Improving Low-level Wind Simulations of Tropical Cyclones by a Regional Hurricane Analysis and Forecast System

Weiguo Wang[1], Bin Liu[1], Zhan Zhang[2], Avichal Mehra[2], Vijay Tallapragada[2]
[1]IMSG @ EMC/NCEP/NWS/NOAA,[2]EMC/NCEP/NWS/NOAA
Email: Weiguo.Wang@noaa.gov

1. Introduction

The Hurricane Analysis and Forecast System (HAFS) is being actively developed under the NOAA Unified Forecast System operational hurricane model. In 2021 tests, the scale-aware TKE-based Eddy-diffusivity Mass-flux (EDMF) planetary boundary layer (PBL) scheme was used to replace the K-profile-based EDMF PBL scheme, which was one of the major differences in the physics configuration compared with the tests in 2020. Test results suggested that the regional HAFS model with the TKE-based EDMF PBL scheme produced smaller errors in both track and intensity, even improving upon the current operational hurricane models at NCEP (i.e., HWRF and HMON). Nevertheless, it was found that the HAFS simulation with the TKE-based EDMF PBL produced a significantly larger negative bias in the intensity than the operational HWRF model. Given the important role of PBL processes in the numerical simulations of tropical cyclones, we examined the mixing length formulation in the PBL scheme and found that it may result in inconsistencies with the length scale of the Monin-Obukhov similarity theory near the surface. Therefore, a modification was proposed, which did improve the intensity bias. Here we briefly summarize this modification and experimental results.

2. Regional HAFS

The FV3-based HAFS system was configured to be a single large domain coupled with the HYbrid Coordinate Ocean Model. The domain is centered at 25N, 62W, with 3120 by 2160 grid cells (105°x60°) and $\triangle x \approx 3$km. The model uses 91 vertical levels on a sigma-pressure hybrid system with a model top of 10 hPa and the lowest level at ~20 m above the surface. There are 23 levels below 1.5 km, with vertical grid size varying approximately from 20 m to 130 m near 1.5 km, to reasonably resolve PBL processes. Initial and boundary conditions are derived from GFS forecasts. The lateral boundary conditions are updated every 3 hours. Vortex initialization, including a data assimilation system for HAFS, was still being developed at the time and, hence, not included in the experiment. The options of the physics parameterization schemes in the control experiment are basically the same as the current operational FV3-based GFS, with the exception that the observation-based surface roughness length is adopted following the operational HWRF and HMON models.

2. Mixing-length formulation

In the TKE-based EDMF PBL scheme, eddy diffusivity, K_φ, is a function of TKE,

$$K_\varphi = c_\varphi l_k \sqrt{TKE} \quad (1)$$

where c_φ is a coefficient ranging from 0.1 to 0.4, depending on stability and height, TKE is a prognostic variable solved from its budget equation, and l_k is a mixing length characterizing the capability of local mixing. The widely-used Blackadar (1962)'s formulation for l_k is currently used,

$$l_k = \left(\frac{1}{l_1} + \frac{1}{l_2}\right)^{-1} . \quad (2)$$

l_1 is a function of the distance (z) to the surface and stability function following the similarity theory, and l_2 is estimated by the parcel method suggested by Bougeault and Lacarrere (1989). The implementation of Eq. (2) near the surface in the model may result in inconsistencies with the length scale of the M-O similarity theory (Lenderink and Holtslag 2004).

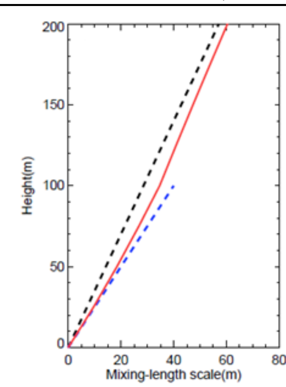

Figure 1 mixing length near the surface for an idealized neutral scenario from similarity theory (blue), control (black), and modified (red).

To illustrate this inconsistency, Figure 1 compares the mixing length scales within the surface layer from Eq. 2 (black line) and similarity theory (blue line) under neutral conditions. It is seen that Eq. 2 could give a length scale 25% smaller than that from the similarity theory; this could affect the simulations of wind and fluxes at the low levels of the model. For an extreme case where l_1 and l_2 are equal, Eq. 2 leads to $l_k = 0.5l_1 = 0.5l_2$, significantly deviating from the similarity theory. A correction to l_k near the surface was proposed so that the mixing length below the surface-layer top exactly follows the similarity theory, i.e.,

$$l_k = \left(\frac{1}{l_1} + c\frac{1}{l_2}\right)^{-1}, \tag{3}$$

where c is introduced so that l_k is equal to l_1 below the surface-layer top (h), and the same as Eq. 2 above $2h$. c is equal to 0 below h, 1 above $2h$, and linearly distributed in between.

3. Results

The regional HAFS model was run using the mixing length formulations Eq. 1 (CNTL) and Eq. 2 (LMOD), respectively. The retrospective runs were initialized every 6 h, covering the periods from Aug. 24 to Sep. 10, 2019, and from Aug. 19 to Sep. 23, 2020. The NHC's verification package was used to verify the simulated track and intensity of TCs against the best-track data. While the track errors between the two runs are very close (not shown), the intensity bias from LMOD run is significantly reduced compared to the CNTL run at all lead times (Fig. 2 left). The absolute intensity error is also improved (Fig. 2 right). These improvements could be due to the increased inflow angle near the surface and enhanced downward mixing of momentum as a result of increased mixing at low levels in the modified formulation.

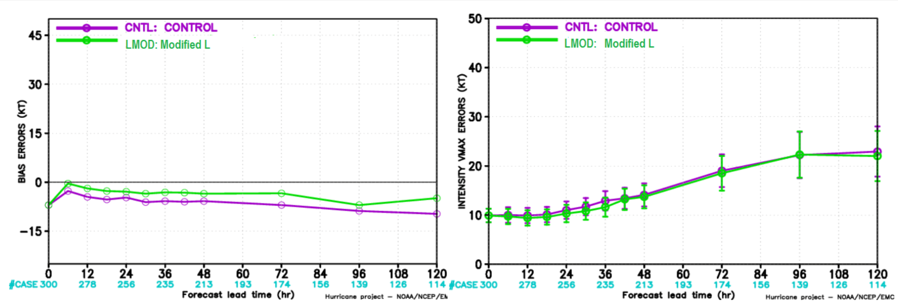

Figure 2 Intensity biases and errors from control and modified runs.

To examine the wind profiles in low levels in the eyewall area, we selected the simulations for one cycle of Hurricane Teddy (20L) initialized at 00UTC, on Sep 17, 2020. During the 5-day simulation, the vortex traveled over the open ocean and both runs produced very close tracks. To compare with published observations (Franklin et al, 2003, Vickery et al. 2009), the vertical profiles of horizontal wind speed in the eyewall area are normalized by the wind values at 3km. It is seen that the averaged profile of the normalized wind speed from the run with the modified l_k is closer to observations than the control run.

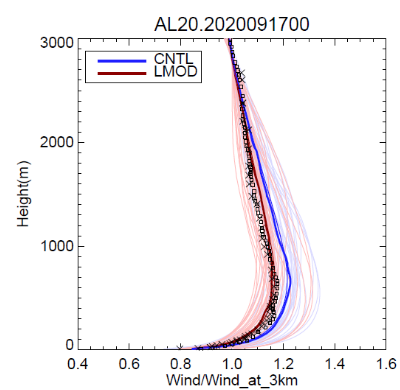

Figure 3 Normalized wind profiles from output every 3 hrs from CNTL run (light blue) and from LMOD run (light red). Thick lines for median values, symbols for composite observations.

4. Summary

The mixing length formulation is modified so that the length scale near the surface is consistent with the similarity theory used in the surface layer scheme. Surface wind and profiles in the eyewall area are improved. More analyses will be done.