A generalized framework for hurricane boundary layer parameterization scheme based on observations

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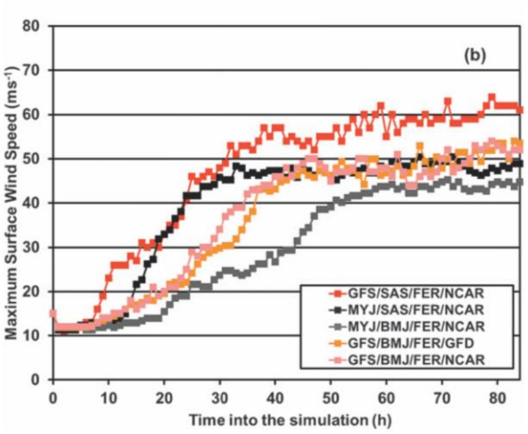
Key Questions Answered in this work

(1) Why do different PBL parameterization schemes applied to hurricane models produce very diverse forecasts of structure and intensity changes?

(2) Can we expect some of these PBL parameterization schemes to converge to the same solution of observed state?



Bao et al., 2012 (MWR)

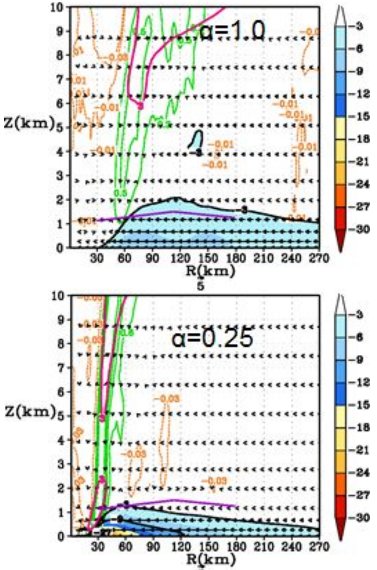
PBL parameterization schemes

Scheme 1: 1st order K Profile Parameterization (KPP)

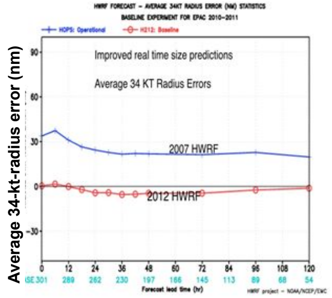
$$K_m = k(U_*/\Phi_m)Z[\boldsymbol{\alpha}(1-Z/h)^2] \qquad (1)$$

(Hong and Pan, 1996; Gopal et al., 2013; Han et al., 2016)

- Improved observation-based PBL in the High Resolution HWRF
- Findings: Improved secondary circulation, stronger inflow & smaller mature storms consistent with observations
- "Models such as the GFS and HWRF use an admittedly simplified parameterization; the study recommended the use of higher-order PBL schemes for TC predictions" (Gopalakrishnan et al. 2013)



Gopal et al., 2013



Tallapragada et al., 2014

PBL parameterization schemes

Scheme 2: 1.5-order-of-closure, TKE parameterization scheme

$K_m = c l E^{0.5}$ (2)

Where

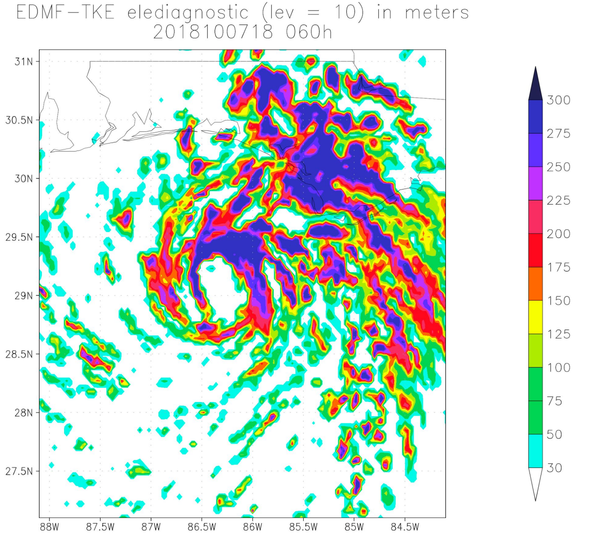
$(dE/dt) =$ Shear Production + Buoyancy + Diffusion of TKE $+ 0.714E^{0.5}/l_d.$

$1/l_k = 1/l_1. + \boxed{1/l_2.}$ (3)

With the assumptions $l_1 = kZ\ l_d. = l_2.$ (4)

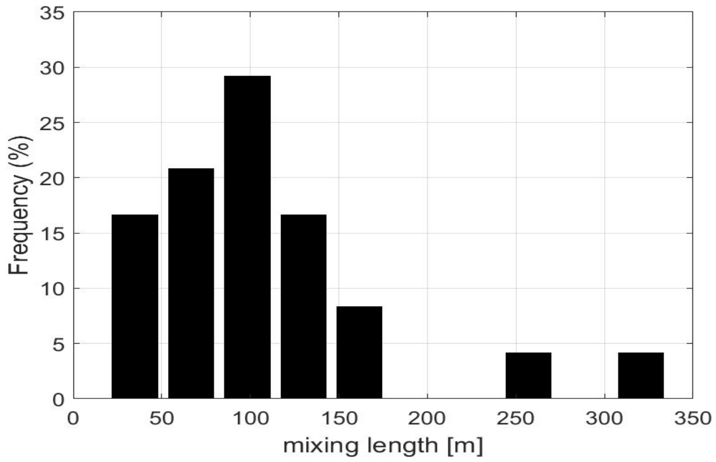
Yamada and Mellor, 1975, Stull, 1987; Sharan and Gopalakrishnan,1997;Han and Bretherton, 2019;
https://ams.confex.com/ams/27WAF23NWP/webprogram/Handout/Paper273301/TKE_based_EDMF_23rdNWP2015_JHANs.pdf

Mixing Length l2



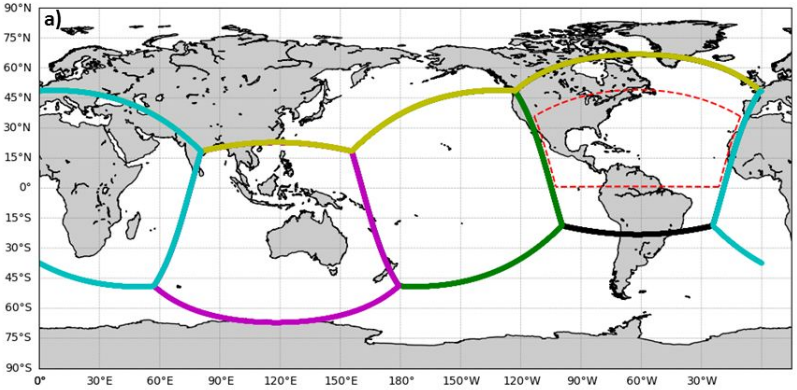
Mixing length from FV3 simulation

Bougeault and Lacarrère (1989) relates the length scale l_2 to the distance that a parcel having an initial TKE can travel upward and downward before being stopped by buoyancy effects and is being extensively used.



Histogram of observational estimates of mixing length (*l2*). The mixing length is estimated based on flight-level data collected in Hurricanes Hugo (1989), Allen (1980) and Frances (2004)

FV3- HAFS details



HAFSV0.B: Global FV3 with an embedded 3-km nest

Physical Process	Scheme	Reference
Convection	**Scale–Aware SAS**	**Han et al. (2017)**
Microphysics	**GFDL**	**Chen and Lin (2013)**
PBL	**EDMF-GFS & EDMF-TKE**	**Han and Pan (2011), Gopalakrishnan et al (2013) Han et al 2016, 2019**
Surface Layer	**HWRF**	**Bender 2007 & Gopalakrishnan et al. (2013) &**
Radiation	**RRTMG**	**Iacono et al. (2008)**

- Hazelton et al 2020: High-resolution ensemble HFV3 forecasts of Hurricane Michael (2018), 2020: Rapid intensification in shear. Monthly Weather Review, 148(5):2009-2032
- Gopal and coauthors: 2019 HFIP R&D Activities Summary: Recent Results and Operational Implementation
- Hurricane Michael initialized at 1800 UTC 7 Oct 2018

https://storm.aoml.noaa.gov/

Observations

- Eddy diffusivity and Mixing length: Flight-level data - Hurricanes Hugo (1989), Allen (1980) and Frances (2004):
- Near-surface (10-m) inflow angles: wind vector data dropwindsondes deployed by aircraft on 187 flights into 18 hurricanes
- Observed composites: 1878 GPS dropsondes deployed by research aircraft in 19 hurricanes,
- Zhang et al. (2011a and b; 2013, 2015) and Zhang and Uhlhorn 2012

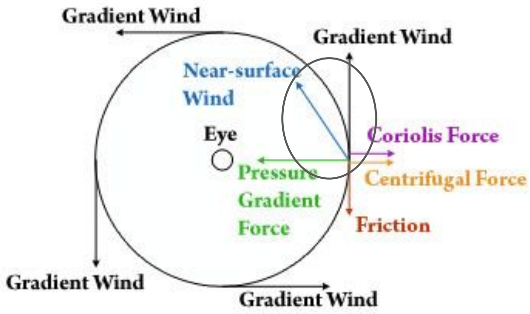
A note on the balance of forces & inflow angle

$$\frac{dv_{\lambda}}{dt} = -\frac{1}{\rho r}\frac{\partial p}{\partial \lambda} \boxed{-\frac{u_r v_{\lambda}}{r} - f u_r} + D_{v\lambda}$$

Generalized Coriolis

$$\frac{du_r}{dt} = \boxed{-\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{v_{\lambda} v_{\lambda}}{r} + f v_{\lambda}} + D_{ur}$$

Gradient wind imbalance



** The observed surface inflow angle to evaluate the winds near the surface may be a more stringent criteria than those posed by theoretical arguments based on Monin-Obukhov similarity profiles that could be best valid under fair-weather conditions over land because the inflow angle is a measure of convergence.

- Montgomery, M. T., and R. K. Smith, 2014: Paradigms for tropical cyclone intensification. Australian Meteorological and Oceanographic Journal, 64, 37–66.
- Zhang, J. A., and E. W. Uhlhorn, 2012: Hurricane sea surface inflow angle and an observation-based parametric model. Mon. Wea. Rev., 140, 3587–3605. https://doi.org/10.1175/MWR-D-11-00339.1

Numerical Experiments

Hurricane Michael initialized at 1800 UTC 7 Oct 2018

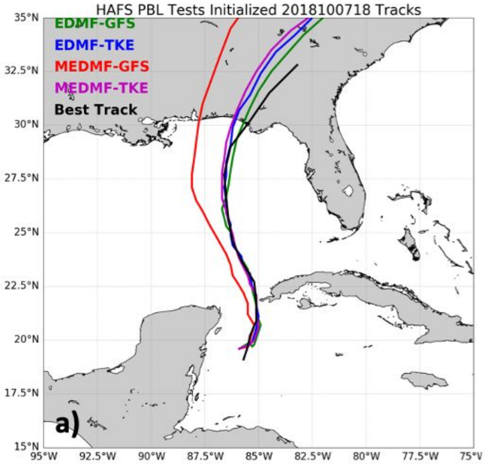
No	Name	Description	Parameter
1	EDMF-GFS	Original EDMF-GFS	$\boldsymbol{\alpha}$=1
2	EDMF-TKE	Original EDMF-TKE	$max\ (l_2)$= 300 m
3	MEDMF-GFS	Modified EDMF-GFS	$\boldsymbol{\alpha}$=0.25
4	MEDMF-TKE	Modified EDMF-TKE	$max\ (l_2)$= 100 m
5	M2EDMF-GFS	HWRF-GFS scheme	$\boldsymbol{\alpha}$=0.50

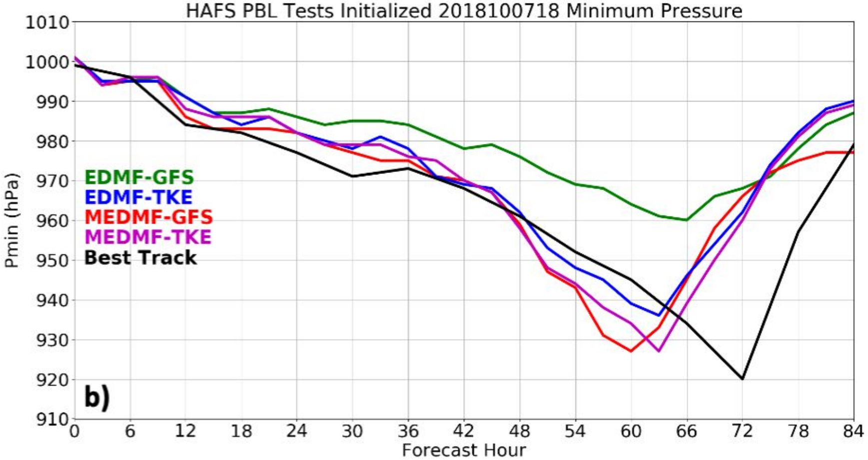
Note: (1) The surface layer scheme was retained as in HWRF

(2) Analysis time: Around 60 hours when the hurricane was strongest

The Problem

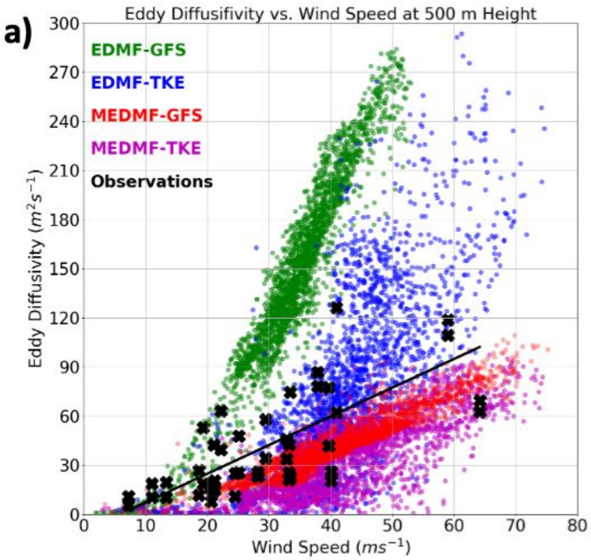
Hurricane Michael initialized at
1800 UTC 7 Oct 2018

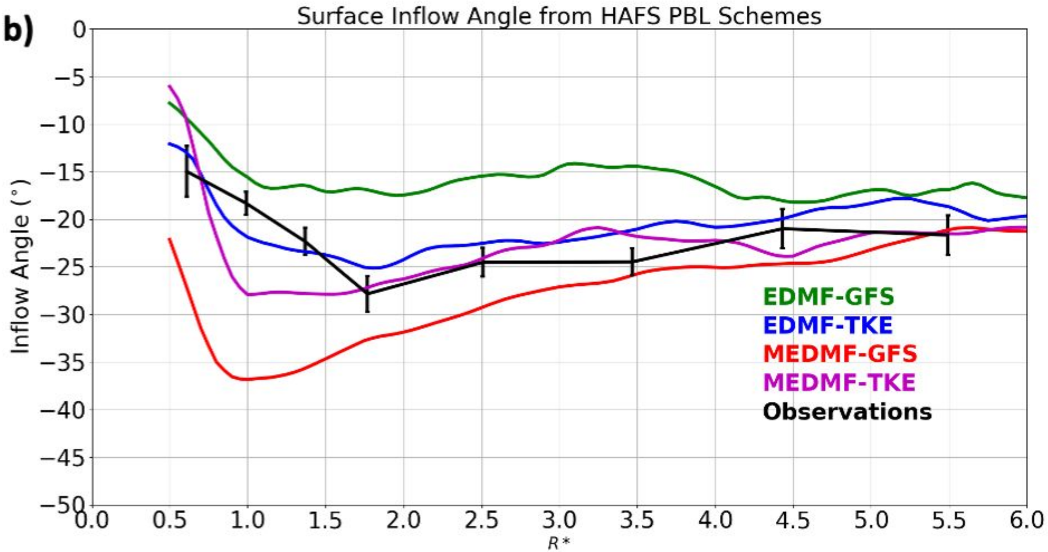




- Two different schemes or simple changes to a PBL scheme produces diversity in both tracks & intensity
- Original GFS is very diffusive and produces the weakest storm
- Modified GFS (alpha=0.25) diverges the most from best track

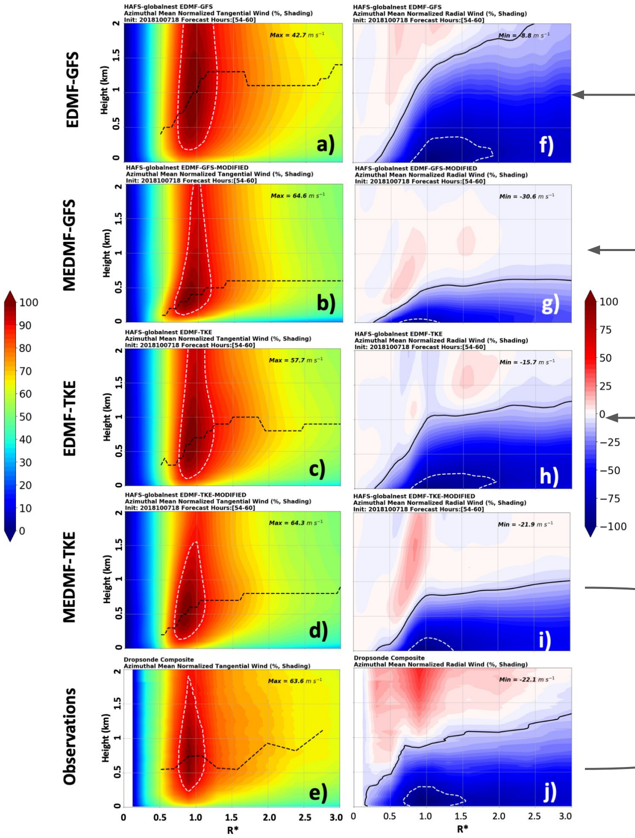
Why do PBL parameterization schemes diverge so widely from one another?





Uncertainty related to some of the key variables used in the definition of the eddy diffusivities

How different schemes or changes to a scheme lead to such diverse structure?



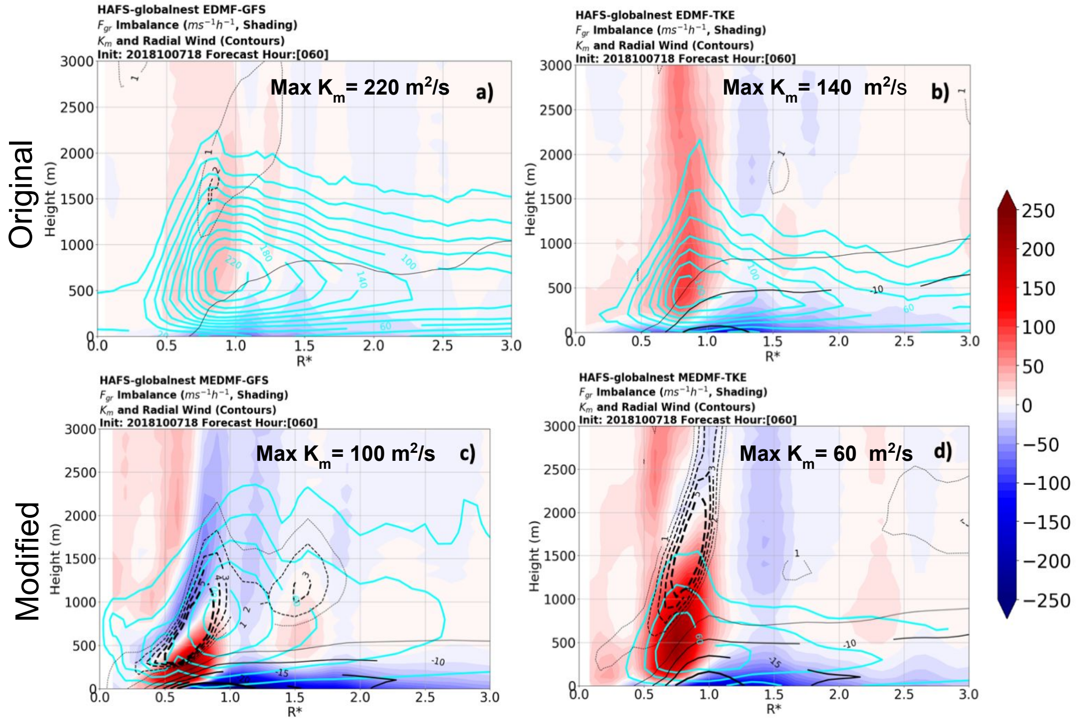
Deep inflow in GFS and weakest tangential wind

Too strong and shallow for alpha=0.25

Shallower than GFS for TKE

Modified TKE closest to observations

How turbulence and mixing processes (eddy diffusivity) actually affect the structure of the secondary circulation and the subsequent TC intensification?



GFS

TKE

R-Z mean; K_m (Cyan), U (Black), Imbalance (shaded)

$$\frac{dv_\lambda}{dt} = -\frac{1}{\rho r}\frac{\partial p}{\partial \lambda} + \boxed{-\frac{u_r v_\lambda}{r} - f u_r} + D_{v\lambda}$$

Generalized Coriolis

$$\frac{du_r}{dt} = \boxed{-\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{v_\lambda v_\lambda}{r} + f v_\lambda} + D_{ur}$$

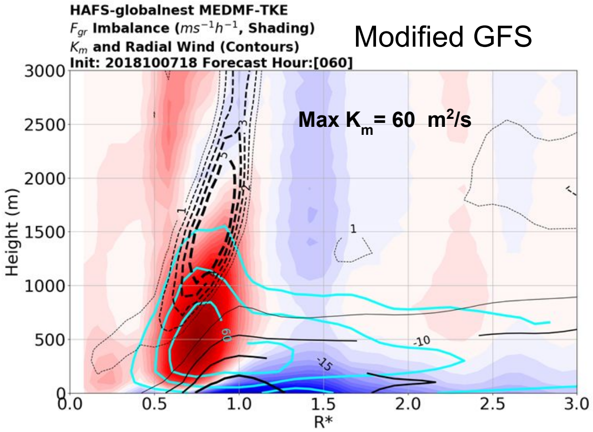
Gradient wind imbalance

- More diffusion in the eyewall region of the hurricane boundary layer negates gradients within the boundary layer and subsequently leads to weaker inflow and a weaker TC.

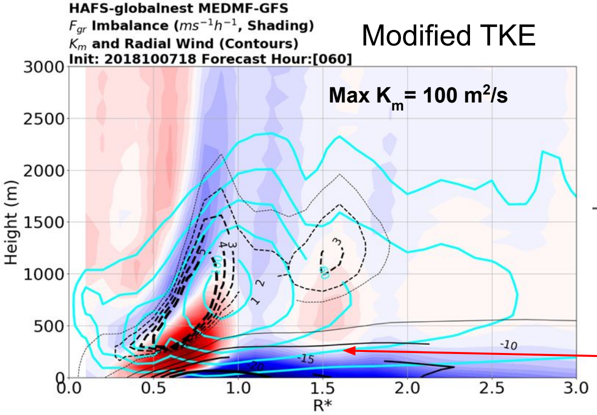
- Smaller diffusion leads to stronger frictional forces, stronger acceleration of inflow, and a stronger TC, consistent with observations.

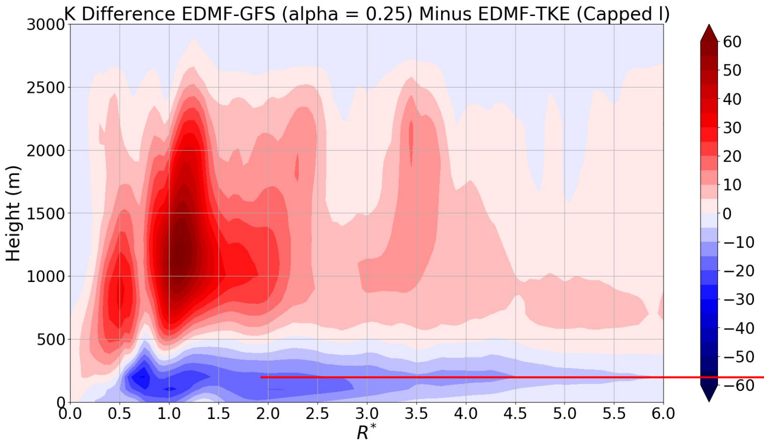
Height dependence of the K profiles

Modified GFS



Modified TKE

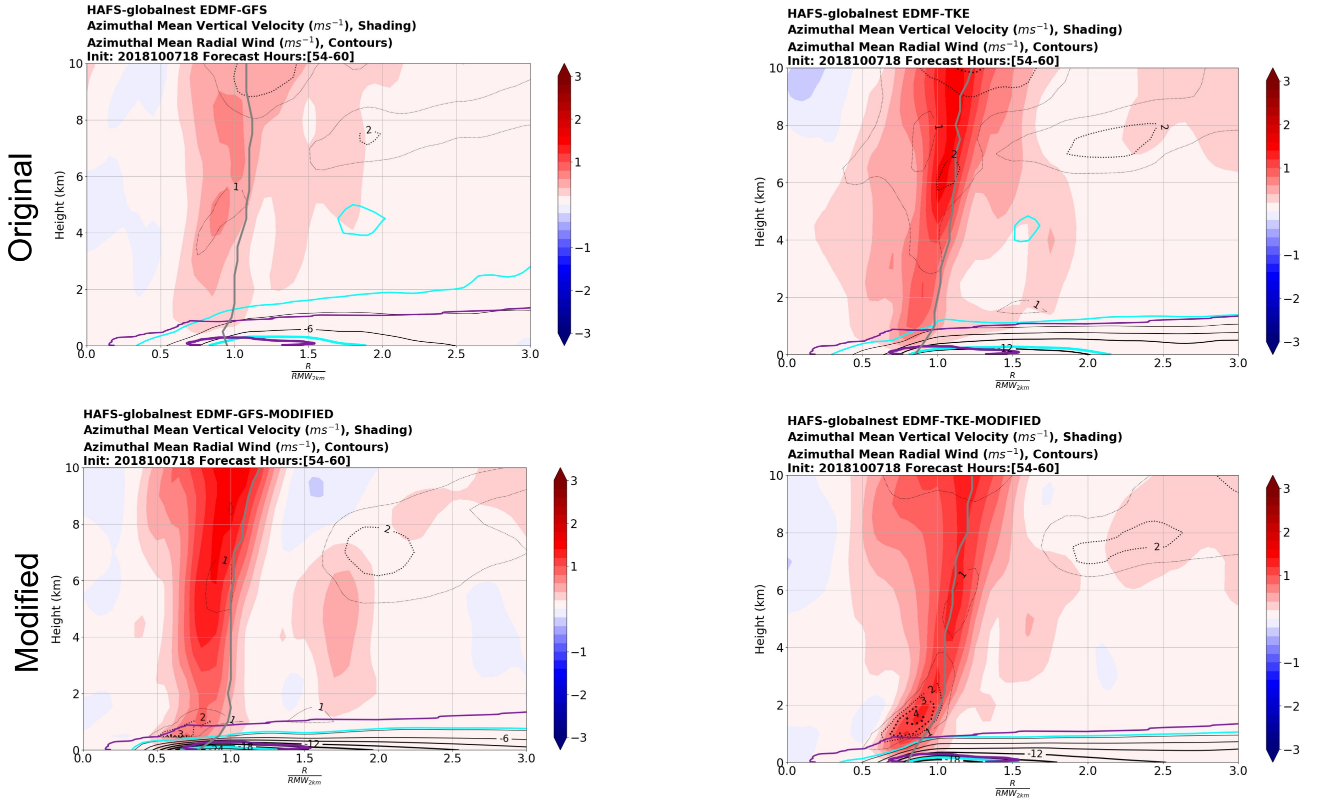




Modified TKE more diffusive 0-500 m

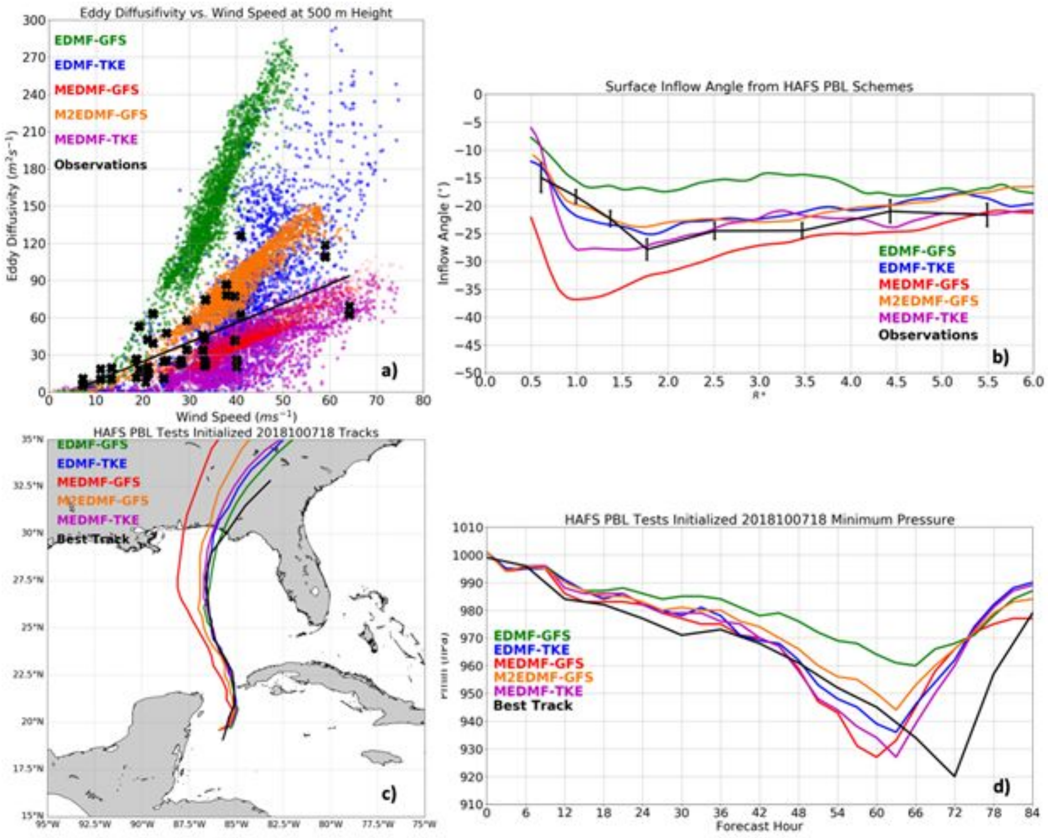
Too strong and shallow for alpha=0.25 despite higher maximum of K_m

How does the secondary circulation evolve in these different schemes?



- Unsurprisingly, PBL changes in both schemes lead to stronger inflow and eyewall W
- Stronger supergradient outflow above the PBL in MEDMF-TKE consistent with Observations

Convergence of solution



Key Messages

- Inaccuracies related to the definition of eddy diffusivity (K_m) or mixing length in the PBL formulations may result in diversity in forecast.
- With minor modifications to the PBL parameterization schemes based on observations, we see the behavior of the two diverse forcings converge towards reality.
- More diffusion in the eyewall region of the hurricane boundary layer negates gradients within the boundary layer and subsequently leads to weaker inflow and a weaker TC. Smaller diffusion leads to stronger frictional forces, stronger acceleration of inflow, stronger eyewall updrafts, and a stronger TC, consistent with observations.
- This study also illustrates that understanding the uncertainty related to the key variables which determine K_m may be important for developing physics based ensembles.
- Advancing mixing length (l2) using observations
- The TC track and intensity is a multi-scale problem. PBL scheme is one facet of the bigger problem!

Questions