HFIP | HURRICANE FORECAST IMPROVEMENT PROGRAM

HAFS Physics Development at AOML & EMC

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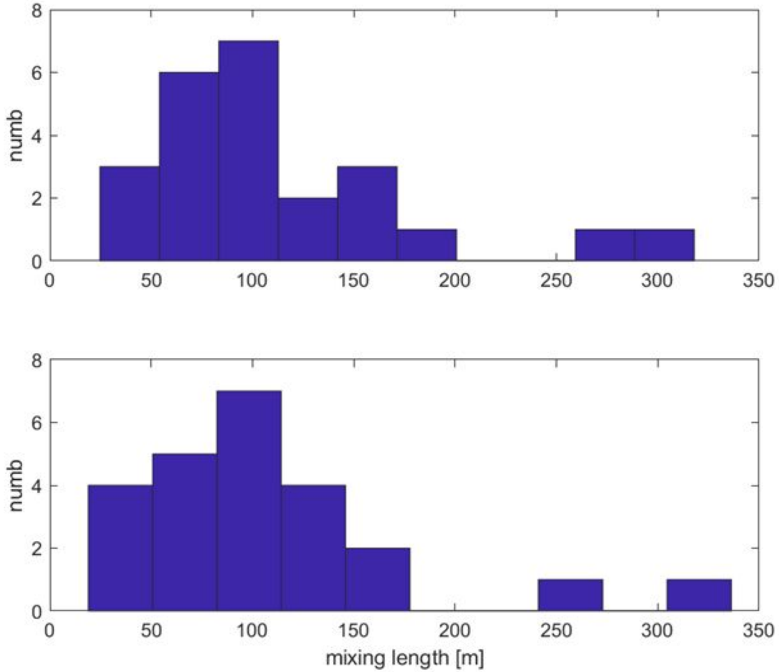
Observational estimates of the vertical mixing length

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

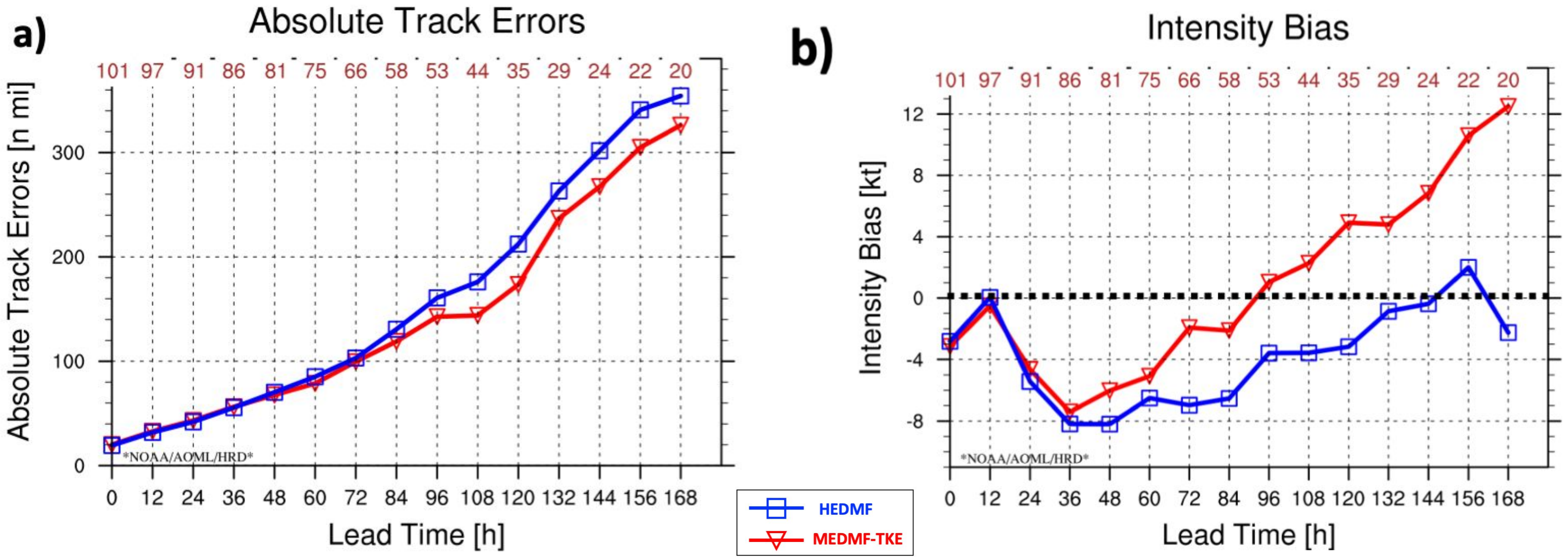
$$K_m = c l E^{0.5}$$

$$K_2 = c_2 e^2/\varepsilon,$$

Scaling method based on Hanna (1968) equation

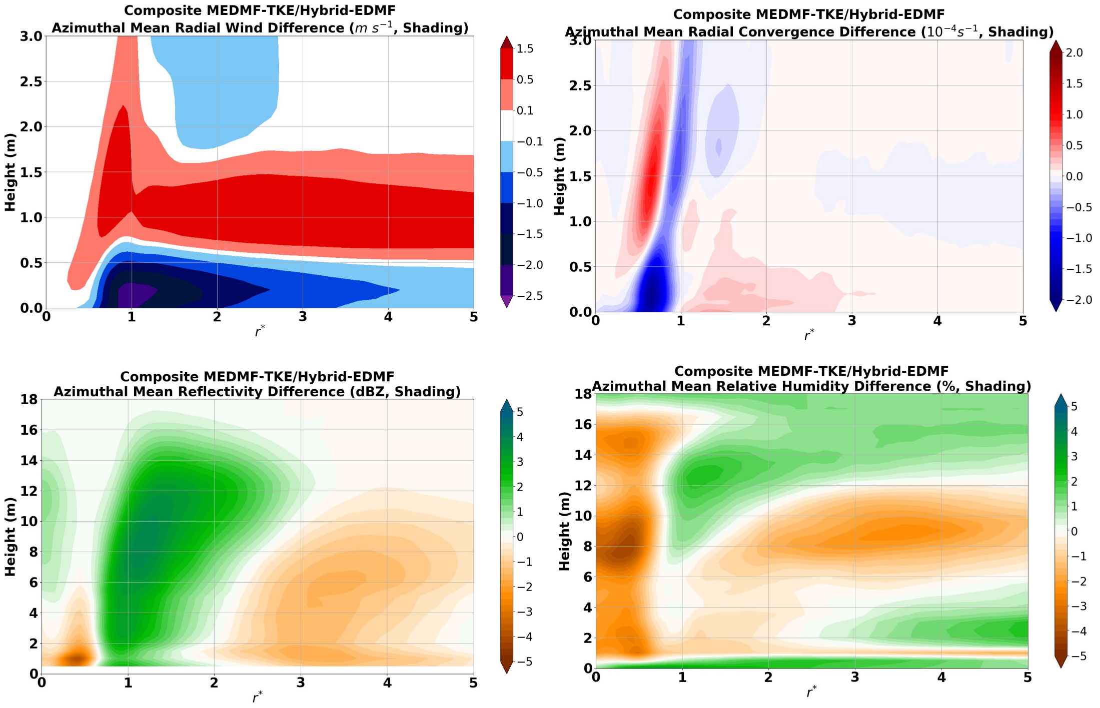
$$l = \sigma_w^3/\varepsilon.$$

MEDMF-TKE vs. HEDMF Composite Study



- Comparison of MEDMF-TKE vs. HEDMF in a set of 2020 cases

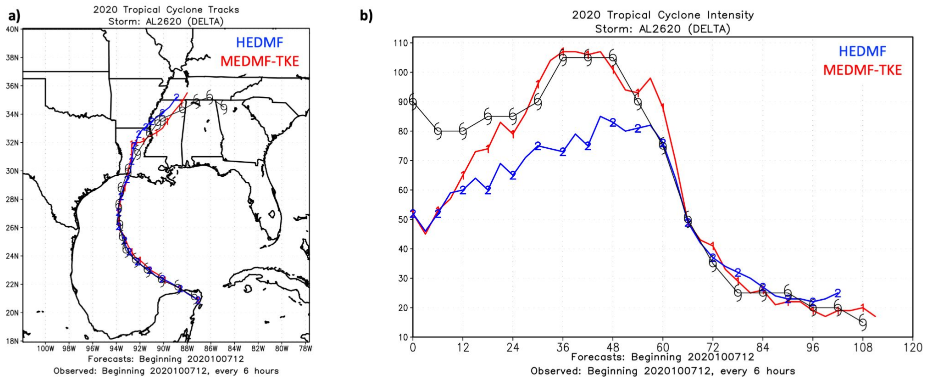
Composite Analysis of MEDMF-TKE vs. K-EDMF

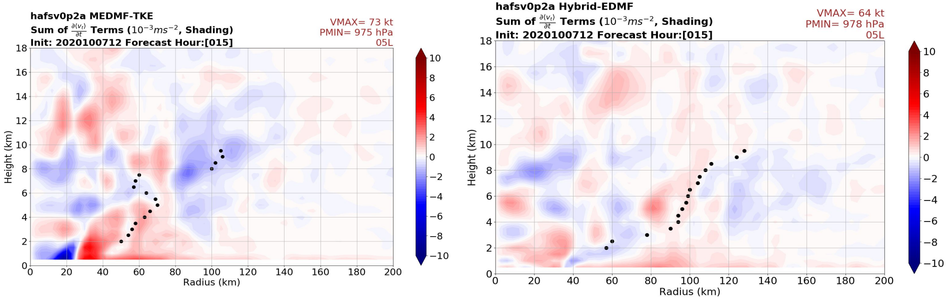


- ➢ Composite differences shown
- ➢ Stronger PBL inflow and supergradient outflow in composites for MEDMF-TKE
- ➢ More low-level moisture and convergence

-***Hazelton, A. T.***, Gopalakrishnan, S., and J. A. Zhang, 2021: Comparison of The Hybrid EDMF and Modified EDMF-TKE PBL Schemes in 2020 Tropical Cyclone Forecasts from the Global-nested Hurricane Analysis and Forecast System, *Wea. Forecasting,* in review.

Hurricane Delta Case Study for HEDMF vs. MEDMF-TKE

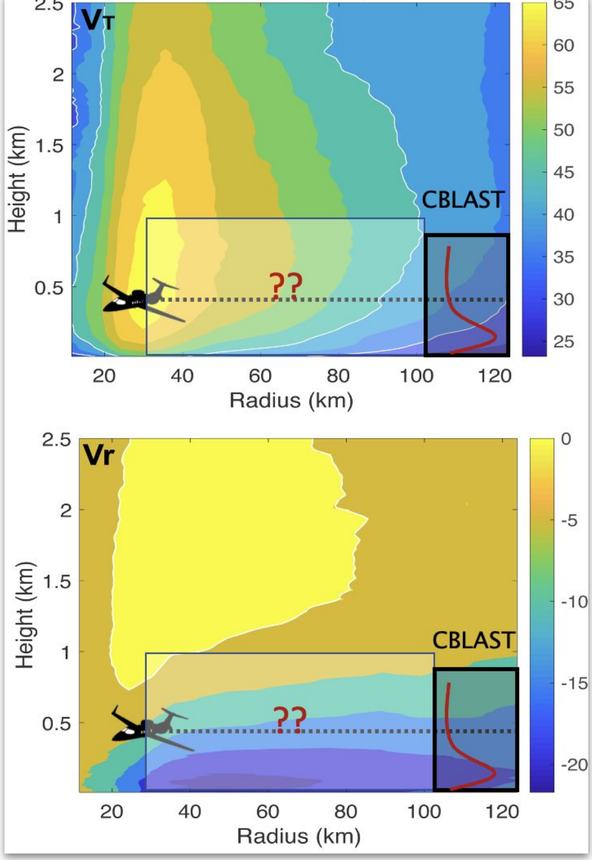




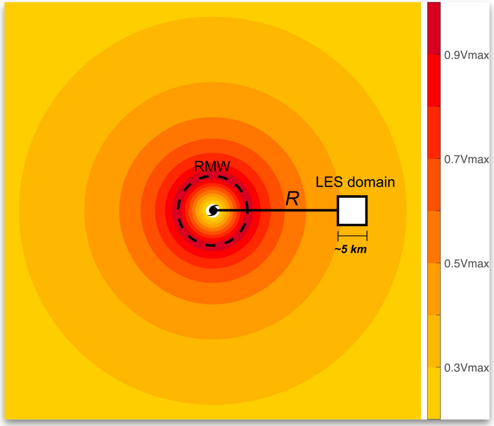
- ➢ RI much closer to reality with MEDMF-TKE
- ➢ Tangential wind budget shows stronger spinup in and just above the PBL with MEDMF-TKE

Profile information of turbulence is missing at hurricane-force winds

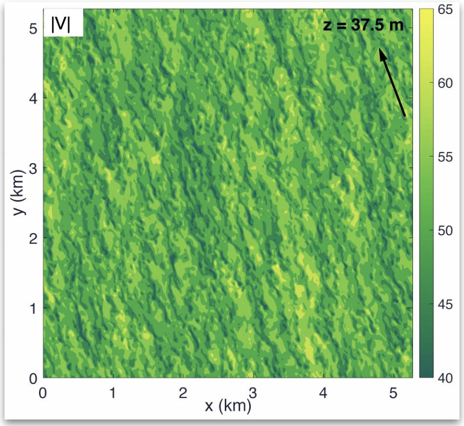
Dropsonde composites



LES setup



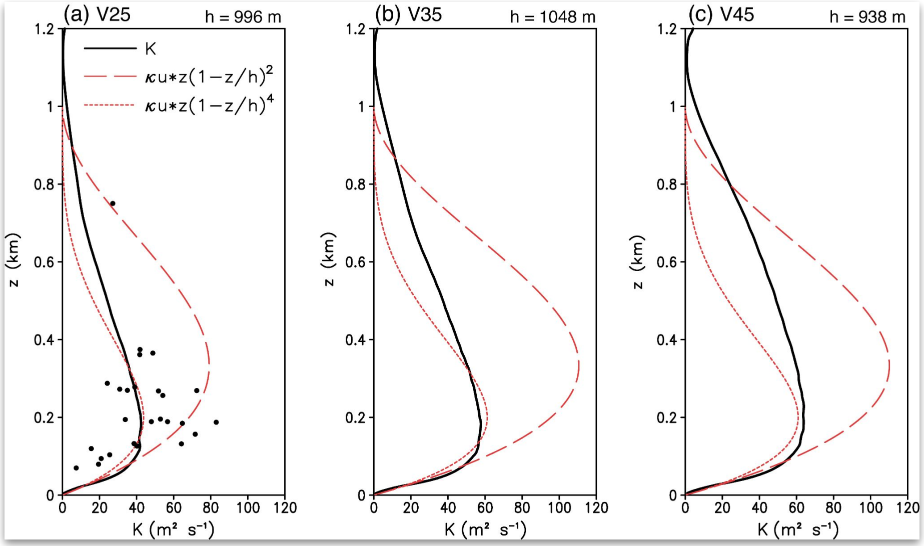
LES results



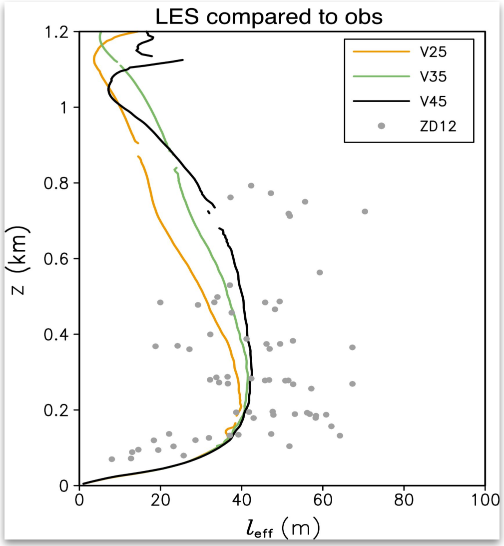
- ➢ Vertical profile of eddy viscosity is only available where surface wind speeds are <30 m/s.
- ➢ Develop a LES framework to fill in the gap and evaluate PBL schemes in hurricane conditions

LES modeling for hurricanes

Evaluation of KPP PBL schemes



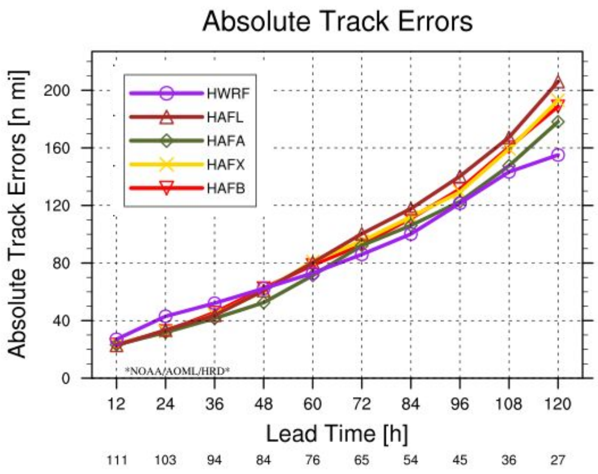
Mixing length

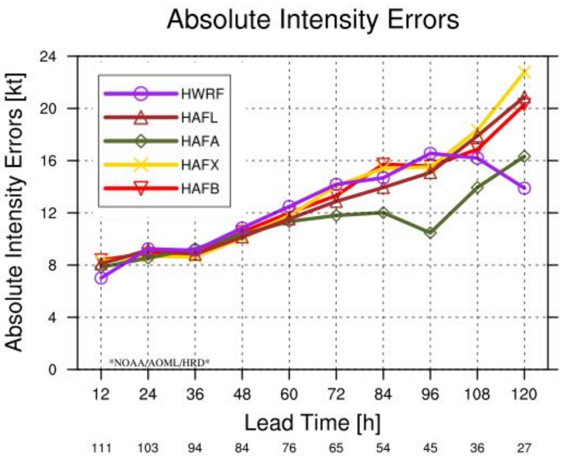


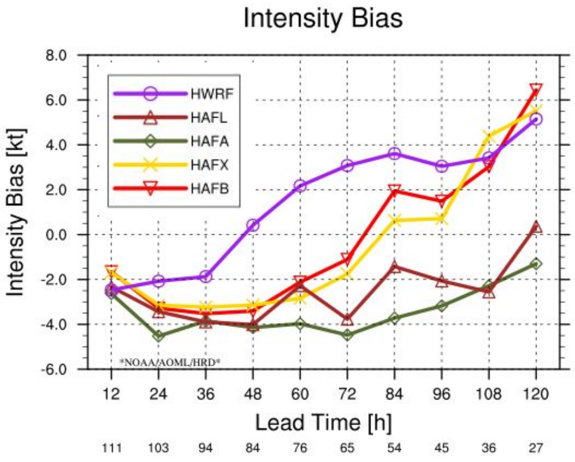
- ➢ The novelty of this framework is the LES is performed **in the thermodynamic conditions derived from actual mature hurricanes**
- ➢ The *K*-profile parameterization (KPP) schemes are inherently flawed in hurricane boundary layers
- ➢ The LES results recommend the maximum mixing length above the surface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

-Chen, X., G.H. Bryan, J.A. Zhang, J.J. Cione, and F.D. Marks, 2021: A framework for simulating the tropical-cyclone boundary layer using large-eddy simulation and its use in evaluating PBL parameterizations. *J. Atmos Sci.*, in press. https://doi.org/10.1175/JAS-D-20-0227.1

HAFX/HAFL Track/Intensity Verification

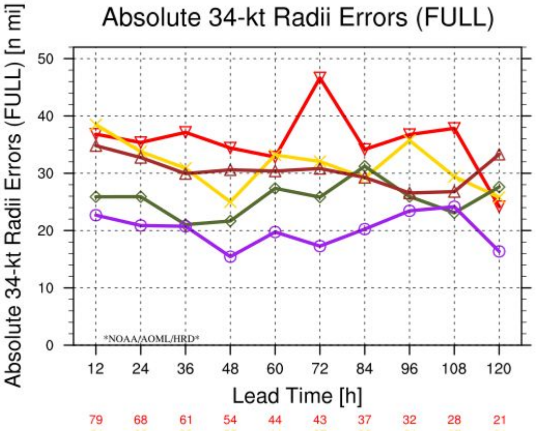


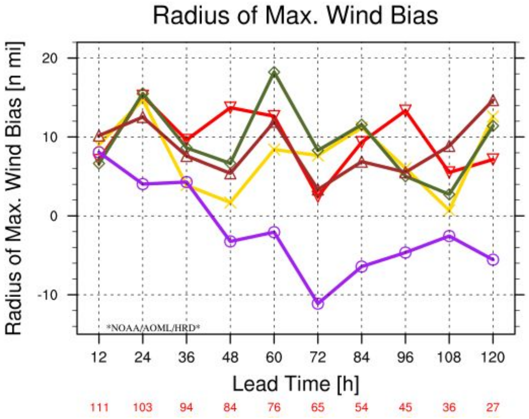


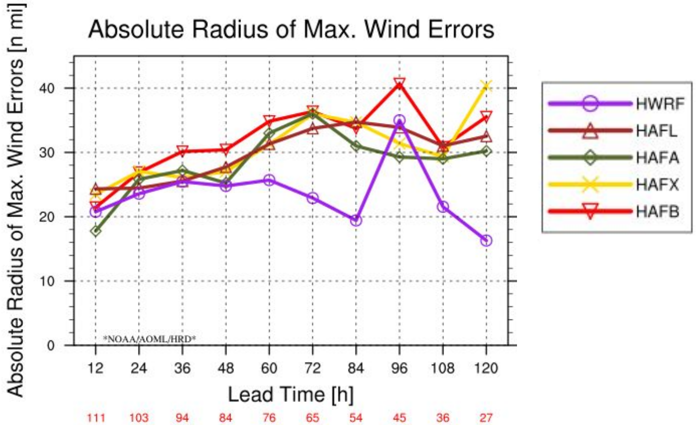


- Little difference in track statistics from experimental HAFX/HAFL configurations
- Intensity errors are also about the same, although HAFL (91 levels) produced intensity bias stats that were much more comparable to HAFA

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

	Surface Layer	PBL	Cumulus	Microphysics	GWD	Land Model	Radiation	Ozone H2O	Fresh Water Lake Model
GFSv16 (HAFSv0.2)	GFS*	sa-TKE-EDMF*	sa-SAS	GFDL	ugwp_v0*	NOAH	RRTMG	2015, h2o	
GFSv17 (HAFSv0.3)	(updates)	(updates)	(updates)	Thompson+	ugwp_v1	NOAH-MP	RRTMGP	(no updates)	FWLM
	MYNN	sa-MYNN	GF			~~RUC~~			
	GFDL	~~saYSU~~	sa-Tiedtke						
		~~HEDMF~~							
		EEPS							

* 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

sa-TKE-EDMF PBL scheme

$$\overline{w'\phi'} = -K_\phi \frac{\partial \overline{\phi}}{\partial z} + M_u(\phi_u - \overline{\phi})|_{sfc} - M_d(\phi_d - \overline{\phi})|_{Sc}$$

$$K_\phi = c l_k \sqrt{\overline{e}}, \qquad \overline{e} = 0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

l_k is a turbulent mixing length, c is a coefficient

$$\frac{d\overline{e}}{dt} = -\frac{\partial}{\partial z}\left(\overline{w'e'} + \frac{1}{\rho}\overline{w'p'}\right) - \overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z} + \frac{g}{\overline{\theta}_v}\overline{w'\theta'_v} - D$$

$$D = c_d \frac{\overline{e}^{3/2}}{l_d}$$ TKE dissipation rate

$$c_p \frac{\partial \overline{T}}{\partial t} \approx D$$ TKE dissipative heating

Turbulent mixing length scale (l_k): combination of surface layer (l_1) and a characteristic length scale (l_2)

$$\frac{1}{l_k} = \frac{1}{l_1} + \frac{1}{l_2}$$

$$l_1 = \kappa z / 3.7 \qquad z/L \geq 1$$

$$l_1 = \kappa z \left(1 + 2.7\frac{z}{L}\right)^{-1} \qquad 0 \leq z/L < 1$$

$$l_1 = \kappa z \left(1 - 100\frac{z}{L}\right)^{0.2} \qquad z/L < 0$$

$$l_2 = f_1 \min\left(l_{up}, l_{down}\right) \qquad l_d = f_1\left(l_{up} l_{down}\right)^{1/2}$$

$$l_0 < l_2 < 300m \qquad l_0 < l_d < 300m \qquad f_1 = 1.0$$

$$\int_z^{z+l_{up}} \frac{g}{\overline{\theta}_v}\left(\overline{\theta}_v(z) - \overline{\theta}_v(z')\right)dz' = \overline{e}(z)$$

$$\int_{z-l_{down}}^{z} \frac{g}{\overline{\theta}_v}\left(\overline{\theta}_v(z') - \overline{\theta}_v(z)\right)dz' = \overline{e}(z)$$

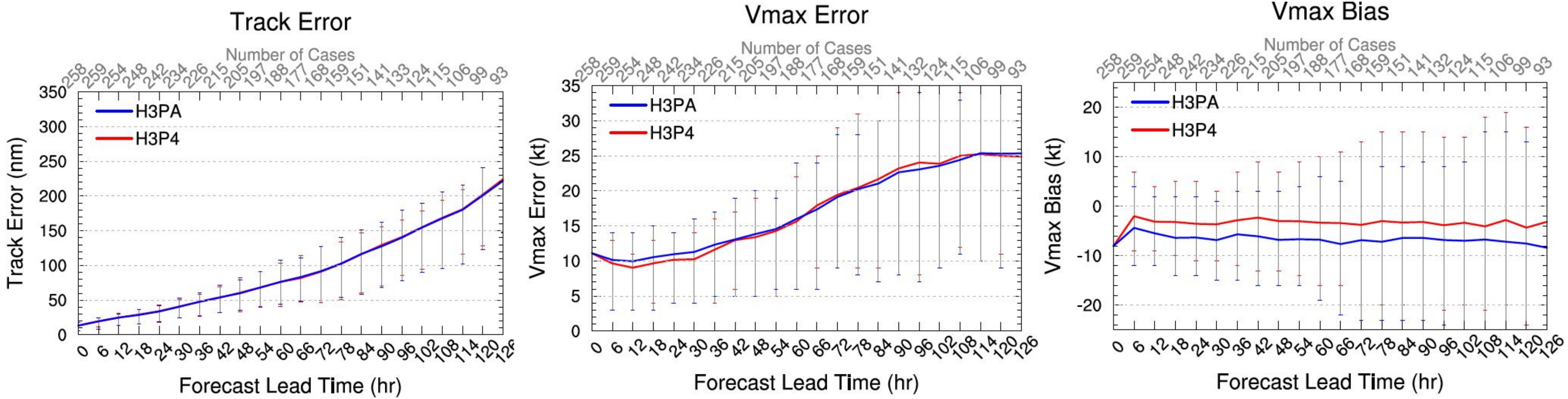
Bougeault & Lacarrere (1989)

(Slide courtesy of Jongil Han)

sa-TKE-EDMF PBL scheme

EMC's modifications to l_k : IF (h < MIN(100., 0.05*h_{pbl})) l_k=l_1

Only apply to unstable regime



H3PA: HAFSv0.2a phase 3 configuration

H3P4: Same as H3PA except for the modified sa-TKE-EDMF scheme

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)
γ is a nonlocal term for heat and moisture

Detering and Etling (1985)
Langland and Liou (1996)
Duynkerke and Driedonks (1987)

(1) $$\frac{dE}{dt} = K_m\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] - K_h P_{\text{buoy}} + C_1 \frac{\partial}{\partial z}\left(K_m \frac{\partial E}{\partial z}\right) - \varepsilon,$$

(2) $$\frac{d\varepsilon}{dt} = \max\left\langle \left\{K_m\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] - K_h P_{\text{buoy}}\right\}, \left\{K_m\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]\right\}\right\rangle C_3 \frac{\varepsilon}{E} - C_4 \frac{\varepsilon^2}{E} + C_5 \frac{\partial}{\partial z}\left(K_m \frac{\partial \varepsilon}{\partial z}\right),$$

(3) $$K_m = C_2 E^2/\varepsilon,$$

(4) $$K_h = \alpha K_m$$

$$(\boldsymbol{E}, \boldsymbol{\varepsilon}, \boldsymbol{K_m}, \boldsymbol{K_h})$$

C1: 1.35
C2: 0.09
C3: 1.44
C4: 1.92
C5: 0.77

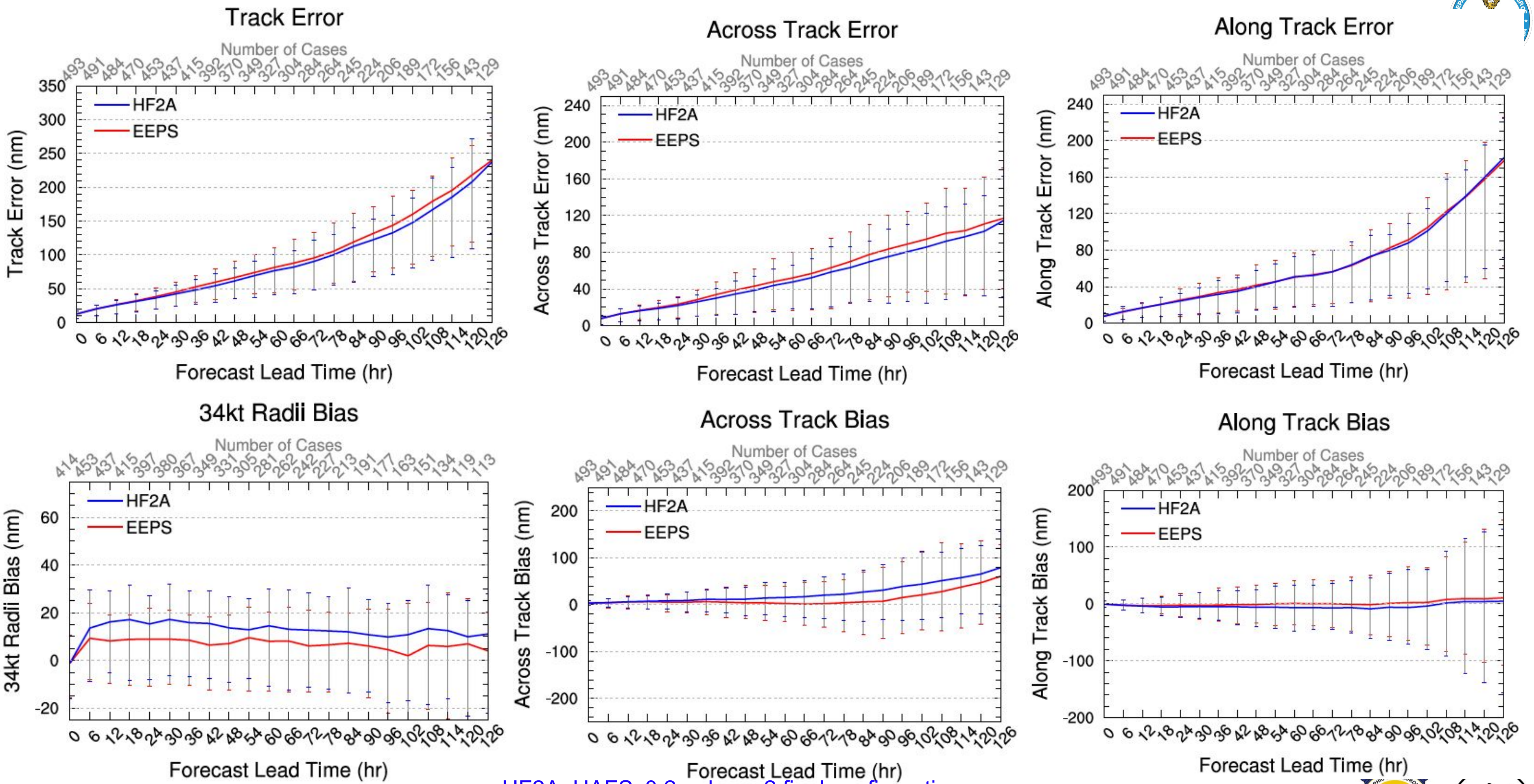
$E_{min} = 1\times10^{-4}$

$\varepsilon_{min} = 1\times10^{-6}$

Background K_m = 0.1
K_h = 0.01

$$\frac{\partial T}{\partial t} = \frac{\varepsilon}{c_p}$$ dissipation heating

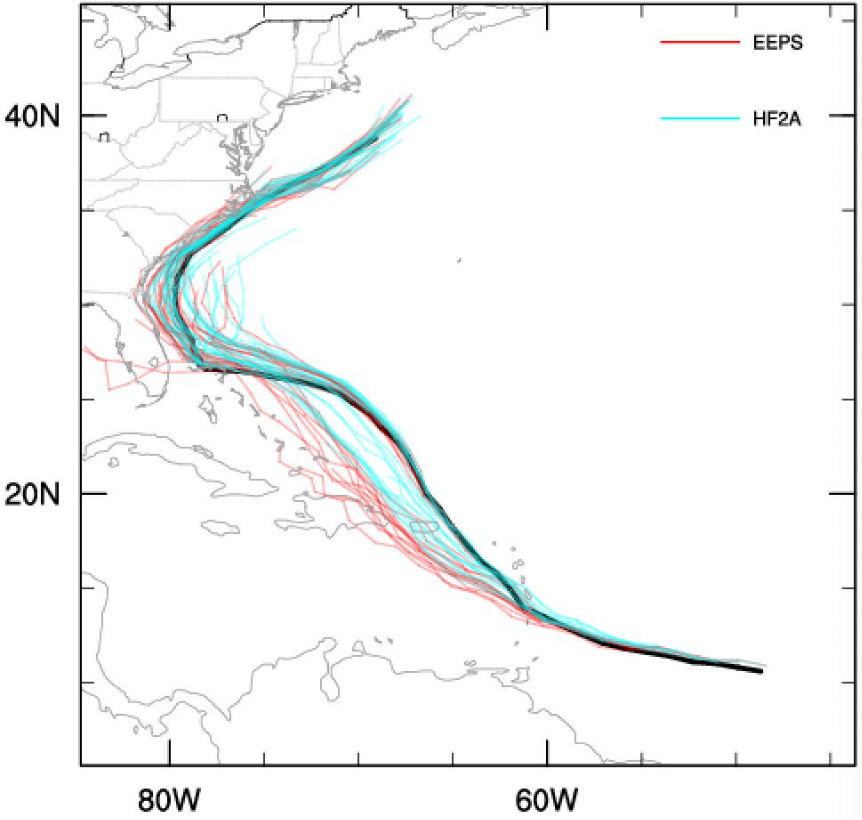
A few iterations with split time steps



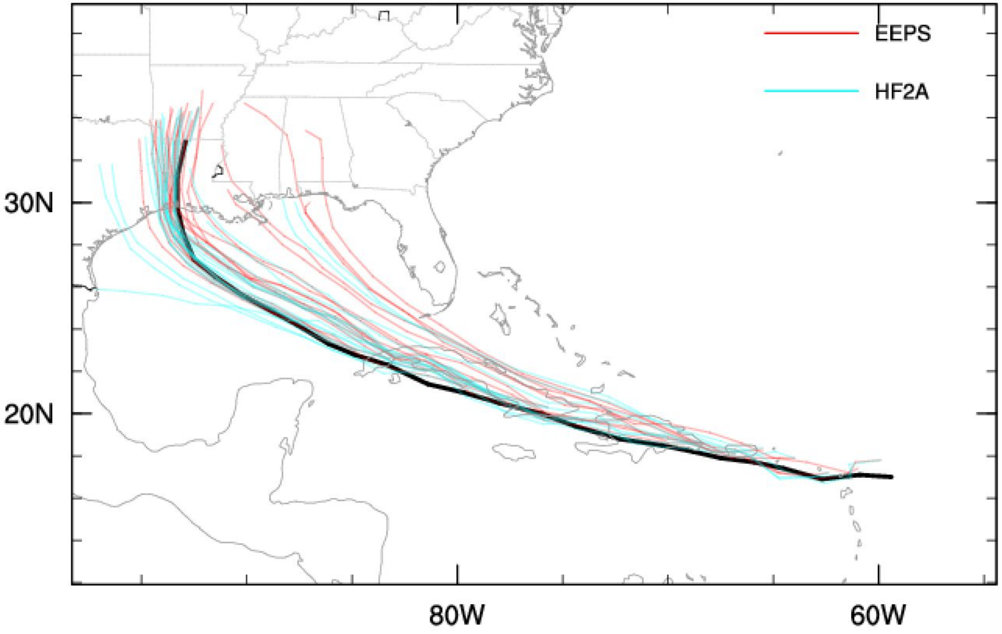
HF2A: HAFSv0.2a phase 2 final configuration

EEPS: Same as HF2A except for the EEPS scheme

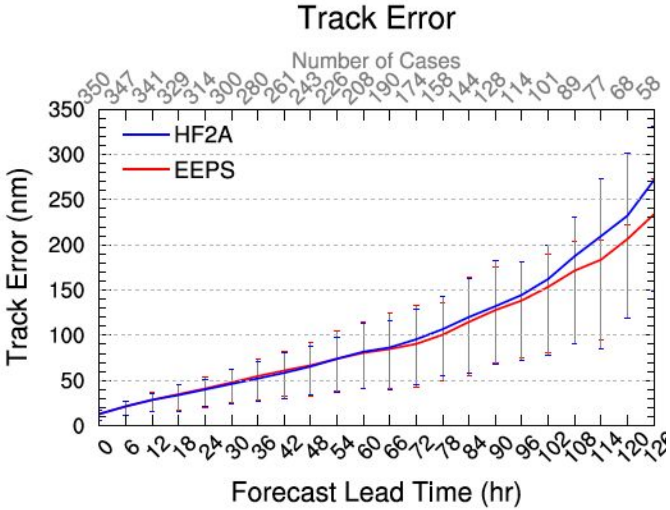
Hurricane Dorian

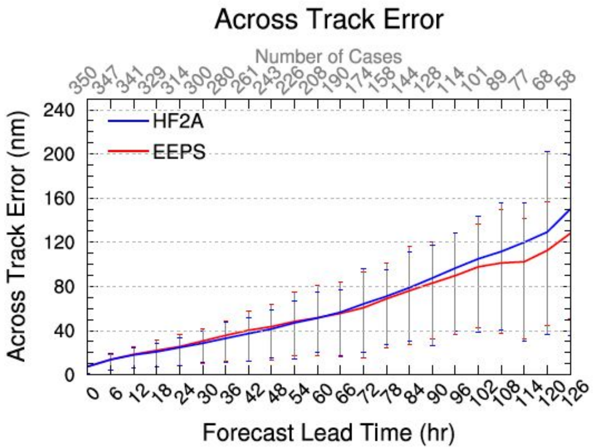


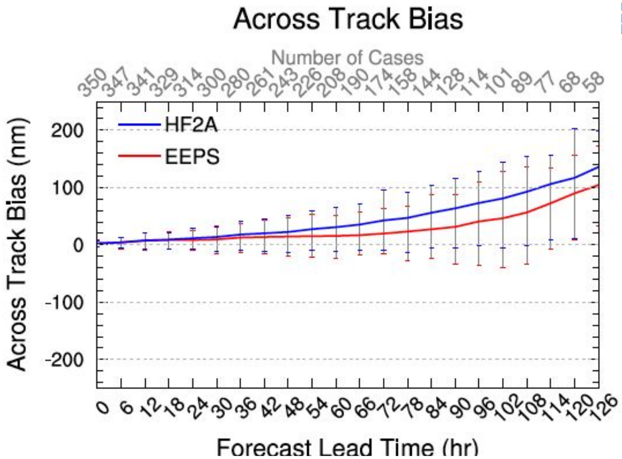
Hurricane Laura

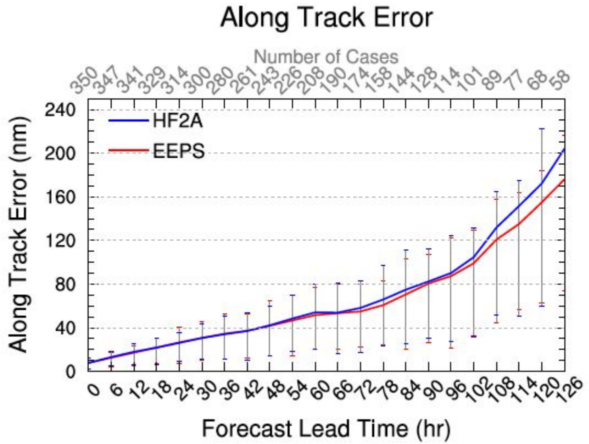


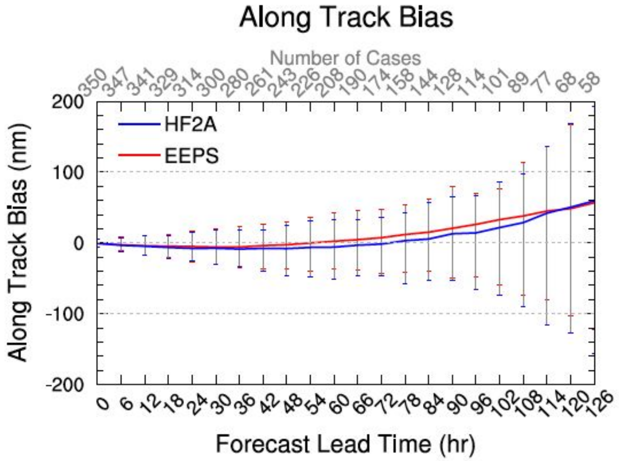
Without: Dorian, Humberto
Laura, Paulette

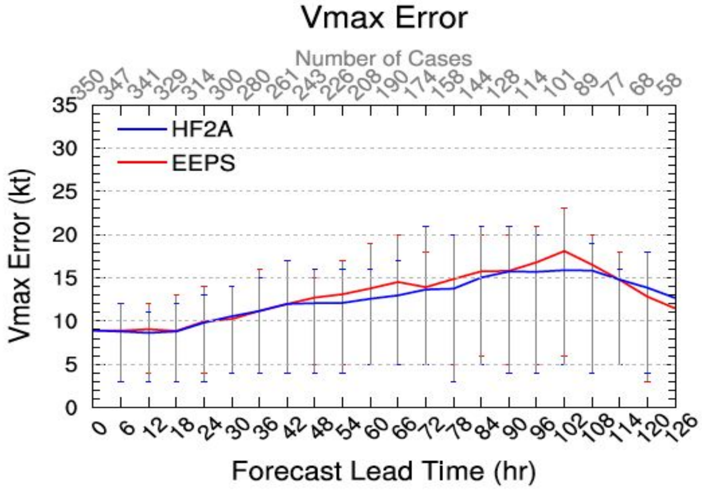


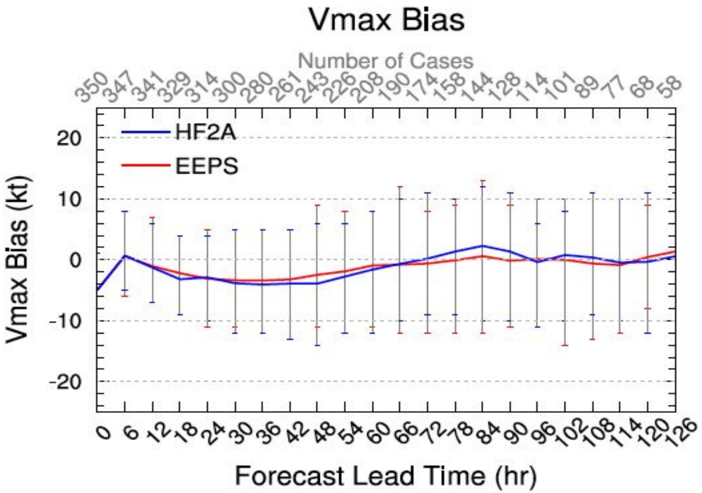


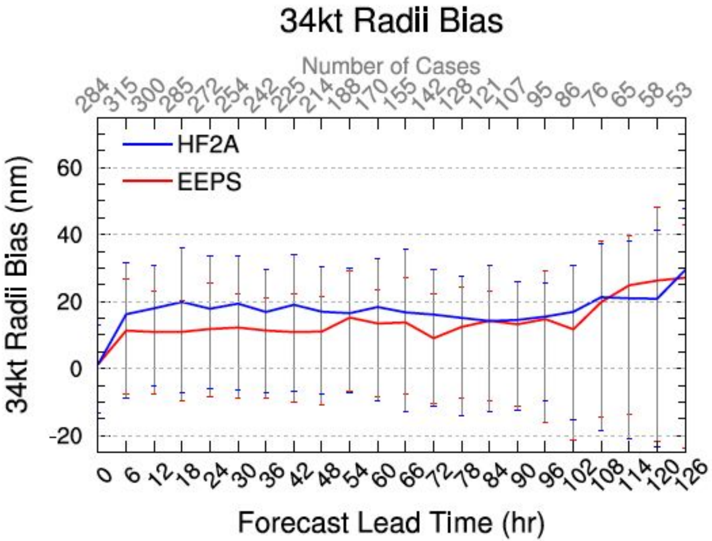


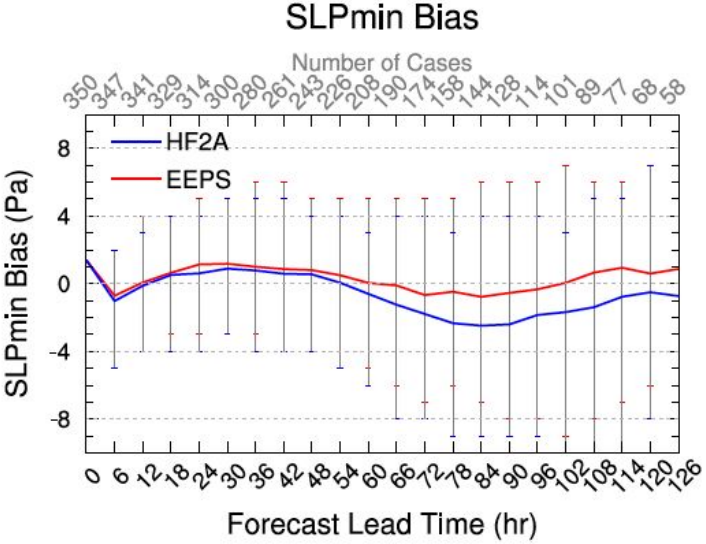




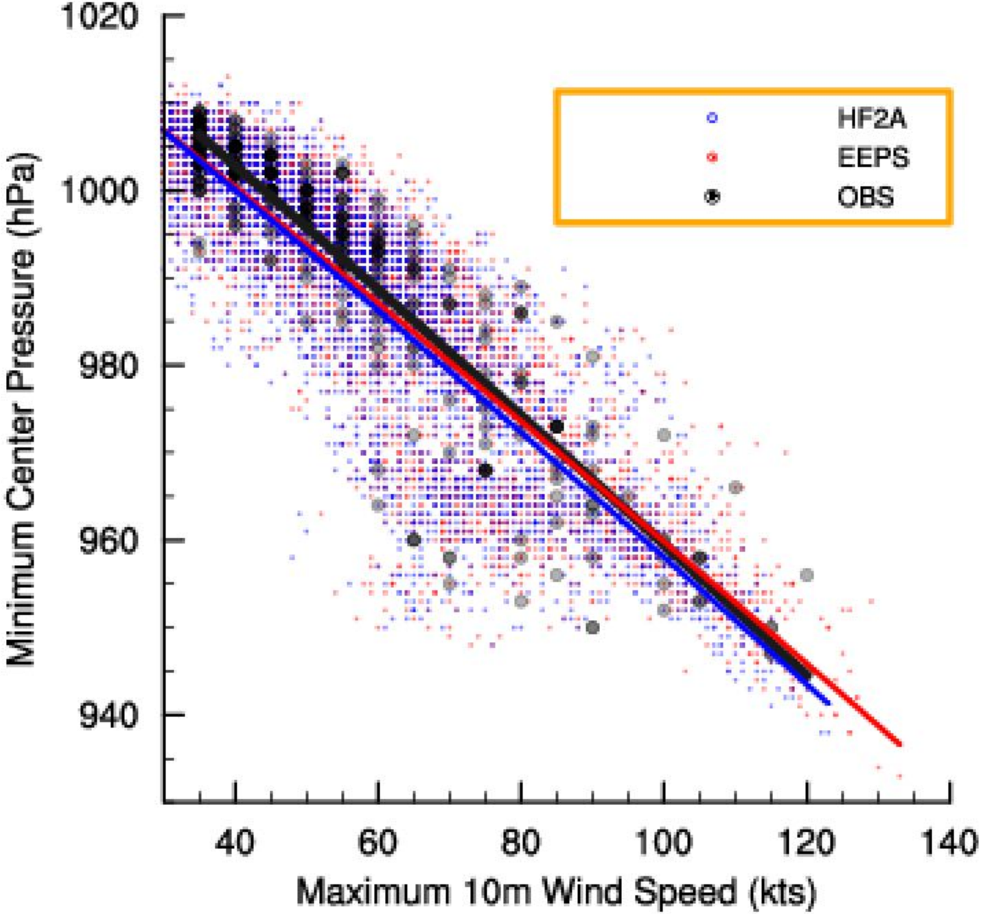

Vmax Error
Number of Cases
350 347 341 329 314 300 280 261 243 226 208 190 174 158 144 128 114 101 89 77 68 58
HF2A
EEPS
Vmax Error (kt)
0 5 10 15 20 25 30 35
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120 126
Forecast Lead Time (hr)


Vmax Bias
Number of Cases
350 347 341 329 314 300 280 261 243 226 208 190 174 158 144 128 114 101 89 77 68 58
HF2A
EEPS
Vmax Bias (kt)
-20 -10 0 10 20
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120 126
Forecast Lead Time (hr)


34kt Radii Bias
Number of Cases
284 315 300 285 272 254 242 225 214 188 170 155 142 128 121 107 95 86 76 65 58 53
HF2A
EEPS
34kt Radii Bias (nm)
-20 0 20 40 60
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120 126
Forecast Lead Time (hr)


SLPmin Bias
Number of Cases
350 347 341 329 314 300 280 261 243 226 208 190 174 158 144 128 114 101 89 77 68 58
HF2A
EEPS
SLPmin Bias (Pa)
-8 -4 0 4 8
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120 126
Forecast Lead Time (hr)

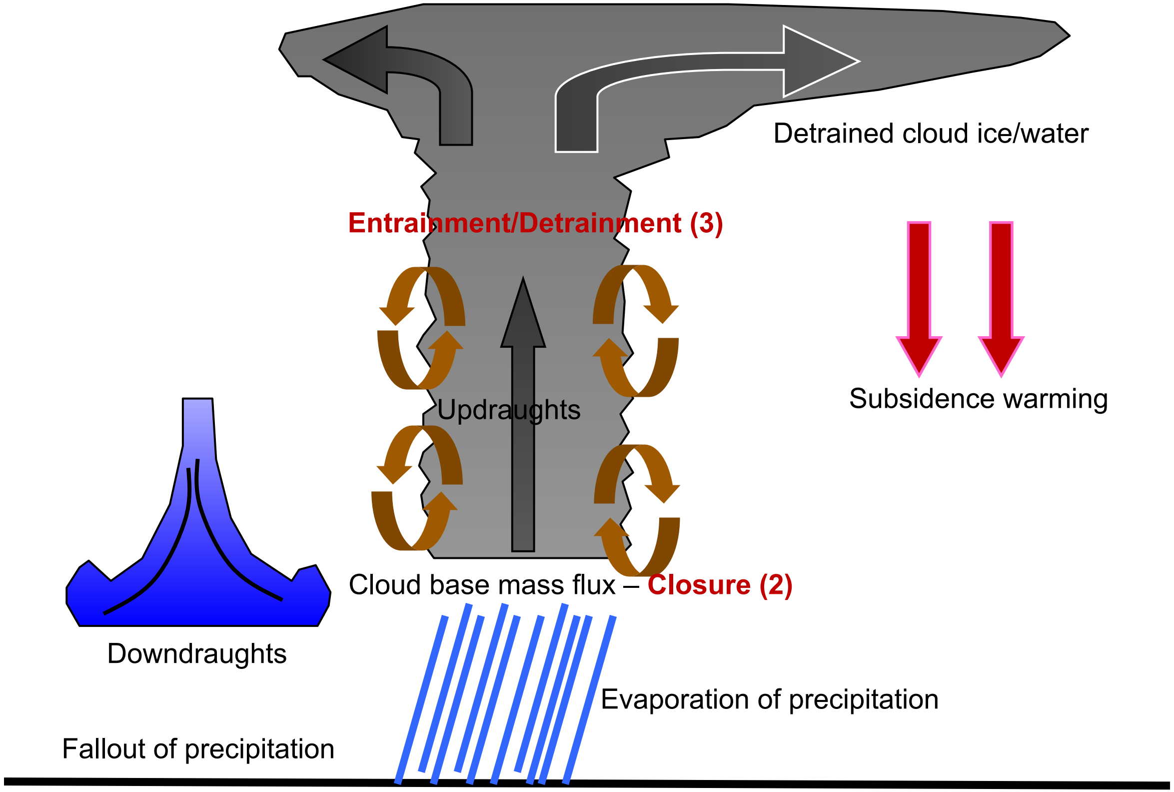
Vmax and SLPmin



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)

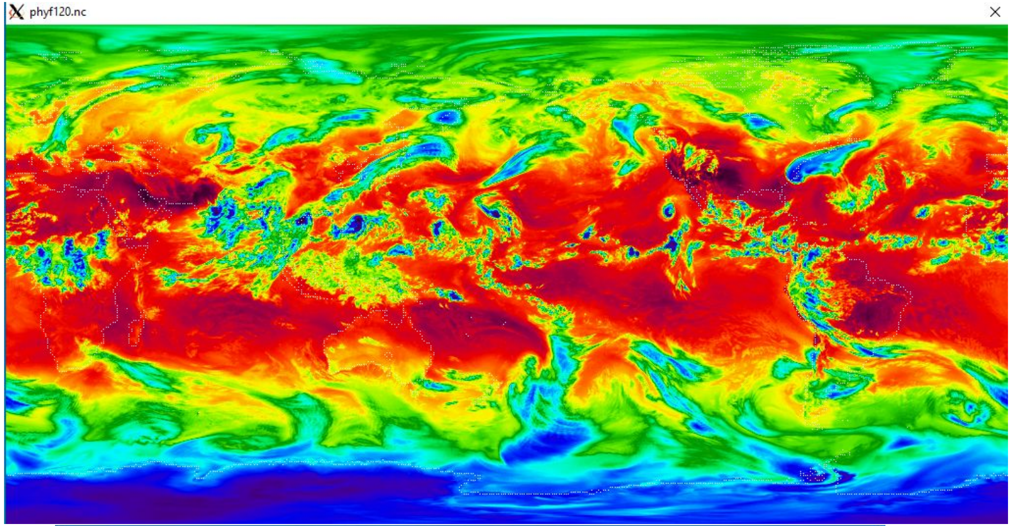
Where & when does convection occur and what type of convection occurs – **Trigger (1)**



OLR

FV3GFS - C768

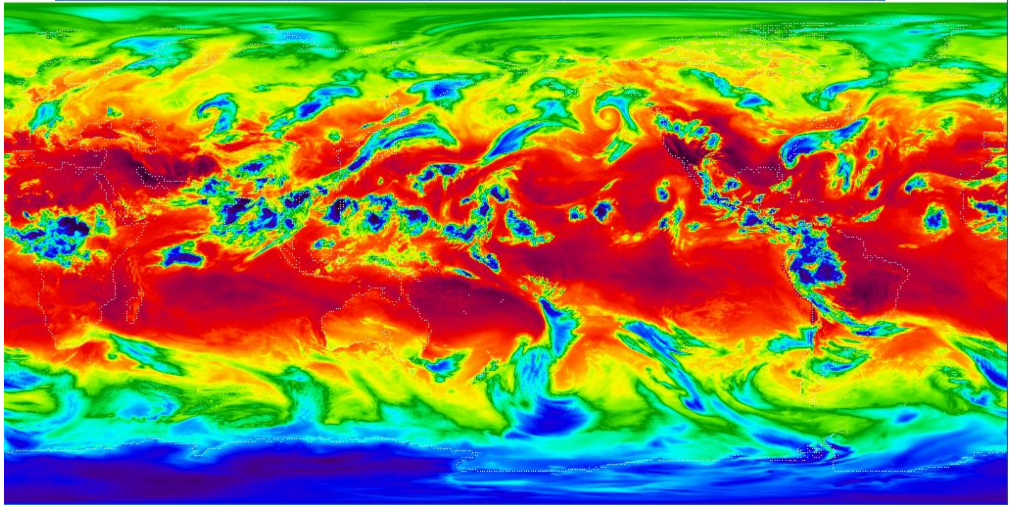
saSAS



@f120

w/m2

nTDK
(new Tiedtke)



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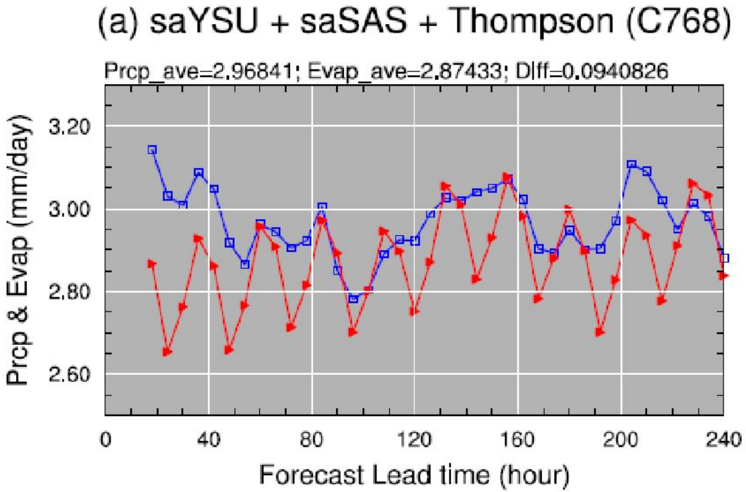
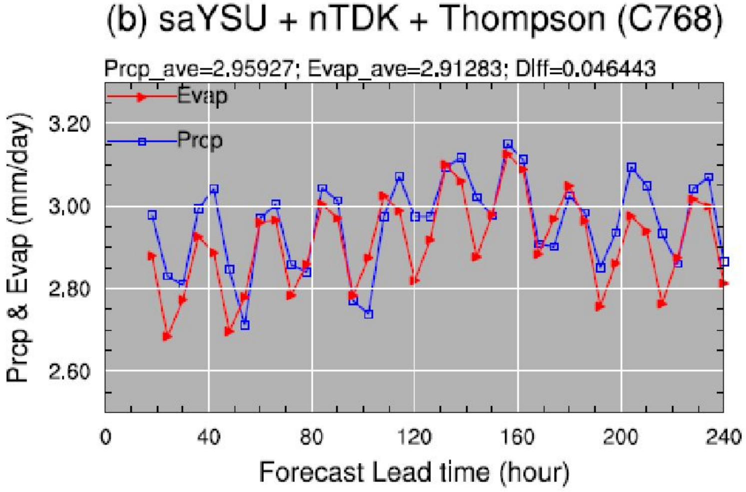
Relationship between global precipitation and evaporation for C768

saSAS

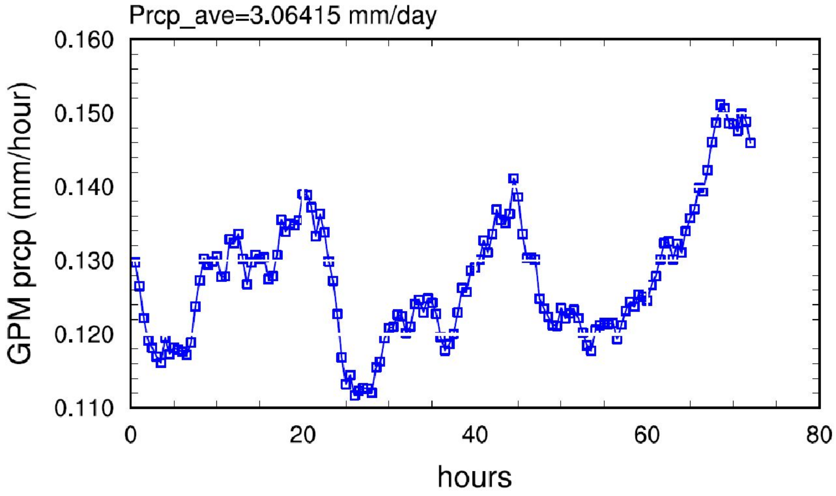


nTDK



Only for (60S, 60N)

GPM precipitation every 30 min



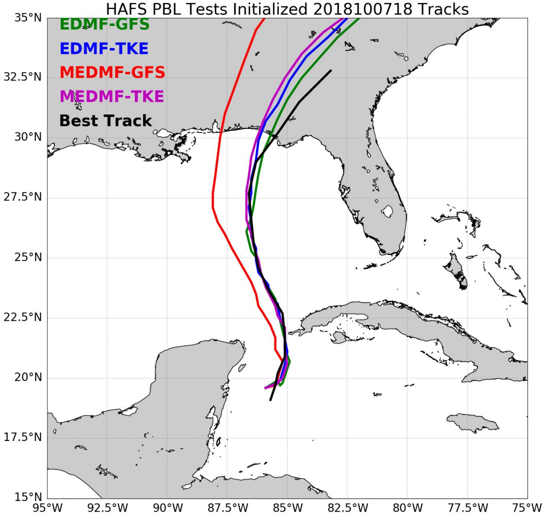
Future work

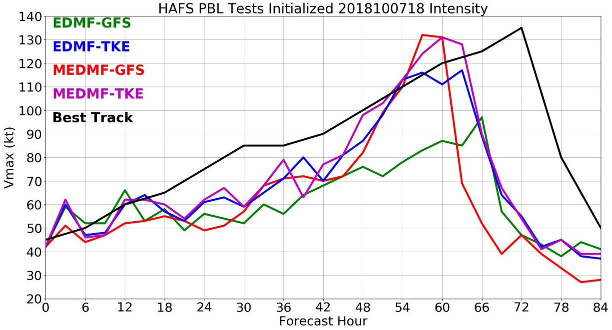
1) The current physics suite for the HAFS is highly dependent on the **GFS physics suite**, and we will follow the development of the **GFS physics suite** and modify the individual schemes if necessary.

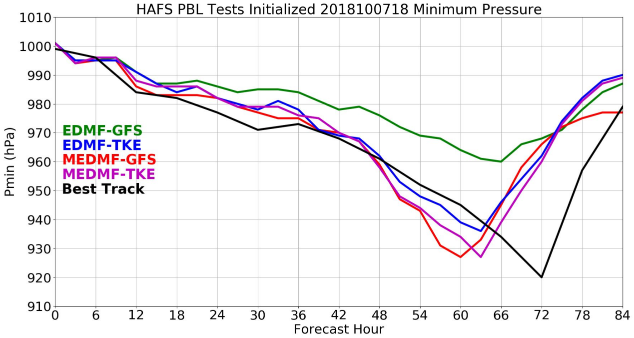
2) We will likely develop **the second physics suite** for the HAFS which is still based on the GFS physics suite but with the replacement of the **PBL** scheme and/or the **cumulus** scheme and/or other schemes.

Extra Slides

Evaluating and improving PBL physics in HAFS

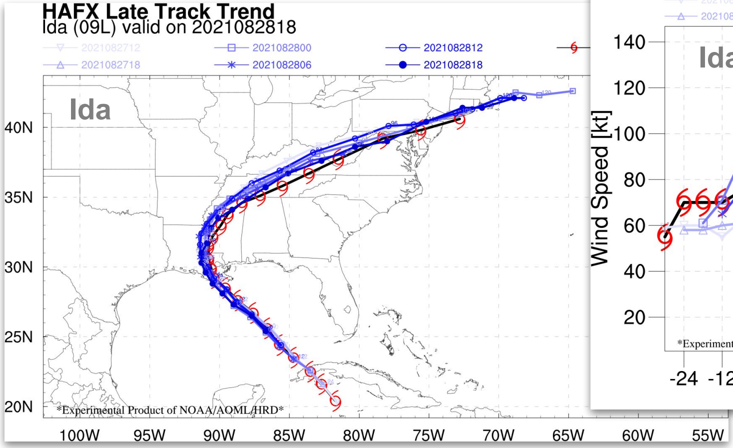


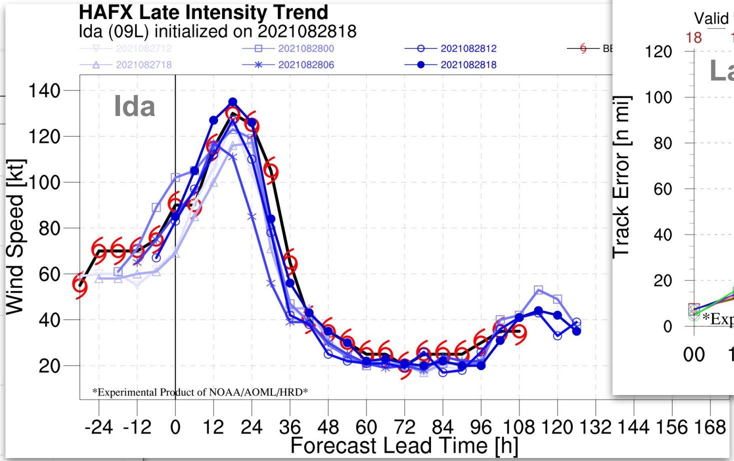


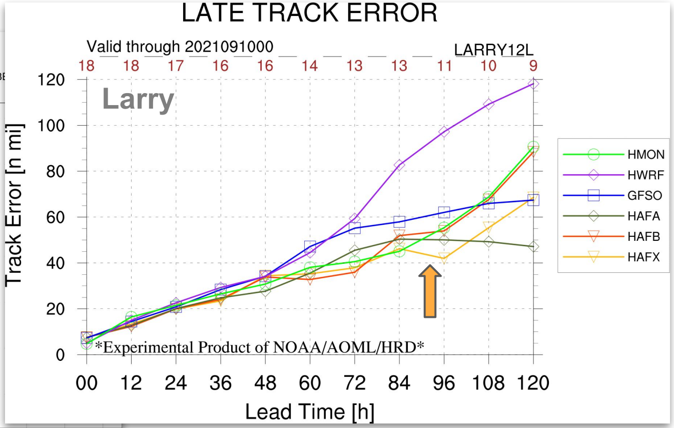


- ¾ schemes close to Best Track
- Modified EDMF-GFS a little bit of an outlier
- Original EDMF-GFS produces worst intensity
- Reducing diffusivity produces wind peak closer to Best Track

HAFX forecasts in the 2021 hurricane season

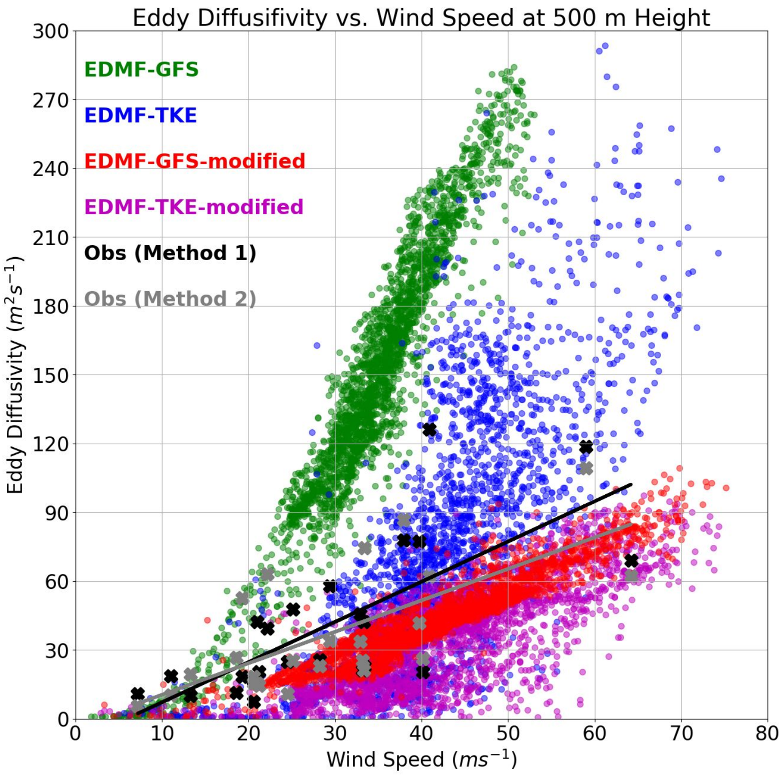






- **HAFX** is a parallel run on Orion using the improved EDMF-TKE PBL scheme based on LES results (Chen et al. 2021, in review)
- HAFX captured well the rapid intensification as well as the track of Hurricane Ida.
- Track error is less than 50 n mi within 4 days for Hurricane Larry.

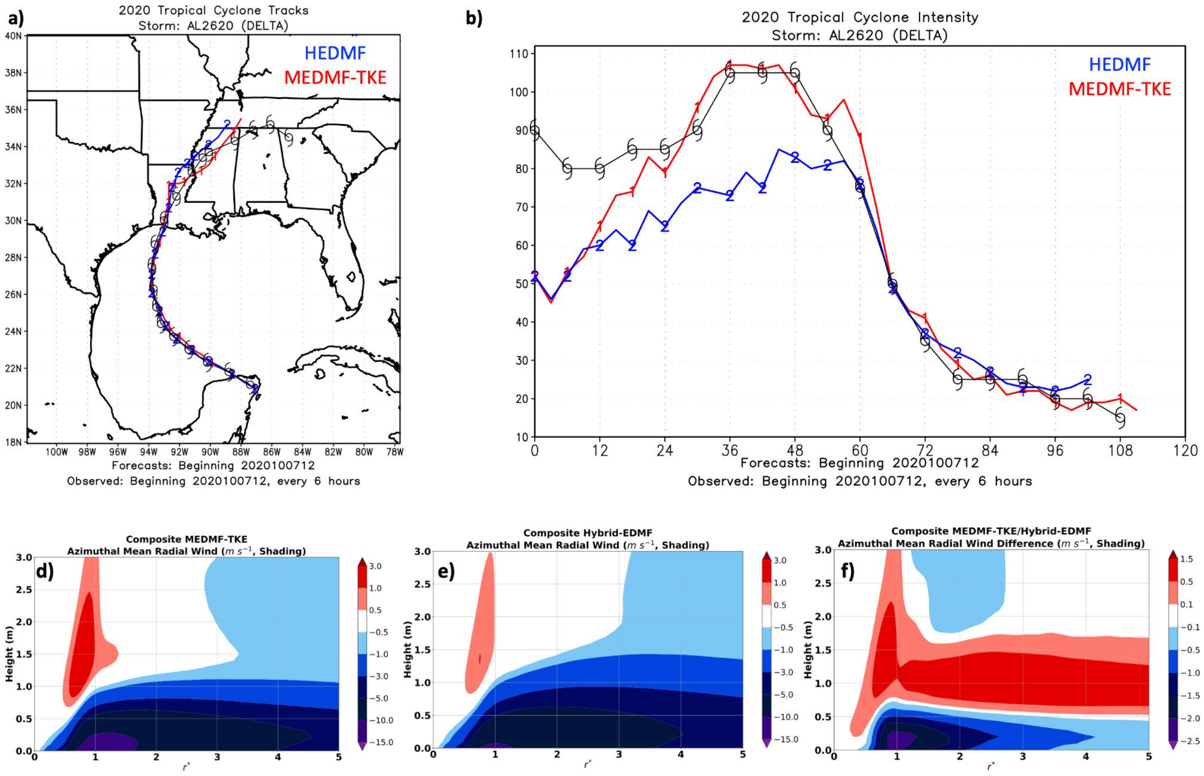
Eddy Diffusivity from All Cases (and Obs)



(Gopal, Hazelton, Zhang, 2021)

- ➢ 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)

Composite Analysis of MEDMF-TKE vs. K-EDMF



- 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

-***Hazelton, A. T.***, Gopalakrishnan, S., and J. A. Zhang, 2021: Comparison of The Hybrid EDMF and Modified EDMF-TKE PBL Schemes in 2020 Tropical Cyclone Forecasts from the Global-nested Hurricane Analysis and Forecast System, *Wea. Forecasting*, in review.