HAFS Physics Development at AOML & EMC

AOML: Andy Hazelton\textsuperscript{1,3}, Xiaomin Chen\textsuperscript{2,3}, Jun Zhang\textsuperscript{1,3}, Frank Marks\textsuperscript{3}, and Sundararaman Gopalakrishnan\textsuperscript{3}

1. University of Miami CIMAS; 2. MSU Northern Gulf Institute; 3. NOAA AOML
4. IMSG@NOAA/NCEP/EMC

EMC: Chunxi Zhang\textsuperscript{4}, Weiguo Wang\textsuperscript{4}, Bin Liu\textsuperscript{4}, Junghoon Shin\textsuperscript{4}, Zhan Zhang\textsuperscript{5}, Avichal Mehra\textsuperscript{5}, and Vijay Tallapragada\textsuperscript{5}

5. NOAA/NCEP/EMC
Observational estimates of the vertical mixing length

Flight-level data at ~500 m altitude collected in Hurricanes Hugo, Allen and Frances. (Marks 1985; Marks et al. 2008; J. Zhang et al. 2011)

TKE method
Dissipation length

\[ K_m = c E^{0.5} \]

\[ K_2 = c_2 e^2 / \varepsilon, \]

Scaling method based on Hanna (1968) equation

\[ l = \sigma^3 / \varepsilon. \]
Comparison of MEDMF-TKE vs. HEDMF in a set of 2020 cases
Composite Analysis of MEDMF-TKE vs. K-EDMF

➢ Composite differences shown
➢ Stronger PBL inflow and supergradient outflow in composites for MEDMF-TKE
➢ More low-level moisture and convergence

Hurricane Delta Case Study for HEDMF vs. MEDMF-TKE

- RI much closer to reality with MEDMF-TKE
- Tangential wind budget shows stronger spinup in and just above the PBL with MEDMF-TKE
Profile information of turbulence is missing at hurricane-force winds.

➢ Vertical profile of eddy viscosity is only available where surface wind speeds are $<30$ m/s.

➢ Develop a LES framework to fill in the gap and evaluate PBL schemes in hurricane conditions.
The novelty of this framework is the LES is performed in the thermodynamic conditions derived from actual mature hurricanes. The K-profile parameterization (KPP) schemes are inherently flawed in hurricane boundary layers. The LES results recommend the maximum mixing length above the surface layer is ~40 m.

HAFX/HAFI Track/Intensity Verification

➢ Little difference in track statistics from experimental HAFX/HAFI configurations
➢ Intensity errors are also about the same, although HAFI (91 levels) produced intensity bias stats that were much more comparable to HAFI
HAFX/HAFL Structure Verification

➢ HAFX: GFSV17 EDMF-TKE PBL schemes modified by LES results
➢ HAFL: GFSV17 EDMF-TKE PBL schemes modified by LES results, 91 vertical levels
➢ Little difference in track statistics from experimental HAFX/HAFL configurations
➢ Intensity errors are also about the same, although HAFL (91 levels) produced intensity bias stats that were much more comparable to HAFA
AOML Future Development/Testing

➢ How do we best utilize LES and observational data to improve EDMF-TKE or other schemes for TC applications? Need more turbulence measurements in the near-surface layer and eyewall region in extreme winds.

➢ How can we understand cases where the PBL physics are improved but the intensity response is not as accurate? (i.e. Larry)

➢ How do PBL physics impact large-scale flow (such as TC steering or the global midlatitude flow)?
## Physics Schemes & Suites in the HAFS

<table>
<thead>
<tr>
<th>Surface Layer</th>
<th>PBL</th>
<th>Cumulus</th>
<th>Microphysics</th>
<th>GWD</th>
<th>Land Model</th>
<th>Radiation</th>
<th>Ozone H2O</th>
<th>Fresh Water Lake Model</th>
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</thead>
<tbody>
<tr>
<td>GFSv16 (HAFSv0.2)</td>
<td>GFS* (updates)</td>
<td>sa-TKE-E DMF* (updates)</td>
<td>GFDL (updates)</td>
<td>ugwp_v0*</td>
<td>NOAH</td>
<td>RRTMG</td>
<td>2015, h2o</td>
<td></td>
</tr>
<tr>
<td>GFSv17 (HAFSv0.3)</td>
<td>MYNN</td>
<td>sa-MYNN</td>
<td>GF</td>
<td>ugwp_v1</td>
<td>NOAH-MP</td>
<td>RRTMGP (no updates)</td>
<td>FWLM</td>
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<tr>
<td>GFDL</td>
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<td>sa-Tiedtke</td>
<td>EEPS</td>
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</tbody>
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* These schemes are modified in the HAFS
+ The instability issue has been solved by using either inner loop or semi-Lagrangian sedimentation of rain;
  More tests are on-going


\[ w' \phi' = -K_\phi \frac{\partial \phi}{\partial z} + M_u (\phi_u - \bar{\phi}) \big|_{sfc} - M_d (\phi_d - \bar{\phi}) \big|_{Sc} \]

\[ K_\phi = c l_k \sqrt{\bar{e}}, \quad \bar{e} = 0.5 \left( u''^2 + v''^2 + w''^2 \right) \]

\[ l_k \] is a turbulent mixing length, \( c \) is a coefficient

\[
\frac{d \bar{e}}{dt} = - \frac{\partial}{\partial z} \left( \frac{w' e'}{\rho} + \frac{1}{\rho} w' p' \right) - u' w' \frac{\partial \bar{u}}{\partial z} - v' w' \frac{\partial \bar{v}}{\partial z} + \frac{g}{\theta_v} w' \theta_v' - D
\]

\[ D = c_d \frac{\bar{e}^{3/2}}{l_d} \] TKE dissipation rate

\[ c_p \frac{\partial T}{\partial t} \approx D \] TKE dissipative heating

Turbulent mixing length scale \((l_k)\):

- Combination of surface layer \((l_1)\) and a characteristic length scale \((l_2)\)

\[
\begin{align*}
\frac{l_1}{l_k} &= \frac{1}{l_1} + \frac{1}{l_2} \\
\frac{1}{l_1} &= \frac{\kappa z}{3.7} & z/L \geq 1 \\
\frac{1}{l_1} &= \frac{1 + 2.7 \frac{z}{L}}{0.2} & 0 \leq z/L < 1 \\
\frac{1}{l_1} &= \frac{1 - 100 \frac{z}{L}}{z/L} & z/L < 0
\end{align*}
\]

\[ l_2 = f_1 \min(l_{up}, l_{down}) \]

\[ l_d = f_1 \left( l_{up} l_{down} \right)^{1/2} \]

\[
\int_{z}^{z+l_{up}} \frac{g}{\theta_v} \left( \bar{\theta}_v(z) - \bar{\theta}_v(z') \right) dz' = \bar{e}(z)
\]

\[
\int_{z-l_{down}}^{z} \frac{g}{\theta_v} \left( \bar{\theta}_v(z') - \bar{\theta}_v(z) \right) dz' = \bar{e}(z)
\]

Bougeault & Lacarrere (1989)

(Slide courtesy of Jongil Han)
EMC’s modifications to $l_k$: IF ($h < \text{MIN}(100., 0.05 \times h_{\text{pbl}})$) $l_k = l_1$

Only apply to unstable regime
The E-epsilon (EEPS) PBL scheme
(Zhang et al. 2020, MWR)

\[ \frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z} \left( K_v \frac{\partial \phi}{\partial z} - \gamma \right) \]

- \( K_v \) is the vertical mixing coefficient with the subscript \( v \) substituted by \( m \) for momentum \( (K_m) \), \( h \) for heat and moisture \( (K_h) \)
- \( \gamma \) is a nonlocal term for heat and moisture

\[ E = \frac{m}{C_m} \left( \frac{\partial u}{\partial z} \right)^2 + \frac{1}{C_m} m \left( \frac{\partial v}{\partial z} \right)^2 - K_m P_{buoy} \]

\[ E = C_1 \frac{\partial E}{\partial z} \]

\[ \frac{\partial E}{\partial t} = K_m \left( \frac{\partial u}{\partial z} \right)^2 + \frac{\partial v}{\partial z} \left( \frac{\partial u}{\partial z} \right)^2 - K_h P_{buoy} \]

\[ C_1 = 1.35 \]
\[ C_2 = 0.09 \]
\[ C_3 = 1.44 \]
\[ C_4 = 1.92 \]
\[ C_5 = 0.77 \]

\[ E_{min} = 1 \times 10^{-4} \]
\[ \epsilon_{min} = 1 \times 10^{-6} \]

\[ K_m = 0.1 \]
\[ K_h = 0.01 \]

\[ \frac{\partial T}{\partial t} = \frac{\epsilon}{c_p} \]

Dissipation heating

A few iterations with split time steps.
HF2A: HAFSv0.2a phase 2 final configuration
EEPS: Same as HF2A except for the EEPS scheme
Without: Dorian, Humberto, Laura, Paulette
The Tiedtke - A bulk mass flux scheme

Tiedtke 1989 (MWR); Zhang et al. 2011 (MWR); Bechtold et al. 2014 (JAS); Zhang and Wang 2017 (JCLI)

Where & when does convection occur and what type of convection occurs – Trigger (1)

Mid-level

Deep

Shallow

Downdraughts

Entrainment/Detrainment (3)

Detrained cloud ice/water

Subsidence warming

Evaporation of precipitation

Cloud base mass flux – Closure (2)

Fallout of precipitation

Updraughts
Relationship between global precipitation and evaporation for C768

(a) saYSU + saSAS + Thompson (C768)

Prpc_ave=2.96841; Evap_ave=2.87433; Dllf=0.0940826

(b) saYSU + nTDK + Thompson (C768)

Prpc_ave=2.95527; Evap_ave=2.91283; Dllf=0.046443

Only for (60S, 60N)

GPM precipitation every 30 min
Future work

1) The current physics suite for the HAFS is highly dependent on the GFS physics suite, and we will follow the development of the GFS physics suite and modify the individual schemes if necessary.

2) We will likely develop the second physics suite for the HAFS which is still based on the GFS physics suite but with the replacement of the PBL scheme and/or the cumulus scheme and/or other schemes.
Extra Slides
Evaluating and improving PBL physics in HAFS

- ¾ schemes close to Best Track
- Modified EDMF-GFS a little bit of an outlier
- Original EDMF-GFS produces worst intensity
- Reducing diffusivity produces wind peak closer to Best Track
HAFX forecasts in the 2021 hurricane season

➢ HAFX is a parallel run on Orion using the improved EDMF-TKE PBL scheme based on LES results (Chen et al. 2021, in review)
➢ HAFX captured well the rapid intensification as well as the track of Hurricane Ida.
➢ Track error is less than 50 n mi within 4 days for Hurricane Larry.
Eddy Diffusivity from All Cases (and Obs)

➢ Default schemes are too diffusive
➢ EDMF-GFS is most diffusive
➢ With modifications (alpha = 0.25 for EDMF-GFS and elmx = 100 m for EDMF-TKE), both schemes have reduced diffusivity closer to obs
➢ Limited obs at high wind speed (an observational need)

(Gopal, Hazelton, Zhang, 2021)
Comparison of 2020 HAFS-B results using MEDMF-TKE (red) vs. tests using Hybrid K-profile EDMF (blue)

Stronger PBL inflow and supergradient outflow in composites for MEDMF-TKE

Produced better RI forecasts in several cases including Hurricane Delta