7D.3 A GRIDDED TCM TO SUPPORT FORECAST OPERATIONS AT NHC AND WFOs

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1. INTRODUCTION

The National Hurricane Center (NHC) **T**ropical **C**yclone forecast advisory **M**essage (TCM) contains forecasts of position, intensity and wind radii at 12-hr intervals out to 48 hours with 34/50/64-knot wind radii, at 72 hours with only 34/50-knot radii, and at 96 and 120 hours with no radii information. From this text product, Weather Forecast Offices (WFOs) are required to create a two-dimensional, 2.5 km resolution gridded forecast of winds with hourly resolution out to 48 hours, 3-hourly out to 72 hours, and 6-hourly out to 120 hours. This ensures that the official WFO wind forecast is constrained by, and consistent with, NHC's official (OFCL) forecast.

For the past 10+ years, WFO forecasters have been using the modified Rankine vortex (Mallen et al. 2005) based algorithm to create a two-dimensional depiction of the tropical cyclone vortex for each forecast time in NHC's OFCL forecast advisory. It is constrained by the wind radii in the forecast and uses CLIPER (**CLI**matology and **PER**sistence) model-based wind radii when that information is not available in an advisory. Then, to fill in the gaps between forecast times, a linear interpolation in time is applied between forecast points at hourly time steps, out to the length of NHC's forecast, which is 120 hours. The algorithm employs a crude constant wind speed reduction factor over land that does not take into account boundary layer physics or variations in the land surface. More recently, to overcome these significant shortcomings, some forecast offices have implemented an approach that uses a grid scale depiction of inland reduction factors to further modify the winds over land. However, this approach is labor-intensive, requiring forecasters to manually create those grids based on model data analyses prior to running the modified Rankine vortex algorithm. Additionally, each office runs this algorithm locally, decoding the OFCL TCM text forecast advisory, which creates a challenge when attempting to collaborate and achieve a consistent depiction of the forecast issued by WFOs. Furthermore, this approach introduces additional errors/uncertainties in the deterministic rendition of NHC's forecasts, in addition to the typical NHC forecast errors (NHC 2017).

In order to address these deficiencies, NHC has been experimenting with a **g**ridded version of the **TCM** (henceforth gTCM), a two-dimensional (2D) time dependent (hourly) rendition of its OFCL forecast, that will be available experimentally to WFOs during the 2018 season. The main improvements over the approach offices have been using over the past 10+ years are: 1) the 2D time dependent depiction of the forecast comes already in a gridded format for offices to ingest, substantially reducing the amount of work offices have to invest to make their gridded wind forecasts congruent with NHC's OFCL forecasts, and 2) incorporation of a parametric boundary layer model that dynamically calculates roughness parameters and friction reduction from land interaction as a function of land use and wind. Although this algorithm still is subject to the limitations of creating a high spatial/temporal resolution (2.5 km/1 hr) product from a very coarse forecast, it is a substantial improvement over the approach used in the past.

This paper describes the algorithm (Section 2), presents an assessment of its consistency with

NHC's official forecast based on internal testing during 2017 (Section 3.1), shows a preliminary validation of its results against surface observations (Section 3.2), explains how the gTCM is used by forecast offices (Section 4), then summarizes and outlines future plans (Section 5).

2. ALGORITHM DESCRIPTION

During the 2017 hurricane season, NHC experimented internally with the gTCM, which is generated by a parametric wind model known as the **G**radient **W**ind **A**symmetric **V**ortex **A**lgorithm (GWAVA). Based on an asymmetric Holland-B vortex in gradient wind balance (Holland 1980, Mattocks and Forbes 2008), it includes an upwind directional surface roughness algorithm to reduce the wind speed inland.

This inland friction parameterization gradually modulates wind speed according to wind direction and the underlying types of land cover encountered upwind as an air parcel approaches a model grid point. It creates smoother, more realistic transitions of winds across land-water boundaries by preventing marine winds from suddenly decelerating when they penetrate inland and, conversely, preventing winds from rapidly accelerating over open water when they blow offshore.

Detailed land use-dependent structures (to the extent that they can be resolved on a 2.5 km grid) emerge in the wind field, including complex acceleration/deceleration patterns where land use transitions from low-drag regions (airport runways, cropland) to high-drag (heavily forested, urban development) areas downwind. These surface roughness footprints (wind speed shadows) can appear anywhere but they are most noticeable in land/water transition zones such as coastal areas, lakes and tree-lined river banks.

Instead of using CLIPER values for missing wind radii, the gTCM uses the RVCN consensus of global/high-resolution numerical hurricane models (a combination of two or more of the interpolated GFS, ECMWF and HWRF trackers/aids during 2017), which provides a much more relevant and accurate estimate of the storm size. Note that the gTCM can use any other model aid as input for the missing wind radii data, depending on which is deemed most appropriate or accurate for a particular storm.

3. METHODOLOGY AND PRELIMINARY VERIFICATION

Two objectives were set forth prior to running the gTCM internally during the 2017 hurricane season: 1) establish its consistency with the track parameters (location, intensity, size, storm motion) in the OFCL forecast, and 2) verify its performance by running the gTCM with NHC Best Track parameters and comparing the results against observations.

The first objective was accomplished by comparing gTCM simulation results against specific forecast advisories, for example Hurricane Irma (Cangialosi et al. 2018) advisory #37, while the second goal was achieved by comparing model-generated time series of 1-minute sustained wind speeds and directions at 10 meters above ground with measurements at surface stations.

3.1 Consistency Assessment

An example of one of the tools used to assess the consistency of the gTCM with NHC's OFCL forecasts is shown in Fig. 1. It shows that, under conditions of pure marine exposure over the ocean, the simulated outermost wind radii in the 48-hr forecast of the wind speed profiles (grey-filled black curves) closely match the numeric values (red dots) in the OFCL forecast listed to the right side of the figure. The differences in the distance (nautical miles) from the center of the storm are mostly in the single digits. The maximum sustained 1-minute wind speed, 130 kt, is also exactly replicated by the gTCM in the northeast quadrant of the storm.

In contrast with Fig. 1, the radial profiles in the 72-hr forecast from the gTCM (Fig. 2) show the impact of the directional upwind surface roughness parameterization on the wind speed when portions of the storm are inland. The far-field winds in the northeast, southeast and southwest quadrants are primarily over the ocean, while the winds in the northwest quadrant are entirely over land. The OFCL forecast wind radii (red dots) follow the wind profiles simulated by the gTCM in areas of pure marine exposure but are drastically reduced over land by the surface drag. The large numeric difference values quantify this impact, especially in the northwest quadrant (right column of the DIFF table).

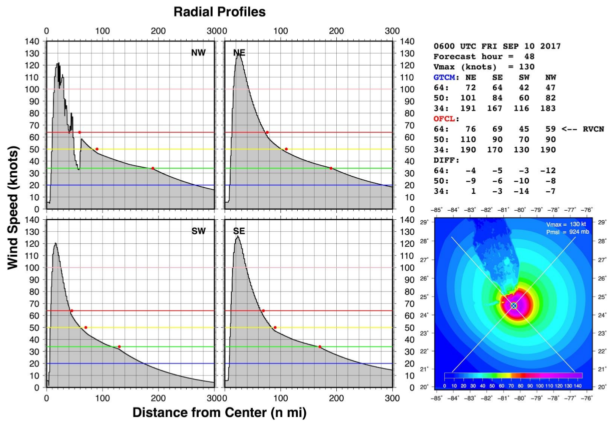


Figure. 1. Radial wind speed profiles (grey-filled black curves) in the 4 standard quadrants (NW top left, NE top right, SW bottom left and SE bottom right panels) as simulated by the gTCM for Hurricane Irma advisory #37. The colored (blue, green, yellow, red) horizontal lines indicate the speed thresholds of the (20, 34, 50, 64 kt) significant wind radii. The red dots indicate values of the wind radii in NHC's OFCL forecast (TCM) at 48 hours, also listed in numeric form on the right side of the figure.

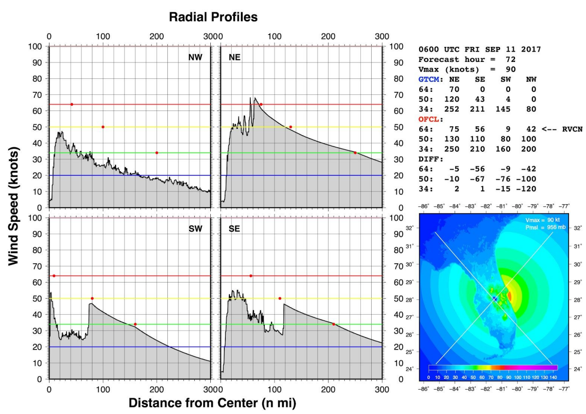


Figure 2. Same as Figure 1, but for the 72-hr forecast.

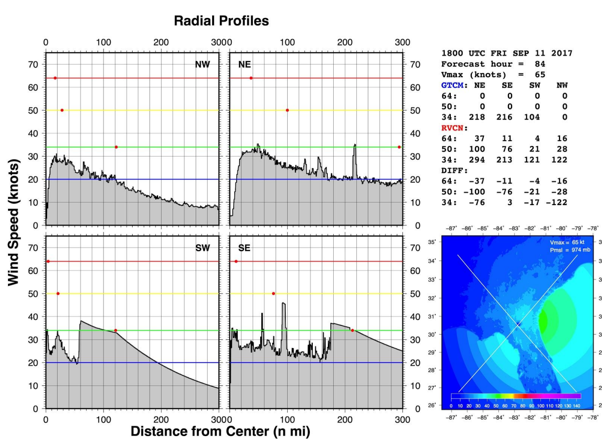


Figure 3. Same as Figure 1, but for the 84-hr forecast.

This impact is even more widespread in the 84-hr forecast results, shown in Fig. 3, when some interesting expressions of the variations in the land surface characteristics become evident. The spikes in the wind field seen in the northeast and southeast quadrants of the storm are due to the winds blowing over smooth surfaces, specifically Lake Moultrie, SC and Lake George, FL, respectively. One could imagine stitching together a pure marine profile by drawing a curve between the wind radii values over these large lakes and the OFCL forecast values.

Careful examination of Figs. 2 and 3 also reveal that, in instances when the center of the storm and radius of maximum wind are entirely over land, the inland friction reduction algorithm will decrease the maximum wind speed in the forecast as well, even when an empirically based inland reduction/adjustment has already been applied at NHC's forecast points. Nevertheless, verification against point data shown in the next sub-section suggests the impact of this is small, on top of the fact that the maximum wind speed (Vmax) in NHC's forecasts are "hot spots" and highly unlikely to be sampled (Uhlhorn and Nolan 2012). That said, this is a topic for discussion on how to best address inland decay in the gTCM and in NHC's forecast process in the future.

3.2 Performance Assessment

To assess how well the gTCM replicated observed measurements of wind speed and direction, time series were extracted from gTCM model hindcast simulations run with NHC's Best Track parameters for Hurricane Irma and compared with time series from surface stations. All data were converted from anemometer height to the standard altitude of 10 meters, time-averaged to 1 minute, and adjusted for exposure. A small sample of the results is shown in Figs. 4-7.

In this assessment, the magnitudes of the wind speeds simulated by the gTCM are quite accurate and the radii are realistic, both at stations near the coast and inland. At some locations, such as Key West, the intensity and radii (as specified in the preliminary Best Track) are a bit high and too large as the storm approaches, but are in good agreement after the storm passes by. The wind directions are also simulated with high fidelity by the gTCM. In many cases (e.g., Key West and Fort Myers), abrupt wind shifts are perfectly captured; in other cases (Virginia Key, located between two islands) there is a slight high bias of 10-20 degrees in the wind direction.

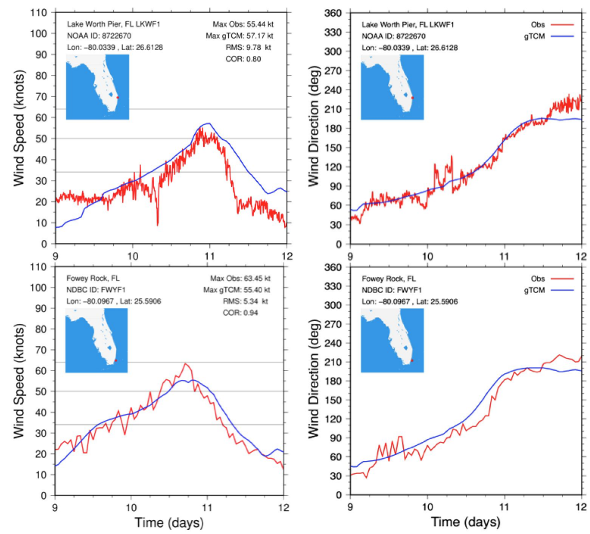


Figure 4. Time series of wind speed (left) and wind direction (right) from a gTCM simulation driven with NHC Best Track parameters for Hurricane Irma (blue) and at surface stations Lake Worth Pier and Fowey Rock lighthouse (red). The map insert shows the geographical location of each surface station.

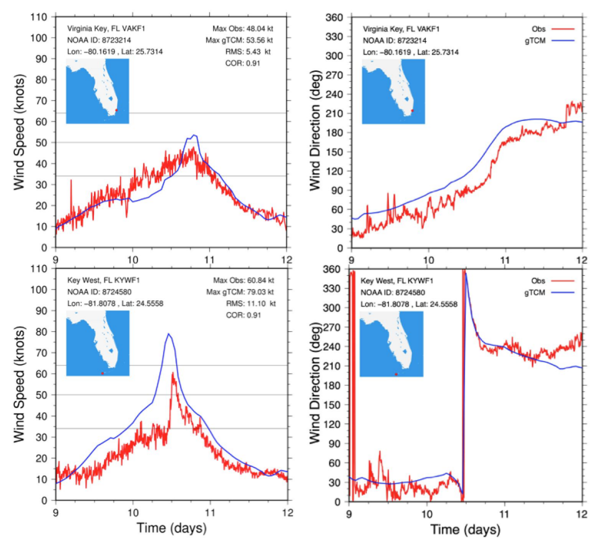


Figure 5. Same as Figure 4, but for Virginia Key and Key West, FL.

Overall, the RMS errors in the wind speeds range from about 4-11 knots and the correlations vary from about 0.80 to 0.95. These results show how appropriate the gradient wind assumption is for tropical cyclones and demonstrate the gTCM's ability to reproduce the magnitude and timing of the observed winds, both over water and on land.

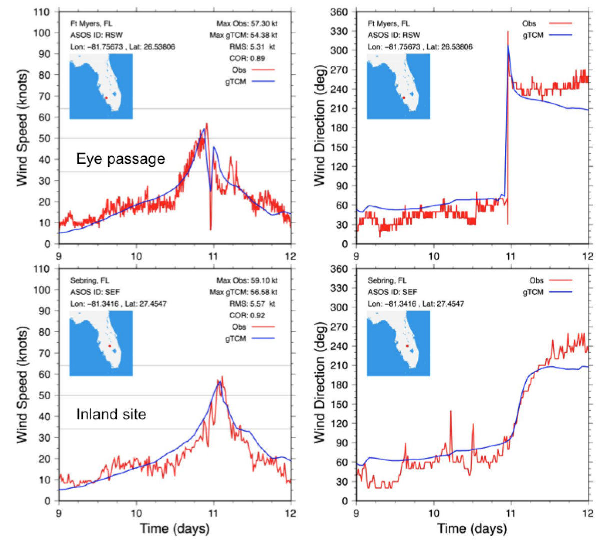


Figure 6. Same as Figure 4, but for Fort Myers and Sebring, FL.

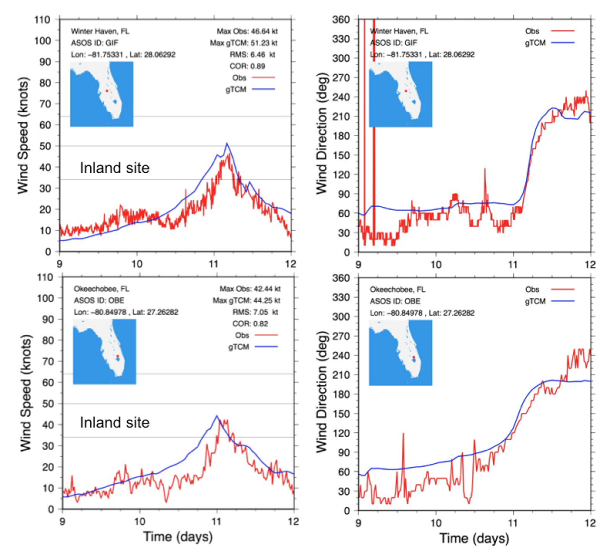
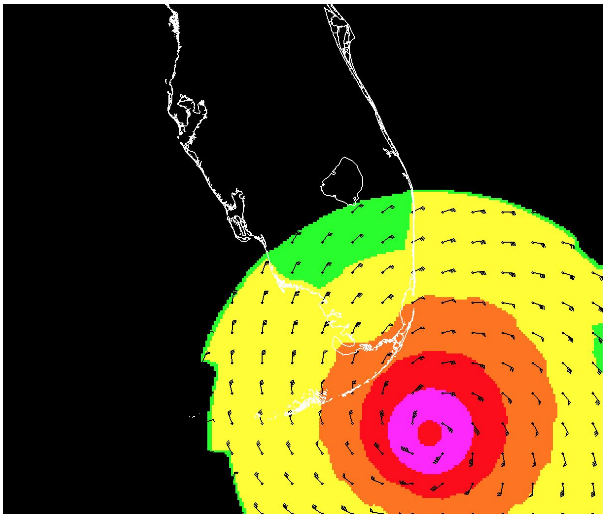


Figure 7. Same as Figure 4, but for Winter Haven and Okeechobee, FL.

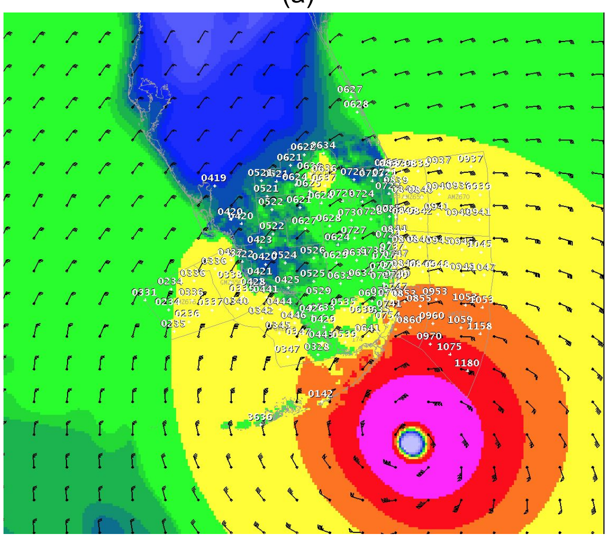
In particular, the preliminary comparisons at inland sites are quite encouraging. The surface roughness parameterization introduced by the gTCM is a significant improvement over the inland decay algorithm currently used by WFOs.

4. OPERATIONAL TESTING

Figures 8 and 9 show the 2D depiction of the wind field in a WFO forecast database from the original modified Rankine vortex algorithm (a) and the new gTCM (b) valid at two different forecast times. Notice the color legend in the caption accompanying Fig. 8. The slightly different wind radii of 34/50/64 knots is in part due to the fact the original algorithm uses CLIPER for periods when that information is missing in the OFCL forecast, while the gTCM uses the RVCN model aid, a consensus of the global (GFS) and vortex structure resolving (HWRF, HMON) models.

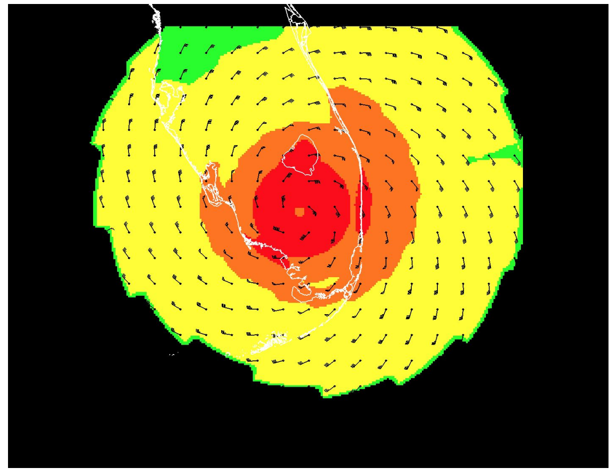


(a)

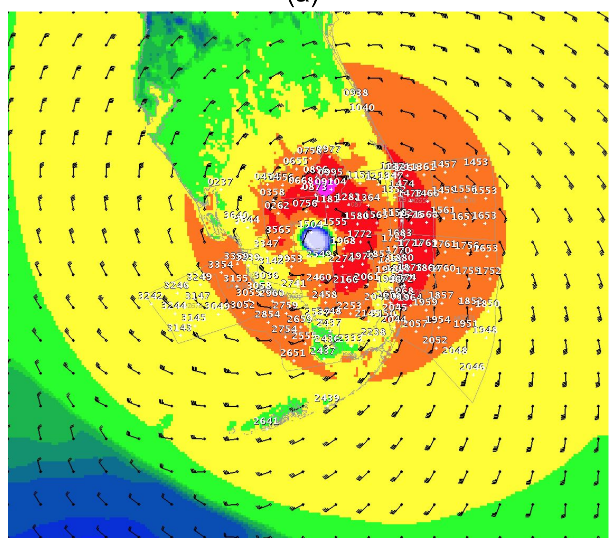


(b)

Figure 8. (a) 2D depiction of NHC's OFCL forecast of Hurricane Irma valid at 0300 UTC on 20180910 from forecast advisory number 37 as depicted in a WFO forecast db using the original modified Rankine vortex formulation with constant inland reduction algorithm. (b) As in (a), but using the gTCM with the upwind directional surface roughness algorithm to reduce the wind speed inland. Colors: yellow 34-49 knots, orange 50-63 knots, red 64-95 knots, magenta > 95 knots.



(a)



(b)

Figure 9. As in Fig. 8, but valid at 1800 UTC on 20180910.

Notice the improved asymmetry, eye structure and, above all, more realistic land friction reduction depicted by the gTCM. The latter parameterization picks up differences between areas of urban land use on the east and west coasts of Florida versus the Everglades (where reductions are less), locally higher winds over Lake Okeechobee and farther north over numerous inland bodies of water in that part of the state. This is attained without any manual intervention required on the part of the forecaster, who would struggle to attempt this manually with the algorithm used in Figs. 8a and 9a. The expressions of inland bodies of water in the gTCM renditions of the wind field are illustrated further in Fig. 10.

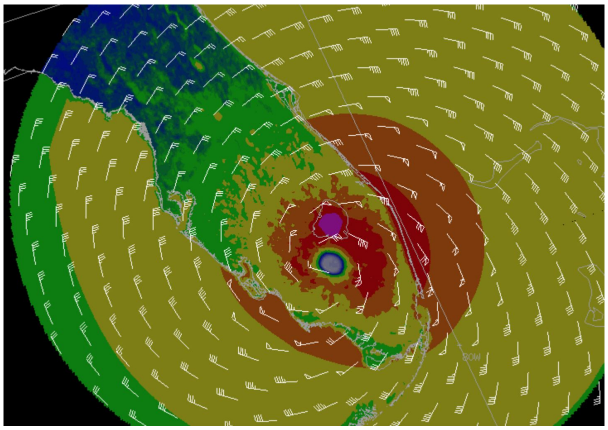


Figure 10. As in Fig. 9b, but from a different perspective, showing the northern reach of the gTCM-derived wind field. Notice the higher winds over numerous inland bodies of water (Lake George, Crescent Lake, St. Johns River) in northeast Florida, while the largest areas of tropical storm force winds remain offshore (yellow). This demonstrates how the upwind directional surface roughness algorithm modulates the wind speed inland according to the surface characteristics.

Although the examples provided in Figs. 8a and 9a only show the hurricane vortex with no background model wind field, it is worth mentioning that, when using this previous version of the algorithm, forecasters have to manually blend this vortex into a meteorological model background while making sure their final depiction of the forecast remains constrained by the NHC official forecast. On the other hand, the results shown in Figs. 8b and 9b from the gTCM have already been blended into a background wind field of choice, while constraining the winds to be consistent with the OFCL forecast – all without any manual intervention required by the forecasters. The result is that, with the gTCM, the forecasters not only obtain a superior 2D depiction of the forecast but also one that allows them to more efficiently update their wind forecast database using NHC's official forecast, while preventing human input errors.

5. SUMMARY

The gTCM enables National Weather Service WFOs to produce a more realistic deterministic rendition of the horizontal wind field that is consistent with NHC's OFCL forecast advisories in a more efficient manner. It produces a better depiction of the wind field inland – onshore/offshore fetches, land use effects (urban/non-urban), inland lake and river effects (if resolvable on its 2.5 km grid) – along with a spatially and temporally higher resolution version of the NHC official forecast.

This digital forecast product provides a common starting point for all coastal forecast offices, thereby improving inter-site coordination (ISC) and consistency. The gTCM will also significantly reduce the amount of manual labor required to prepare wind grids, giving forecasters more time to fuse local mesoscale features into their forecasts.

During 2018, the gTCM will be available for forecast offices to use on an experimental basis while its verification continues. The grid domain will be expanded across the Atlantic Ocean and further south into the Caribbean Sea and, in future years, into the Pacific Region as well. As part of this expansion, land use data for the inland decay/friction algorithm will be processed for Mexico, Puerto Rico and the Virgin Islands. A terrain elevation adjustment option will also be activated in the wind model, which is critically important for the islands of the Caribbean and storms penetrating well inland into the southeast U.S. The goal is to evaluate and decide on an operational implementation over the next couple of years.

DISCLAIMER

Operational forecasters are cautioned not to become overly dependent on the gTCM since, after all, it is still a deterministic product with empirical approximations and includes the uncertainties inherent in NHC's forecasts. It should be used in conjunction with probabilistic products, especially during unpredictable or high-risk forecast scenarios.

6. REFERENCES

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