Section 4

Parameterization of atmospheric and surface processes, effects of different physical parameterizations.

Improving the Earth System Model Development process via a Hierarchical System Development approach and use of the Common Community Physics Package

Mike Ek (ek@ucar.edu)[1,2], Weiwei Li(weiweili@ucar.edu)[1,2], Louisa Nance (nance@ucar.edu)[1,2],
Grant Firl (grant.firl@noaa.gov)[2,3,4], Ligia Bernardet (ligia.bernardet@noaa.gov)[2,4], and
Dom Heinzeller (dom.heinzeller@ucar.edu)[5]

[1] National Center for Atmospheric Research/Research Applications Laboratory/Joint Numerical Testbed
[2] Developmental Testbed Center
[3] Colorado State University/Cooperative Institute for Research in the Atmosphere
[4] NOAA Global Systems Laboratory
[5] University Corporation for Atmospheric Research/UCAR Community Programs/Joint Center for Satellite Data Assimilation

Hierarchical System Development (HSD) is an efficient approach to effectively connect the “Research-to-Operations” and “Operations-to-Research” (R2O2R) process, with the ability to test small elements (e.g., atmospheric physics subroutines) of an Earth System Model (ESM) first in isolation, then progressively connecting those elements with increased coupling between ESM components and HSD steps. *System* in the HSD is end-to-end in that it includes data ingest and quality control, data assimilation, modeling, post-processing, and verification. The HSD includes Single Column Models (SCMs; including individual physics elements within the SCM), small-domain atmosphere-only models, all the way up to complex fully-coupled ESMs with components for atmosphere/chemistry/aerosols, ocean/waves/sea-ice, land-hydrology/snow/land-ice, and biogeochemical cycles/ecosystems. Figure 1 illustrates the HSD approach and the different tiers in the HSD Testing “Harness”.

Although an ESM subset (i.e. atmosphere-land and specified ocean conditions) has traditionally addressed Numerical Weather Prediction (NWP) needs, we assert that the R2O2R process may be improved by further utilizing the complexity spectrum inherent with the HSD approach. Datasets for use in the different tiers of the HSD are obtained from measurements (e.g. field programs and observational networks), ESM output, or idealized conditions (e.g. a constant background flow to simplify physics interactions, or extreme winds, or instability to “stress-test” system components across the HSD steps, among other options). The requirements for advancing from one HSD step to the next are appropriate evaluation metrics/benchmarks of ESM performance, many of which are at the physical process level.

It is important to note that this process is concurrent and iterative such that more complex HSD steps can provide information to be used at simpler HSD steps, and vice versa. The HSD approach can also help increase understanding of spatial and temporal dependencies in model physics where there is a need for consistencies in model solutions between higher-resolution/limited-area short-range, global medium/extended-range and subseasonal-to-seasonal, as well as longer term climate time scales.

An effective “enabler” of a physics-focused HSD approach is the Common Community Physics Package (CCPP), which is designed to lower the bar for community involvement in physics testing and development through increased interoperability, improved documentation, and continuous support to developers and users. The CCPP is a collection of atmospheric physical parameterizations and a framework that couples the physics for use in ESMs. The CCPP Framework was developed by the U.S. Developmental Testbed Center (DTC) and is now an integral part of the Unified Forecast System (UFS), where the UFS is being used by the National Oceanic and Atmospheric Administration (NOAA) for their operational NWP models as well as by the NWP community for research. The CCPP is also being experimented with in the U.S. Navy Research Laboratory NEPTUNE model (NEPTUNE: Navy Environmental Prediction System Using the NUMA Core; NUMA: Nonhydrostatic Unified Model of the Atmosphere), and at the National Center for Atmospheric Research (NCAR) for the WRF, MPAS, and CAM/CESM models (WRF: Weather Research and Forecasting; MPAS: Model for Prediction Across Scales; CAM: Community Atmosphere Model; CESM: Community Earth System Model).

A primary goal for the CCPP is to facilitate research and development of physical parameterizations, while simultaneously offering capabilities for use in operational models. The CCPP Framework supports configurations ranging from process studies to operational NWP as it enables host models to assemble the parameterizations in suites. Framework capabilities include flexibility with respect to the order in which schemes are called, ability to group parameterizations for calls in different parts of the host model (including the dynamical core), and ability to call some parameterizations more often than others with a reduced time step or in an iterative process. Furthermore, the CCPP is distributed with a SCM to test innovations and conduct HSD studies in which physics and dynamics are decoupled, in order to isolate processes and more easily identify systematic errors or biases.

The CCPP is developed as open-source code and has received contributions from the broad community in the form of new schemes and innovations within existing schemes. Today, there are more than 30 primary parameterizations in the CCPP, representing a wide range of meteorological and surface processes. Physics schemes are typically used by the host models in suites, and classified as operational or experimental. The CCPP is scheduled for all upcoming operational implementations of the UFS Weather Model, and the CCPP v6 release (planned for June 2022) is publicly supported for use with the CCPP SCM and the UFS Medium- and Short-Range Weather Applications. For existing CCPP resources for users and developers, which includes information on public releases, documentation, tutorials and forums, see: https://dtcenter.org/community-code/common-community-physics-package-ccpp.

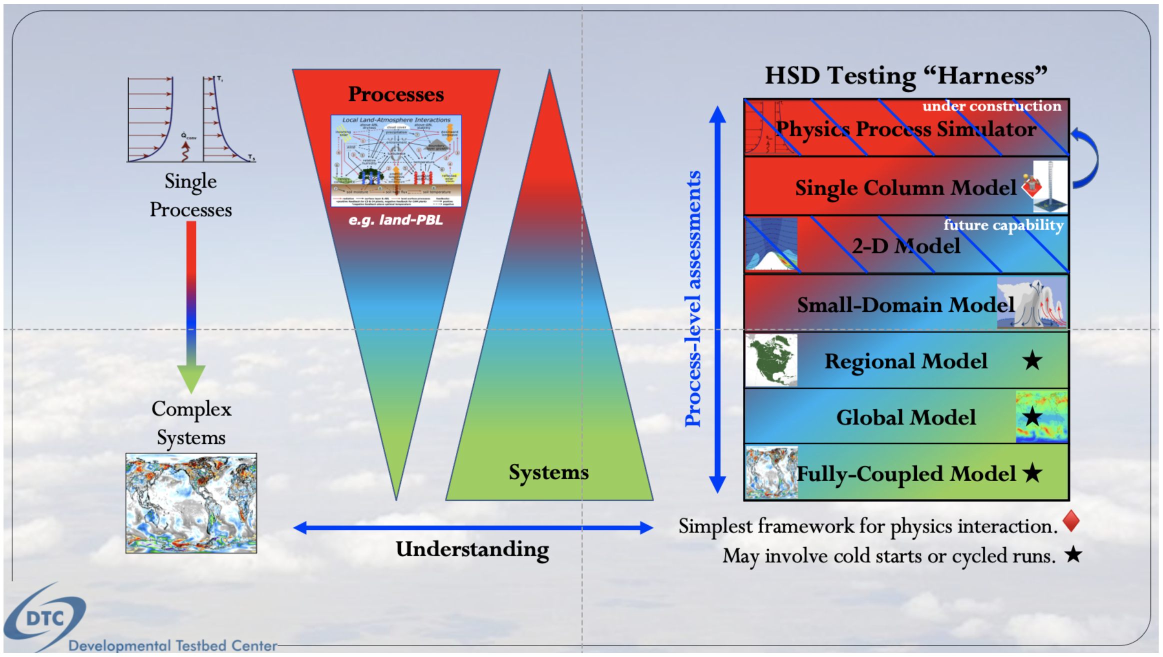

Figure 1. Hierarchical System Development (HSD): A simple-to-more-complex comprehensive approach to identify systematic errors or biases and improve Earth System Models (ESMs) for weather and climate. Important understanding about a single process does not yield corresponding understanding about a complex system of which it is a part, and conversely, important understanding about a complex system does not necessarily yield corresponding understanding about a single process. The HSD Testing “Harness” allows examination of processes and modeling systems across different tiers of the HSD. Datasets to drive and validate models for different HSD steps come from measurements, model output, or idealized conditions, with “cumulative” performance benchmarks, including process-level assessments, at all HSD steps.

Simulations of Marine Boundary Layer Clouds Using the Common Community Physics Package Single-Column Model

Tracy Hertneky[1], Weiwei Li[1], Lulin Xue[1], Jimy Dudhia[1], and Ligia Bernardet[2]

[1]National Center for Atmospheric Research and Developmental Testbed Center (DTC)
[2]NOAA Global Systems Laboratory and DTC
Correspondence: hertneky@ucar.edu

Introduction

The Marine ARM GPCI Investigation of Clouds (MAGIC) campaign aimed at observing the characteristics of clouds and radiation in the transition from the stratocumulus (Sc) regime to scattered shallow cumulus (Cu) onboard a ship traversing between Los Angeles, CA to Honolulu, HI. Leg 15A (CA to HI) spanning 20-25 July 2013 sampled a well-defined Sc-to-Cu transition and boundary layer decoupling. The Common Community Physics Package (CCPP) Single-Column Model (SCM) was used to diagnose systematic errors in cloud coverage and radiative fluxes within the marine boundary layer with the Global Forecast System (GFS) v16 physics, where an underestimation of marine Sc remains during the boreal summer off the west coasts of continents.

SCM Simulation Setup

The SCM initial conditions were from the third sounding of Leg15A at 05:27 UTC on 21 July 2013 and ship-following large-scale forcings were from the European Center for Medium-Range Weather Forecasts (ECMWF) 1-hour forecasts, with relaxation towards the ECMWF analysis [initial and large-scale forcing data from Zheng et al. (2020) and McGibbon and Bretherton (2017)]. The three-day simulation used the GFS v16 physics and was driven by prescribed surface fluxes computed using the Coupled Ocean-Atmosphere Response Experiment (COARE) air-sea flux algorithm.

SCM Results

At the start of the simulation, an observed Sc layer is present at the top of the well mixed boundary layer through the end of day 2 when it breaks apart and transitions to scattered Cu on the third day (Fig. 1a). The simulated cloud fraction (Fig. 1b) also produces a Sc topped boundary layer; however, the cloud layer appears thinner and growth is slower compared to observed, which is directly related to the PBL deepening at a slower rate (Fig. 1c, d). Additionally, the simulated breakup is delayed by a day and fails to reproduce Cu on day 3. On day 1, the observed and simulated PBL heights are similar, with a cold and moist bias present at cloud top (Fig. 1c, d), which is an indication of underpredicted cloud-top entrainment. This could in part explain the slower growth rate of the simulated PBL on days 2-3 and the later Sc break-up as well if there is a deficiency in free-tropospheric air from above the inversion being mixed down. The thermal stratification of the inversion plays a key role in cloud-top entrainment, where entrainment is inhibited more the stronger the inversion is. Simulated hourly averaged liquid water potential temperature profiles show a

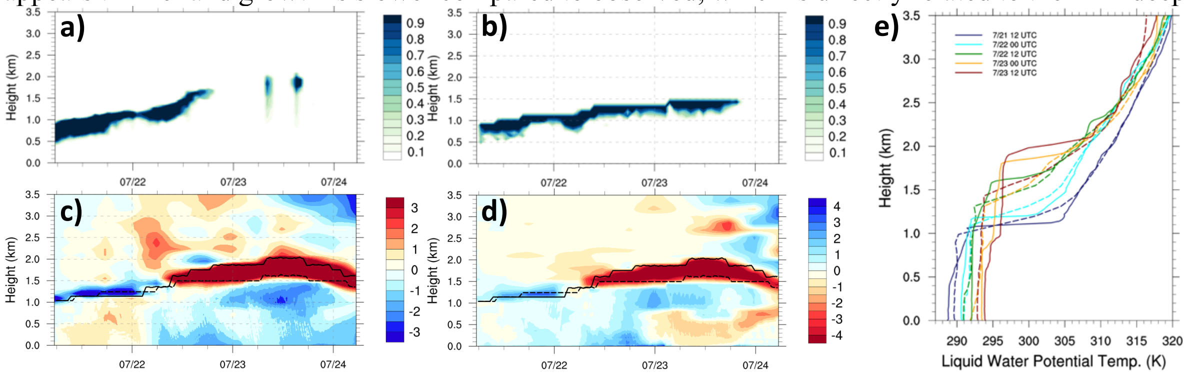

Figure 1. Contour plots of a) observed cloud fraction computed from the ARM ka-band zenith radar and cloud ceiling (Zheng et al. 2020) and b) simulated cloud fraction; difference (SCM minus observation) of c) potential temperature (K) and d) specific humidity (g kg^{-1}), where the solid lines are the observed PBL heights and the dashed lines are the SCM PBL heights, and e) the simulated (dashed) and observed (solid) profiles of liquid water potential temperature with 12-h interval.

larger temperature gradient across the inversion compared to observations as a result of a cooler inversion base throughout the run (Fig. 1e). Additional investigations will look into longwave cloud-top cooling, where weaker radiative cooling can also lower the entrainment rate.

Simulation Sensitivities

Sensitivities to the large-scale forcings were examined in order to assess the impact of each component. Runs included i) no forcing, ii) large-scale vertical velocity (omega) only, iii) large-scale advection of potential temperature only, and iv) large-scale advection of specific humidity only. The simulations with no forcings (Fig. 2a) and inclusion of moisture advection (Fig. 2c) have a persistent Sc layer for the entire duration. The inclusion of large-scale omega (Fig 2d) leads to a simulated cloud similar to the control as in Fig. 1b. The simulation advecting only potential temperature (Fig. 2b) produces the most realistic Sc as in Fig. 1a and PBL heights (not shown), which is similar to the observed break up near the end of day 2, but still fails to simulate scattered Cu. These results suggest a possible overabundance of moisture advection.

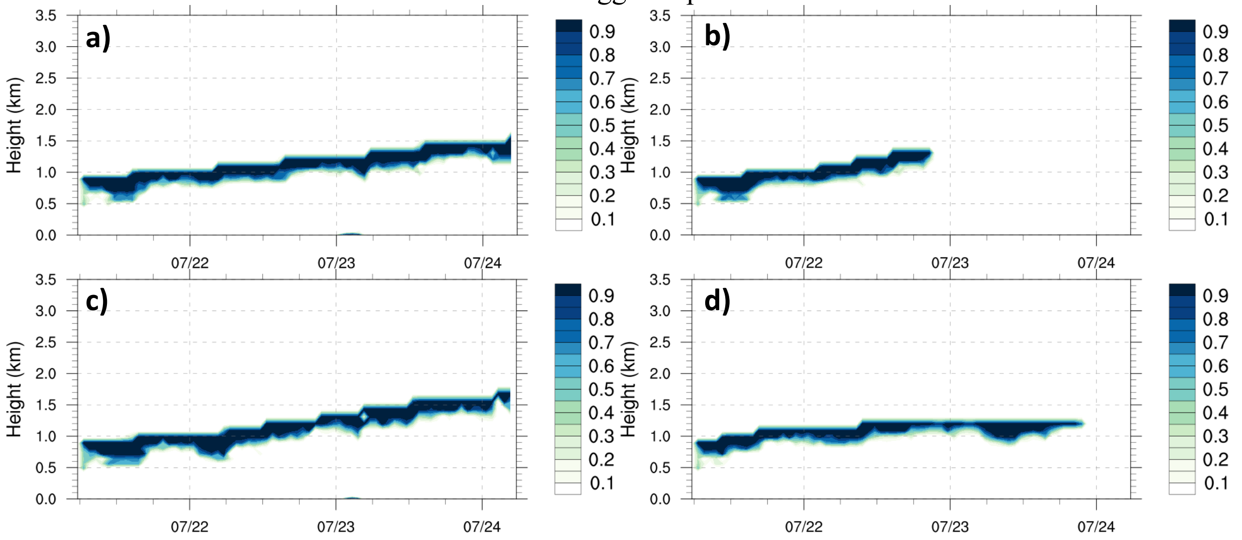

Figure 2. Simulated cloud fraction from runs with a) no large-scale forcing, b) advection of θ only, c) advection of specific humidity only, and d) advection of omega only.

Summary

This study examines biases in cloud coverage and the transition from Sc-to-Cu over the northeast Pacific, where there is a known underestimate of marine boundary layer clouds off the coast during the summer with the GFS v16. Contrary to the findings from the operational model, while the SCM simulated Sc appeared thinner, they were not largely underestimate and in fact were overestimated on day 3. During the first 6-24 hours of the simulation a cold and moist bias lead to a slower growth rate of the PBL and cloud base on days 2-3, which is a symptom of underpredicted cloud-top entrainment and could be a result of the stronger inversion present. Further sensitivities examined the impact of large-scale forcings and found that when only advecting potential temperature, Sc breakup occurred at a similar time compared to observations, indicating that other forcings may negatively contribute to the cloud bias (e.g., too much moisture advection). Further sensitivities and analysis will be conducted to examine key physical processes and error sources related to these biases, such as the relationship of entrainment and cloud-top radiative cooling and deactivating the nudging parameters.

References

McGibbon, J., and C. S. Bretherton, 2017: Skill of ship-following large-eddy simulations in reproducing MAGIC observations across the northeast Pacific stratocumulus to cumulus transition region. *J. Adv. Model. Earth Syst.*, 9, 810–831.

Zheng, X., Klein, S., Ghate, V., Santos, S., Mcgibbon, J., Caldwell, P., et al. (2020). Assessment of precipitating marine stratocumulus clouds in the E3SMv1 atmosphere model: A case study from the ARM MAGIC field campaign. *Monthly Weather Review*, 148.

Optimization of orographic drag parametrizations in the JMA operational global model using COORDE-type experiments

Chihiro Matsukawa, Yukihiro Kuroki, and Takafumi Kanehama
Japan Meteorological Agency
Email: chi_matsukawa@met.kishou.go.jp

1. Introduction

The orographic drag inter-comparison project recently proposed and conducted under the auspices of the Working Group for Numerical Experimentation (WGNE) and the Global Atmospheric System Studies (GASS), the COnstraining ORographic Drag Effects (COORDE; van Niekerk et al. 2020), offers new insights on orographic drag parametrizations in global numerical weather prediction models. The Japan Meteorological Agency (JMA) Global Spectral Model (GSM) exhibits greater deceleration of zonal wind due to overly strong orographic gravity wave drag (OGWD) at lower altitudes among participated models. Zonal wind field deterioration in the winter stratosphere was evident when the orographic drag parametrizations described below were incorporated into the GSM, while significant improvement of short- to medium-range forecast skill in the Northern Hemisphere winter troposphere was also achieved (Yonehara et al. 2020). We consider the deterioration in the winter stratosphere to be associated with increased gravity wave forcing at lower altitudes than in other models. In this study, orographic drag parametrizations were optimized in COORDE experiments.

2. Parametrizations and Experimental design

The GSM employs sub-grid scale orographic (SSO) drag parametrization for consideration of low-level flow blocking and OGWD based on Lott and Miller (1997) and the turbulent orographic form drag (TOFD) of Beljaars et al. (2004) (JMA 2022). To mitigate excessive parametrized OGWD in the lower stratosphere, generation of gravity wave stress at the surface is adjusted by decreasing the tunable parameter n_{eff} from 2.4 to 1.0 to multiply effective gravity wave amplitude. The gravity wave drag coefficient G was increased from 0.25 to 0.6, resulting in greater upward propagation and peaking at higher altitude. The parameter α in TOFD was doubled to compensate for reduced gravity wave drag and related deterioration of forecast accuracy in the lower troposphere.

The COORDE experiments of van Niekerk et al. (2020) were conducted using the GSM with current and new orographic drag configurations (Table 1) at low-resolution (LR: TL159 (~110 km)). All forecasts were initialized from JMA's own analysis at 00 UTC from 1st to 14th January 2015. Forecasts at T+24 were evaluated via averaging over 14 cases.

3. Results

The impacts of parametrized orographic drag on zonal wind (i.e., LR_CNTL − LR_NOSSO, LR_REVISED − LR_NOSSO) were compared with those of resolved drag (i.e., HR_CNTL − HR_LROR) (Fig. 1). While the impacts of OGWD in LR_CNTL are stronger at lower altitudes than resolved as pointed out in van Niekerk et al. (2020), the revised orographic drag represents impacts closer to those of resolved drag in the lower stratosphere due to lower generated gravity wave stress and increased vertically propagating gravity waves with the new parameters. As a result, the noticeable negative zonal wind biases in LR_CNTL are significantly alleviated in LR_REVISED (Fig. 2).

References

Beljaars, A., A. R. Brown, and N. Wood., 2004: A new parametrization of turbulent orographic form drag. *Q. J. R. Meteorol. Soc.*, **130**, 1327-1347.

Japan Meteorological Agency, 2022: *Outline of the operational numerical weather prediction at the Japan Meteorological Agency.* JMA.

Lott, F. and M. J. Miller, 1997: A new subgrid - scale orographic drag parametrization: Its formulation and testing. *Q. J. R. Meteorol. Soc.*, **123**, 101-127.

van Niekerk, A. and Coauthors, 2020: COnstraining ORographic Drag Effects (COORDE): a model comparison of resolved and parametrized orographic drag. *Journal of Advances in Modeling Earth Systems*, **12**(11).

Yonehara, H. and Coauthors, 2020: Upgrade of JMA's Operational Global Model. *WGNE Res. Activ. Earth Sys. Modell, **50**. WCRP Report No.12, WMO, Geneva,pp.6-19--6-20.*

Table.1 Experiments.

Experiment	Description
LR_CNTL	Low-resolution (LR: ~110 km) control experiment with SSO drag turned on
LR_NOSSO	Low-resolution (LR: ~110 km) control experiment with SSO drag turned off
LR_REVISED	Low-resolution (LR: ~110 km) experiment with parameter-revised SSO drag turned on
HR_CNTL	High-resolution (HR: ~10 km) control experiment with SSO drag turned off
HR_LROR	High-resolution (HR: ~10 km) control experiment with low-resolution (~110 km) mean orography with SSO drag turned off

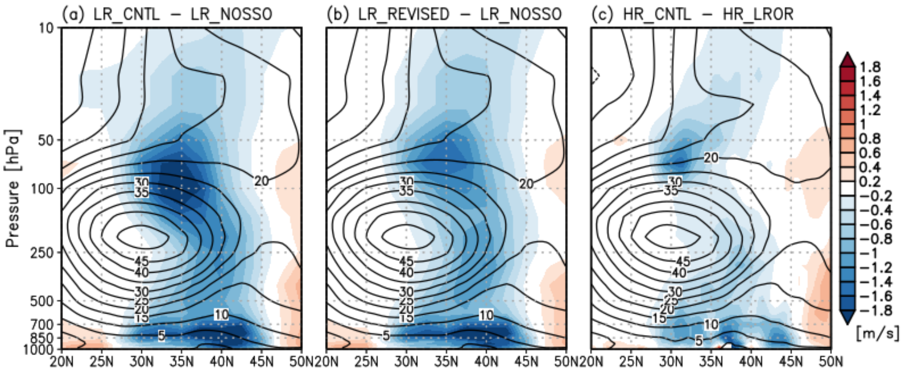

Fig. 1 Latitude-height cross section showing impacts of SSO drag on zonal wind [m/s] averaged over the Middle East (28 – 68°E). (a) LR_CNTL minus LR_NOSSO; (b) LR_REVISED minus LR_NOSSO; (c) HR_CNTL minus HR_LROR. Contours represent mean zonal wind in each experiment.

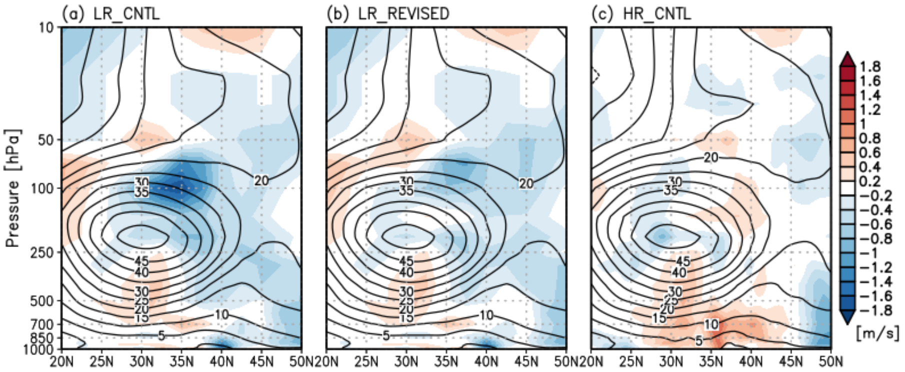

Fig. 2 Latitude-height cross section of zonal wind mean error against analysis [m/s] averaged over the Middle East region (28 – 68°E). (a) LR_CNTL; (b) LR_REVISED; (c) HR_CNTL. Contours represent mean zonal wind in each experiment.

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). 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

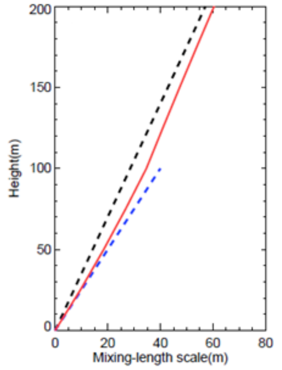

Figure 1 mixing length near the surface for an idealized neutral scenario from similarity theory (blue), control (black), and modified (red).

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.

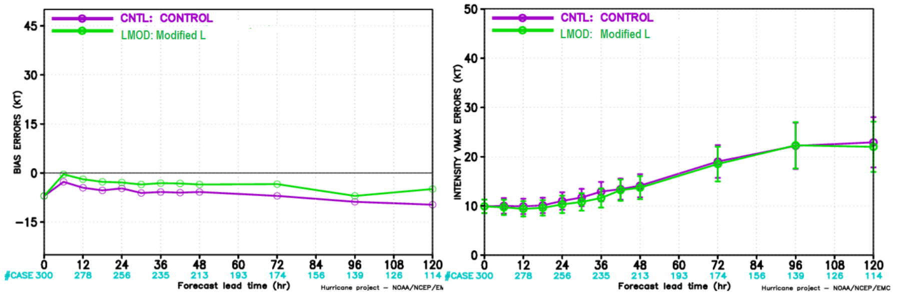

Figure 2 Intensity biases and errors from control and modified runs.

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.

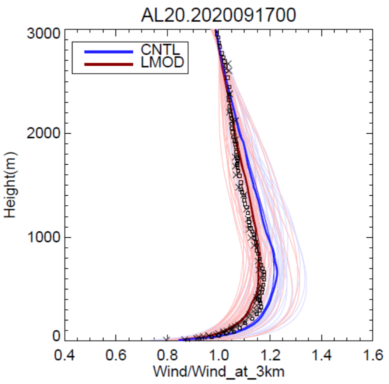

Figure 3 Normalized wind profiles from output every 3 hrs from CNTL run (light blue) and from LMOD run (light red). Thick lines for median values, symbols for composite observations.

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.