown following the legend format of Figure 10.

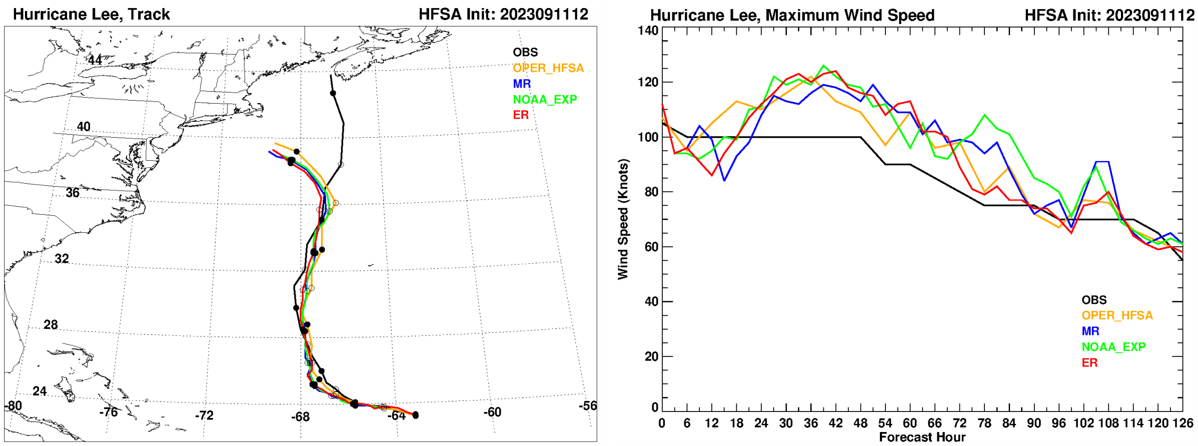

Figure 16. Hurricane Lee predictions for track (left) and maximum wind speed (right) for a forecast cycle initialized at 12 UTC on 11 September 2023 as simulated by HAFS-A using three cloud overlap methods including MR (blue), NOAA_EXP (green), and ER (red). Also shown are the observed "best-track" position of Idalia (black) during this period and the tracks as predicted in real-time by the operational HAFS-A (yellow).

Parent domain averaged statistics for the single Hurricane Lee HAFS forecast cycle are presented in Figure 17 following the legend format of Figure 10. Shown are 500 hPa geopotential height (GPH) anomaly correlation (left panel) and RMSE errors (right panel). Note that the HAFS-A parent domain for this case extends over the entire Atlantic basin. Anomaly correlation for GPH shows low sensitivity to cloud overlap in the tropical (red) and mid-latitude (green) zones, while RMSE errors show modest sensitivity in the mid-latitude zone, especially during forecast days 2 and 3. RMSE errors for 850 hPa temperature (left panel) and zonal wind component (right panel) are shown in Figure 18. Generally low sensitivity to cloud overlap is seen for both statistics with larger RMSE errors present in the mid-latitude zone.

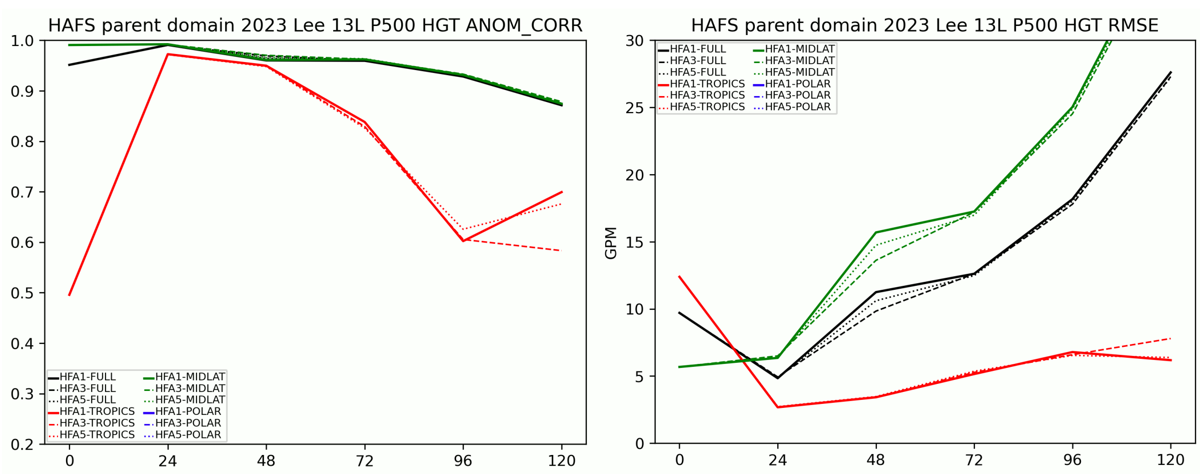

Figure 17. Synoptic-scale anomaly correlation (left) and RMSE forecast errors (right; HAFS-A forecast minus GFS analysis) for 500 hPa geopotential height over the Hurricane Lee parent domain derived for the forecast cycle completed for this storm. Results are shown following the legend format of Figure 10.

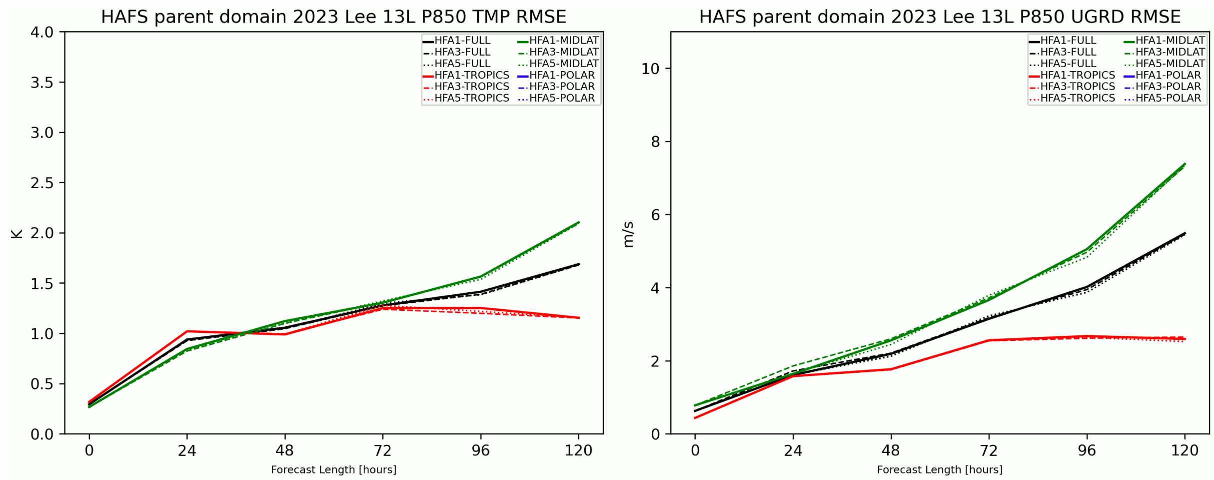

Figure 18. Synoptic-scale RMSE forecast errors (HAFS-A forecast minus GFS analysis) for 850 hPa temperature (left) and zonal wind component (right) over the Hurricane Lee parent domain derived for the forecast cycle completed for this storm. Results are shown following the legend format of Figure 10.

Hurricane Otis (EP182023)

Two HAFS-A cloud overlap sensitivity experiments were completed for East Pacific Hurricane Otis for forecast cycles initialized at 12 UTC 22 October 2023 and 00 UTC on 23 October 2023. These cycles were selected to capture the development and rapid intensification (RI) phases of the storm and the landfall of Otis near Acapulco, Mexico on 25 October 2023. In the 24 hours just before landfall, Otis intensified extremely rapidly from a 55-knot tropical storm to a 145-knot Category 5 hurricane with a central pressure drop of 74 hPa from 996 to 922 hPa in one day. Otis was the strongest landfalling hurricane in the East Pacific since the National Hurricane Center assumed forecast responsibility for the basin in 1988 (*Reinhart and Reinhart*, 2024). Official track and intensity forecasts in the early development stages of Otis had substantial errors as the dynamical and statistical guidance failed to capture the internal structure, position, and RI of the relatively small cyclone. Otis was included in this analysis due to its historic intensity and very high societal impact, though the expectation of sensitivity of the HAFS-A track and intensity forecast errors to gradual cloud overlap effects was low due to the cyclone's RI.

In general, HAFS-A predictions of Hurricane Otis were little affected by cloud overlap method as expected. Track predictions for the two completed forecast cycles with HAFS-A are shown in Figure 19. In the earlier cycle, the model runs closely follow the track of the operational HAFS-A, which was too far east, though some cloud overlap sensitivity is seen. In the latter cycle, the models were closer to the observed position, but they remained offshore throughout this period. Intensity predictions of central pressure (top panels) and maximum wind speed (bottom panels) for the two cycles are shown in Figure 20. All model runs completely miss the extreme RI of Otis, though some sensitivity to cloud overlap is apparent during days 4 and 5 of the latter cycle.

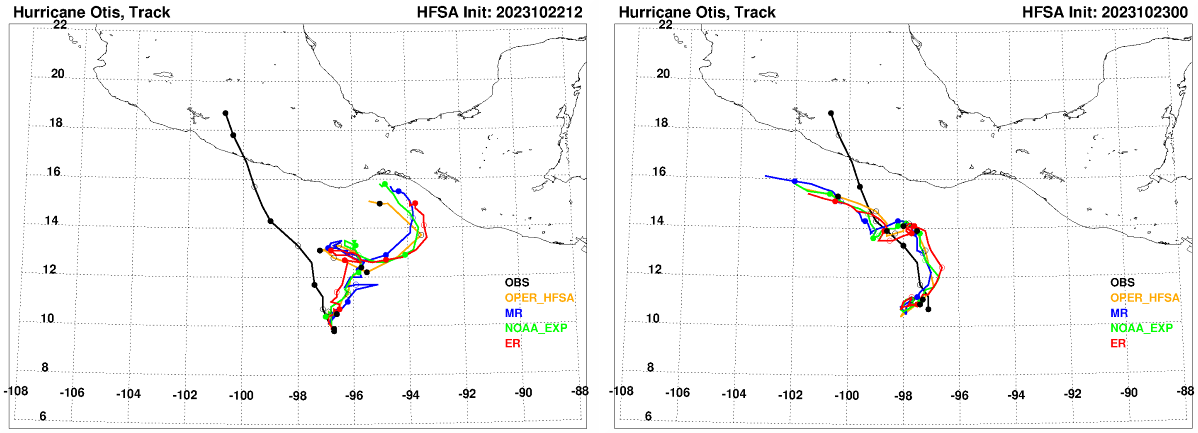

Figure 19. Eastern Pacific Hurricane Otis track predictions for forecast cycles initialized at 12 UTC on 22 October 2023 (left) and at 00 UTC on 23 October 2023 (right) as simulated by HAFS-A using three cloud overlap methods including MR (blue), NOAA_EXP (green), and ER (red). Also shown are the observed "best-track" position of Otis (black) during this period and the tracks as predicted in real-time by the operational HAFS-A (yellow).

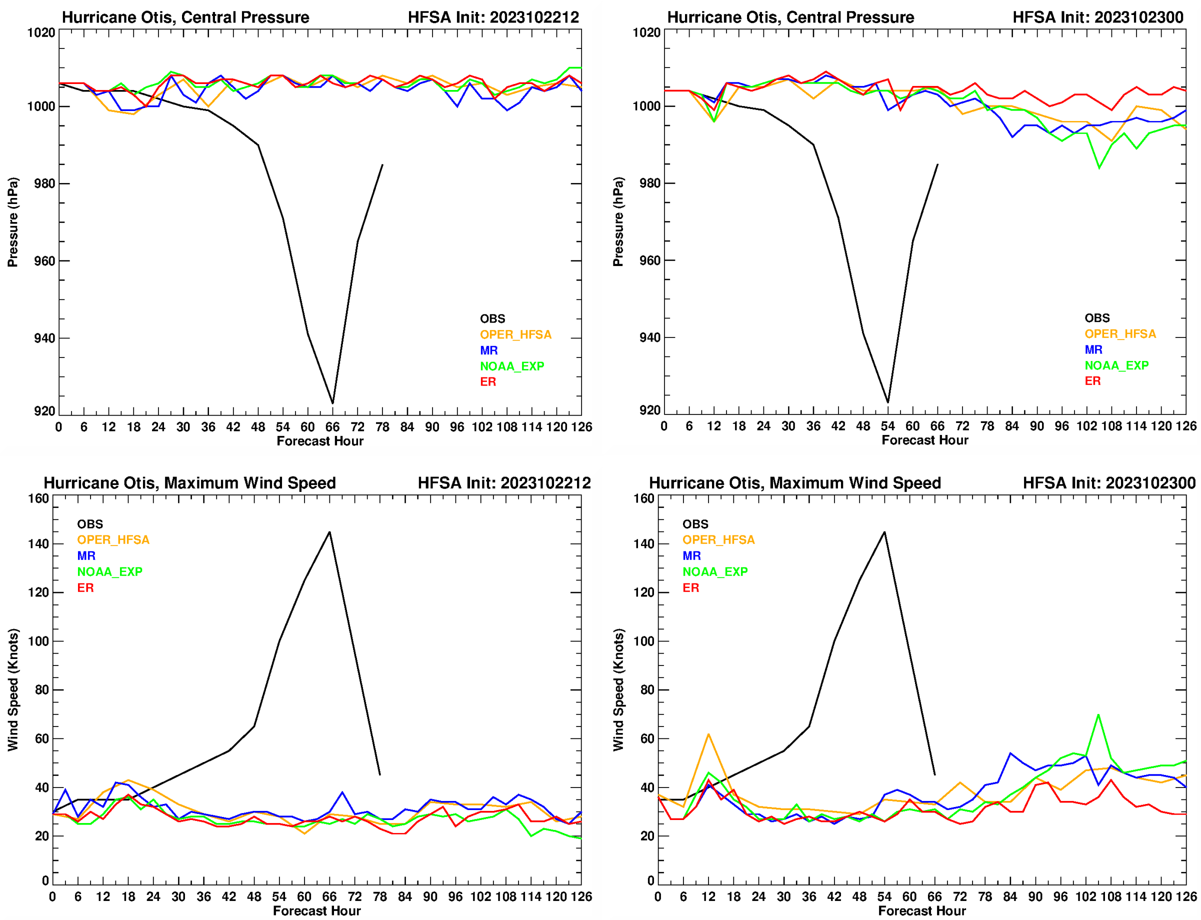

Figure 20. As in Figure 19 for Hurricane Otis central pressure predictions (top panels, hPa) and for maximum wind speed (bottom panels, knots) for the same forecast cycles.

Storm domain averaged statistics for the two Hurricane Otis HAFS-A forecast cycles are presented in Figures 21 and 22 following the legend format of Figure 10. Figure 21 shows the 500 hPa GPH anomaly correlation (left panel) and RMSE error (right panel). In these cycles, the storm domain remained primarily in the tropical zone defined for these statistics. Anomaly correlation drops off quickly with forecast time for all model runs, with considerable sensitivity to cloud overlap, especially in days 4 and 5. RMSE errors show modest sensitivity and also increase with time. RMSE errors for 850 hPa temperature (left panel) and meridional wind component (right panel) are shown in Figure 22. Generally moderate sensitivity to cloud overlap is seen for both statistics especially after 48 hours. Note that we include storm domain statistics to highlight their somewhat higher sensitivity to cloud overlap in general relative to parent domain statistics.

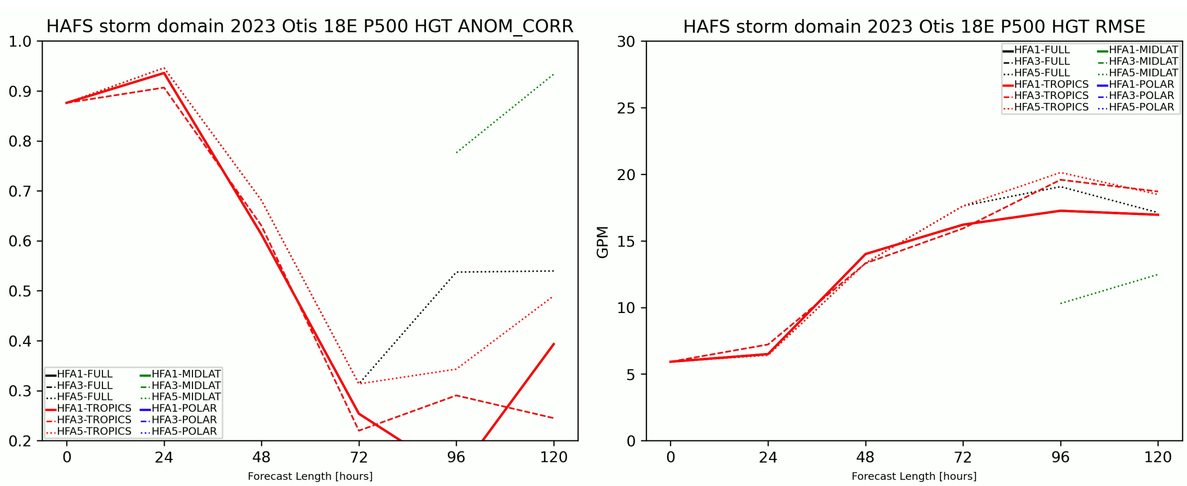

Figure 21. Storm-scale anomaly correlation (left) and RMSE forecast errors (right; HAFS-A forecast minus GFS analysis) for 500 hPa geopotential height over the Hurricane Otis storm domain derived for the two forecast cycles completed for this storm. Results are shown following the legend format of Figure 10

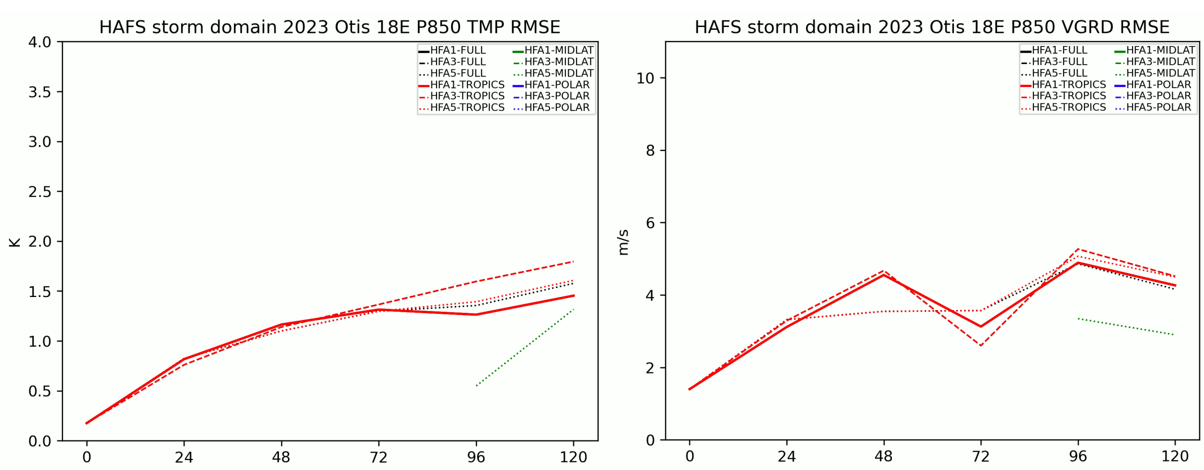

Figure 22. Storm-scale RMSE forecast errors (HAFS-A forecast minus GFS analysis) for 850 hPa temperature (left) and meridional wind component (right) over the Hurricane Otis storm domain derived for the two forecast cycles completed for this storm. Results are shown following the legend format of Figure 10.

4. Conclusions and Future Work

This DTC Visitor Program project advanced our investigation of enhancements to the cloud overlap and decorrelation length methods used in the RRTMG radiation code within NOAA operations in the context of HAFS-A hurricane predictions. Based on our earlier efforts, NOAA adopted the EXP cloud overlap method in the 2018 operational HWRF and ER in the 2020 operational HWRF, and these transitions prompted this investigation of the optimal cloud overlap approach for HAFS operations. For this project, DTC and AER, in collaboration with EMC, performed and analyzed multiple forecast cycle experiments for several tropical cyclones from the 2021, 2022 and 2023 seasons to evaluate the impact on TC track and intensity predictions of the older MR cloud overlap treatment, the NOAA_EXP method (default in GFSv16), and the ER approach. Each of the exponential approaches were tested with different latitude varying methods for specifying the vertical decorrelation length. In some TC cases, predicted track and intensity showed noticeable sensitivity to cloud overlap method. In part due to this analysis, EMC will perform more comprehensive testing of ER overlap in support of selecting the default cloud overlap approach for the 2025 operational HAFS model.

Cloud overlap sensitivity experiments were performed using a DTC version of HAFS-A that was close to the 2023 operational version of this model. TC cases examined included Ida (2021), Ian (2022), and Franklin, Idalia, Lee, and Otis (2023). Most of these cases showed only slight track sensitivity to cloud overlap method, with generally larger impacts late in the forecast cycle as the physics change caused the surrounding environment to evolve. Many cases showed larger sensitivity of TC intensity to cloud overlap, both in terms of storm central pressure and maximum wind speed, and improvement was noted in several cases due to one of the exponential cloud overlap methods relative to the real-time operational forecast. The response of 34-knot wind radii to cloud overlap was examined for Franklin and Idalia. Despite being a highly variable diagnostic, wind radii were shown to be sensitive to cloud overlap for these TC cases, though only modest departures from the operational forecasts of this parameter were noted. The historic RI of hurricane Otis was shown to be largely insensitive to the cloud overlap method.

Anomaly correlation and RMSE error statistics for both the storm domain and the parent domain were generated in several latitude zones for all storms examined during this study for 500 hPa geopotential height, 850 hPa temperature, and 850 hPa wind components. An important conclusion of this aspect of the study is that modification of the cloud overlap method does not significantly alter the synoptic scale simulation of these basic parameters. EXP and ER were shown to provide modest improvement in these statistics relative to the MR approach in some TC cases and parameters at a few forecast times, while modest degradation was seen at other forecast times.

More comprehensive testing over a larger number of cases is required to draw final conclusions about which method is optimal for NOAA operations.

There are several possible directions for continuing this work in the future. First, a recent update to the latitude varying decorrelation method for EXP and ER (*Oreopoulos et al.,* 2022) was implemented in HAFS (version 2) for this project. Testing of this option is in progress, and this new method will be provided to NOAA EMC via CCPP for further testing for the 2025 operational HAFS. Our future efforts will emphasize this newer decorrelation length approach. The capability to represent the sub-grid variability and vertical overlap of cloud condensate using an approach that aligns closely with the method used previously for cloud fraction overlap has been implemented in RRTMG, though it has not yet been evaluated in the context of hurricane predictions. Finally, future research will investigate the potential benefit of spatially selecting both the cloud overlap treatment and the decorrelation length method using more sophisticated approaches that depend on atmospheric state parameters that influence the vertical correlation of clouds such as wind shear and vertical velocity in the context of tropical cyclone predictions.

5. Project Deliverables

This project resulted in one source code related deliverable and two supporting documents including a new journal article and this final project report:

1) Source code for the *Oreopoulos et al.* (2022) day-of-year and latitude varying decorrelation length treatment was implemented into RRTMG in CCPP for testing in HAFS.v2, and these changes will be merged into the CCPP github repository for general application by NOAA in 2024.
2) Iacono, M.J., J.M. Henderson, M. Biswas, K. Newman, B. Liu, and Z. Zhang, Application of exponential cloud overlap methods to tropical cyclone predictions with HWRF and HAFS, (to be submitted to *J. Geophys. Res. – Atmospheres*, Fall 2024).
3) Iacono, M.J., and J.M. Henderson, Evaluating sub-grid cloud variability enhancements in HAFS tropical cyclone predictions, 2022-2024, DTC Visitor Program Project Final Report, Developmental Testbed Center, May 2024.

In addition, one poster presentation was delivered during this project at the AMS 36th Conference on Hurricanes and Tropical Meteorology, which included elements of this research:

1) Henderson, J., M.J. Iacono, M. Biswas, K. Newman, B. Liu, and Z. Zhang, Enhancements to cloud overlap radiative effects for tropical cyclone prediction, Poster presentation at the 36th American Meteorological Society Conference on Hurricanes and Tropical Meteorology, Long Beach, California, May 6-10, 2024.

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