

Rapid Intensification Changes: Improving Sub-Grid Scale Model Parameterization and Microphysical-Dynamical Interaction

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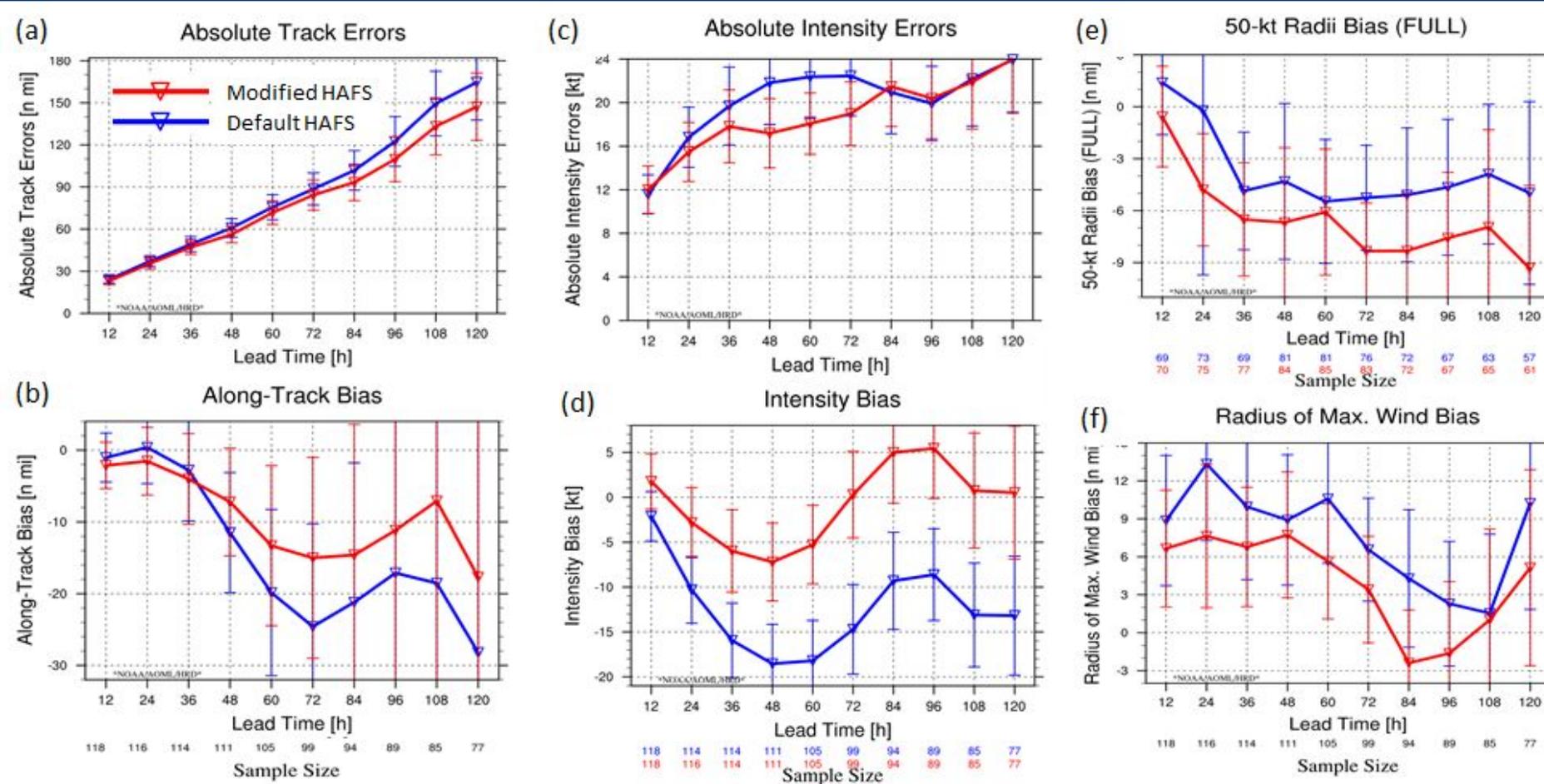
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Outline

- Milestone and deliverable of the funded research in the past year
- Issues on the TKE turbulence schemes used for TC simulations
- TC intensification in numerical simulations

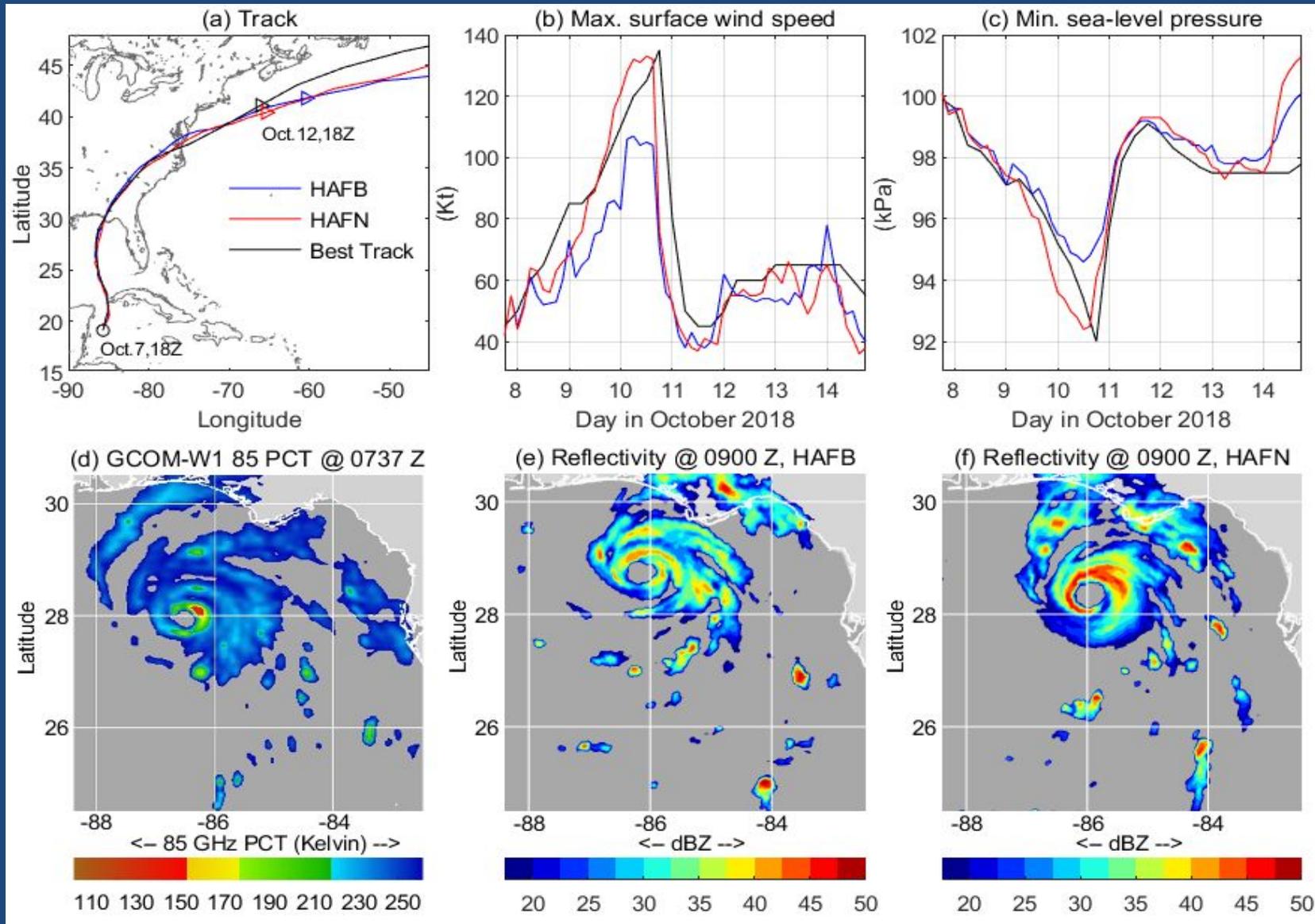
1. Importance of eyewall turbulent transport to TC intensification

Turbulent transport in TC inner core, particularly in the eyewall, plays an important role in TC intensification. But HWRF and HAFS have problems to capture the intense turbulent mixing above the boundary layer in the eyewall due to a poor estimation of the stability in eyewall clouds using $N^2 = \frac{g}{\theta_v} \frac{\partial \theta_v}{\partial z}$. The problem has been fixed by including the effects of multi-phase water (vapor, liquid, and solid) in the stability calculation.



HAFS-B simulations of 21 storms in the North Atlantic basin of 2016 – 2019 hurricane seasons totaling 118 forecast cycles. The stability correction improves HAFS-B’s skill in predicting storm track, intensity, and structure.

HAFS-B simulations of Hurricane Michael (2018)

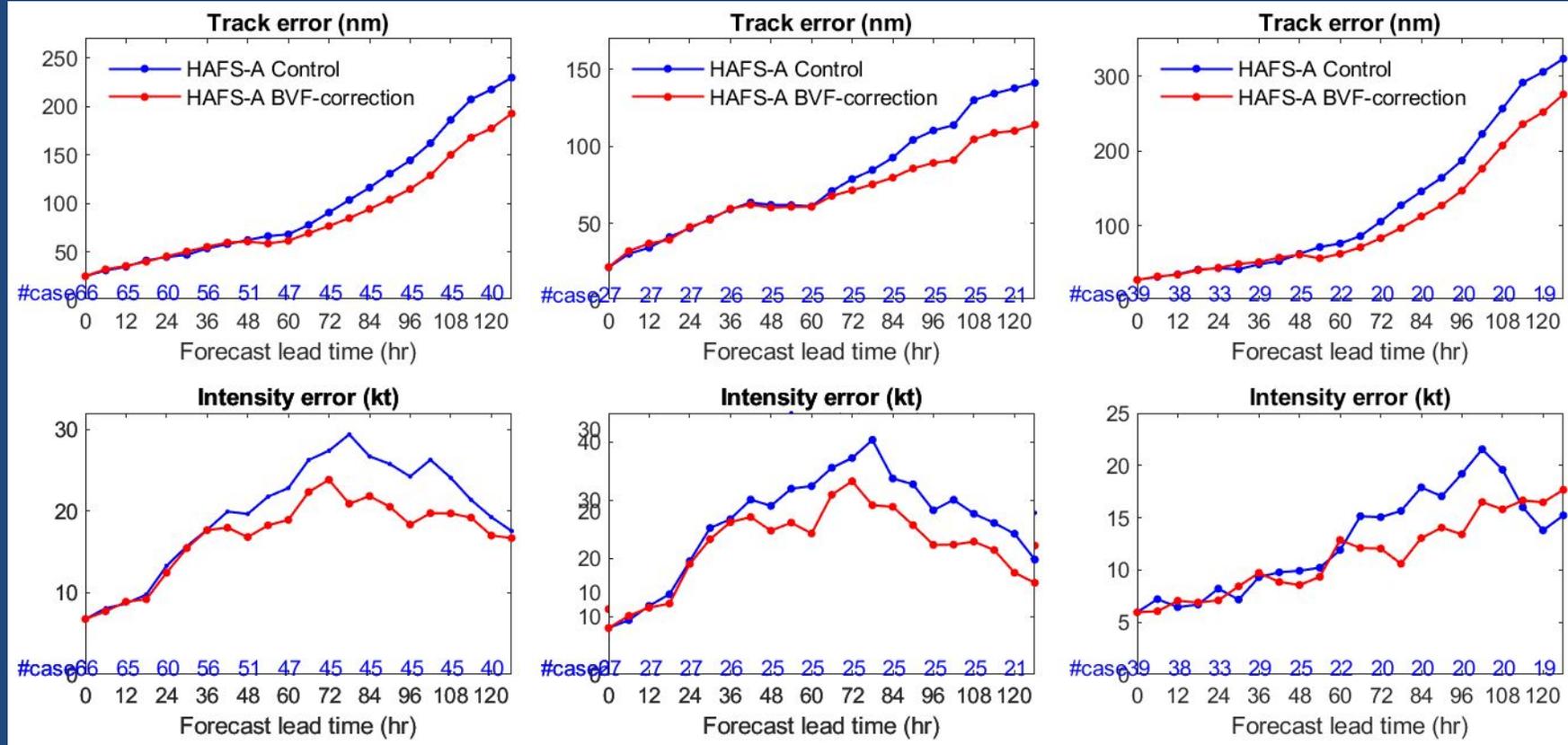


The stability correction allows HAFS-B to successfully capture the RI and peak intensity of Michael.

All storms

CAT 3-5

CAT 1-2 & TS



HAFS-A simulations of 21 storms in the North Atlantic basin of 2018 – 2020 hurricane seasons totaling 68 forecast cycles. The stability correction improves HAFS-A’s skill in predicting storm track and intensity for both strong and weak storms.

The stability correction allows HAFS to successfully capture the turbulent transport in the eyewall, which not only generates a robust dynamical-microphysical interaction in eyewall clouds but also plays a pivotal role in initiating a WISHE-like positive feedback underlying the RI of a TC.

The Role of Eyewall Turbulent Transport in the Pathway to Intensification of Tropical Cyclones. Zhu P., Hazelton A., Zhang Z., Marks F. D., and Tallapragada V. *JGR-Atmosphere*, e2021JD034983, 10.1029/2021JD034983.

This work has been selected for featuring as an Editor’s Highlight and has just been published on Eos.org: <https://eos.org/editor-highlights/hurricane-forecast-improvement-with-better-turbulent-processes>.

2. Vertical turbulent mixing schemes

EDMF hybrid PBL scheme

vs

EDMF TKE turbulence scheme

$$K_m = \kappa \frac{u_*}{\phi_m} \alpha z \left(1 - \frac{z}{h}\right)^2, \quad z \leq h;$$

$$K_m = l^2 f_m(R_i) S, \quad z > h$$

$$K_{m,h} = S_{m,h} l q; \quad q^2 = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

$$\frac{dq^2}{dt} = -\overline{w'u'} \frac{\partial \bar{u}}{\partial z} - \overline{w'v'} \frac{\partial \bar{v}}{\partial z} + \frac{g}{\bar{\theta}_v} \overline{w'\theta_v'} - \frac{\partial}{\partial z} \left(\overline{w'e'} + \frac{1}{\rho} \overline{w'p'} \right) - \varepsilon$$

The scheme is closed by h and the mixing length above h .

The scheme is closed the mixing length in the entire vertical column.

3. Mixing length l

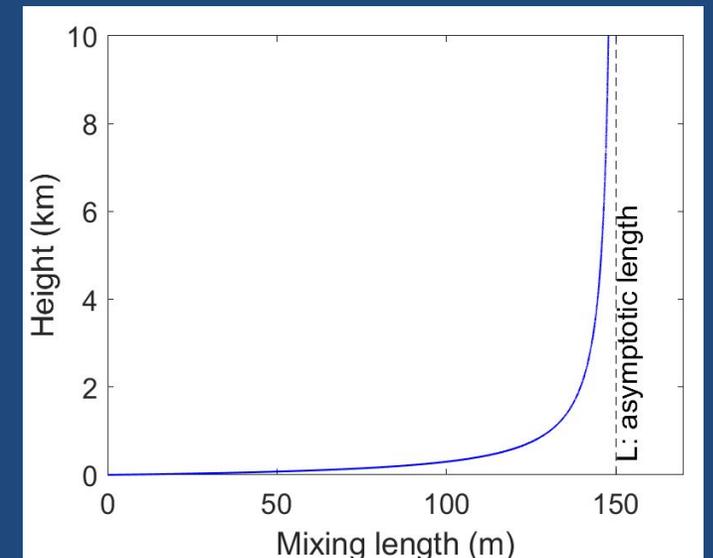
Mixing length, which describes the mixing ability of turbulent eddies, must be determined empirically.

$$\frac{1}{l} = \frac{1}{\kappa z} + \frac{1}{l_o} \quad (\text{Commonly used in simulations})$$

$$\frac{1}{l} = \frac{1}{\kappa z (\beta_1 + \beta_2 z)^{\beta_3}} + \frac{1}{l_o} \quad (\text{HAFS EDMF TKE})$$

l_o is an asymptotic length scale.

These relations were formulated empirically in non-TC conditions, it remains unknown if they can be appropriately applied to the eyewall where turbulence extends all the ways up to the tropopause.



4. Sensitivity tests of TC intensification to mixing length using HWRF simulations with a diagnostic TKE scheme that includes stability correction.

The TKE scheme is developed based on Mellor & Yamada (1982) level 2.5 model:

$$\begin{pmatrix} \overline{u'^2} \\ \overline{v'^2} \\ \overline{w'^2} \end{pmatrix} = \begin{pmatrix} \frac{q^3}{3} \left(1 - \frac{6a_1}{b_1}\right) - \frac{6a_1 l}{q} \frac{\partial \bar{u}}{\partial z} \overline{w'u'} \\ \frac{q^3}{3} \left(1 - \frac{6a_1}{b_1}\right) - \frac{6a_1 l}{q} \frac{\partial \bar{v}}{\partial z} \overline{w'v'} \\ \frac{q^3}{3} \left(1 - \frac{6a_1}{b_1}\right) - \frac{6a_1 l}{q} \frac{g}{\bar{B}} \overline{w'B'} \end{pmatrix}; \quad \begin{pmatrix} \overline{u'v'} \\ \overline{w'u'} \\ \overline{w'v'} \end{pmatrix} = -\frac{3a_1 l}{q} \begin{pmatrix} \overline{w'u'} \frac{\partial \bar{v}}{\partial z} - \overline{w'v'} \frac{\partial \bar{u}}{\partial z} \\ (\overline{w'^2} - c_1 q^2) \frac{\partial \bar{u}}{\partial z} - \frac{g}{\bar{B}} \overline{u'B'} \\ (\overline{w'^2} - c_1 q^2) \frac{\partial \bar{v}}{\partial z} - \frac{g}{\bar{B}} \overline{v'B'} \end{pmatrix}; \quad \begin{pmatrix} \overline{u'B'} \\ \overline{v'B'} \\ \overline{w'B'} \end{pmatrix} = -\frac{3a_2 l}{q} \begin{pmatrix} \overline{w'u'} \frac{\partial \bar{B}}{\partial z} + \overline{w'B'} \frac{\partial \bar{u}}{\partial z} \\ \overline{w'v'} \frac{\partial \bar{B}}{\partial z} + \overline{w'B'} \frac{\partial \bar{v}}{\partial z} \\ \left(\overline{w'^2} + \frac{g}{\theta_v} \frac{b_2 l}{q} \overline{w'B'}\right) \frac{\partial \bar{B}}{\partial z} \end{pmatrix}$$

$$N_m^2 = \frac{g}{T_v} \left(\frac{\partial T_v}{\partial z} - \Gamma_m \right) = \frac{g}{\bar{B}} \frac{\partial \bar{B}}{\partial z}, \quad \Gamma_m = \frac{g}{C_{pd}} \cdot \frac{(1 + \bar{q}_t) \left(1 + \frac{l_s \bar{q}_s}{R_d \bar{T}}\right) + \frac{l_f}{g} \frac{\partial \bar{q}_w}{\partial z}}{1 + \frac{C_{pv} \bar{q}_s + C_w \bar{q}_w + C_i \bar{q}_i}{C_{pd}} + \frac{(\epsilon + \bar{q}_s) l_s l_m \bar{q}_s}{C_{pd} R_d \bar{T}^2}}$$

$$\begin{pmatrix} \overline{w'u'} \\ \overline{w'v'} \\ \overline{w'B'} \end{pmatrix} = \begin{pmatrix} -P_m l q \frac{\partial \bar{u}}{\partial z} \\ -P_m l q \frac{\partial \bar{v}}{\partial z} \\ -P_h l q \frac{\partial \bar{B}}{\partial z} \end{pmatrix}; \quad \begin{pmatrix} P_h = \frac{d_5}{1 + d_3 G_h} \\ P_m = \frac{d_1 + d_2 G_h}{(1 + d_3 G_h)(1 + d_4 G_h)} \\ G_h = -\left(\frac{l}{q}\right)^2 N_m^2 \end{pmatrix} \quad (1)$$

$$\text{TKE budget:} \quad -\overline{w'u'} \frac{\partial \bar{u}}{\partial z} - \overline{w'v'} \frac{\partial \bar{v}}{\partial z} + \frac{g}{\bar{B}} \overline{w'B'} = D. \quad (2)$$

$$\text{TKE dissipation:} \quad D = \frac{q^2}{b_1 l^2} \quad (3)$$

$$(1) \text{ and } (3) \square (2): \quad q = Sl \sqrt{b_1 (P_m - P_h R_i)}$$

$$S = \sqrt{\left| \frac{\partial \bar{u}}{\partial z} \right|^2 + \left| \frac{\partial \bar{v}}{\partial z} \right|^2} \quad R_i: \text{Richardson number}$$

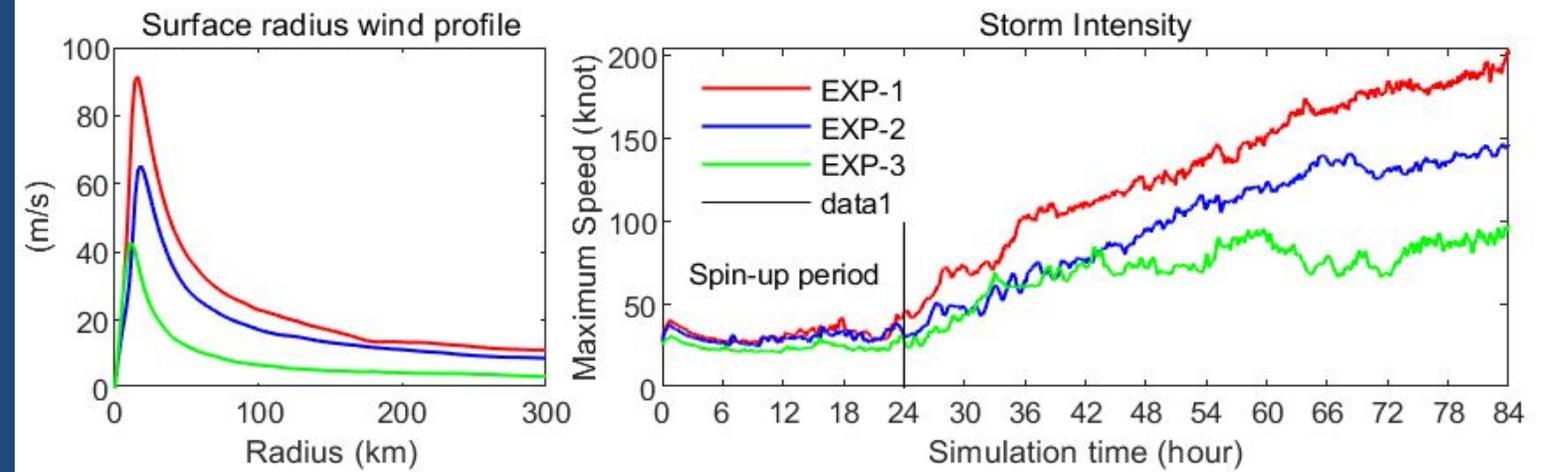
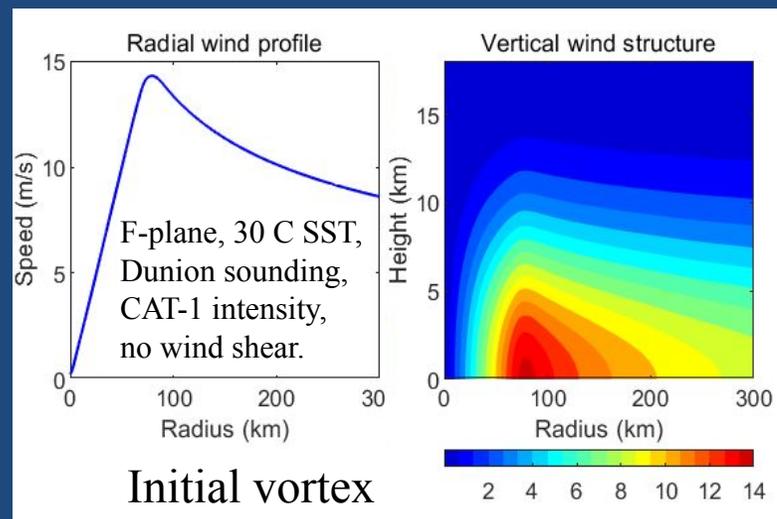
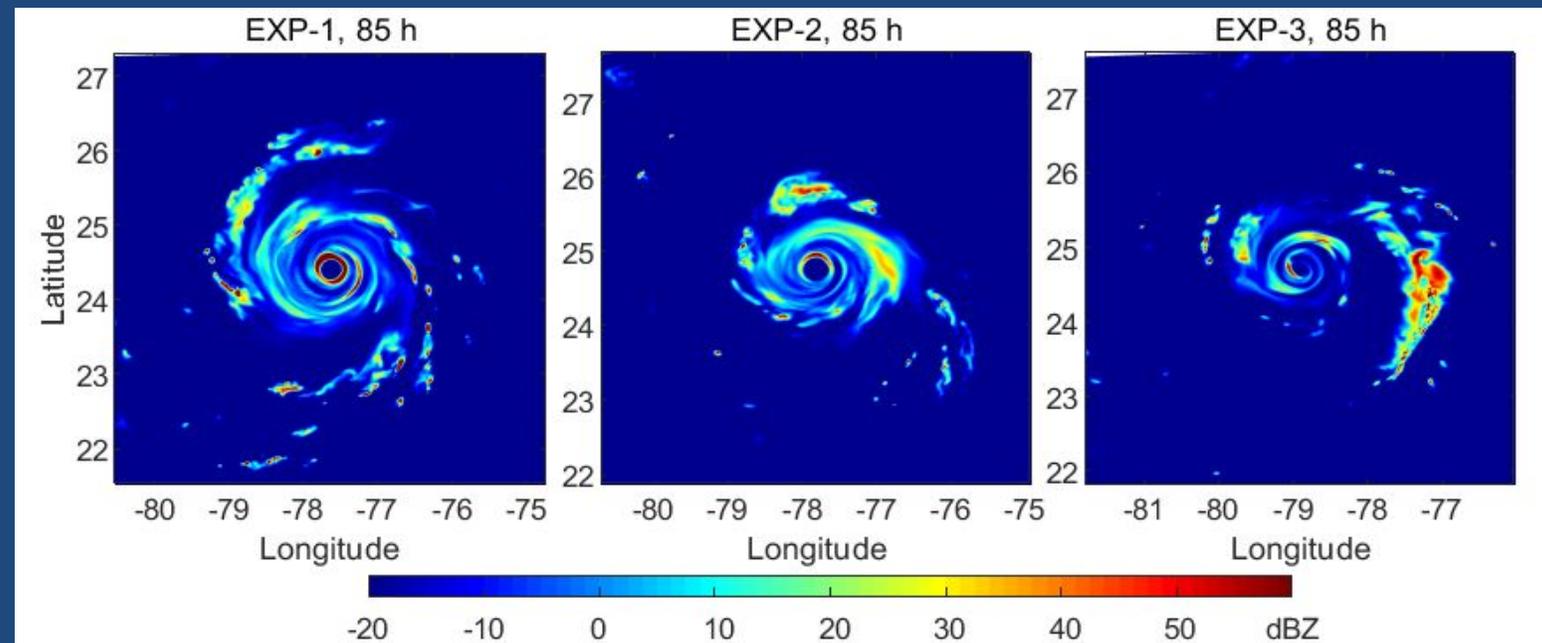
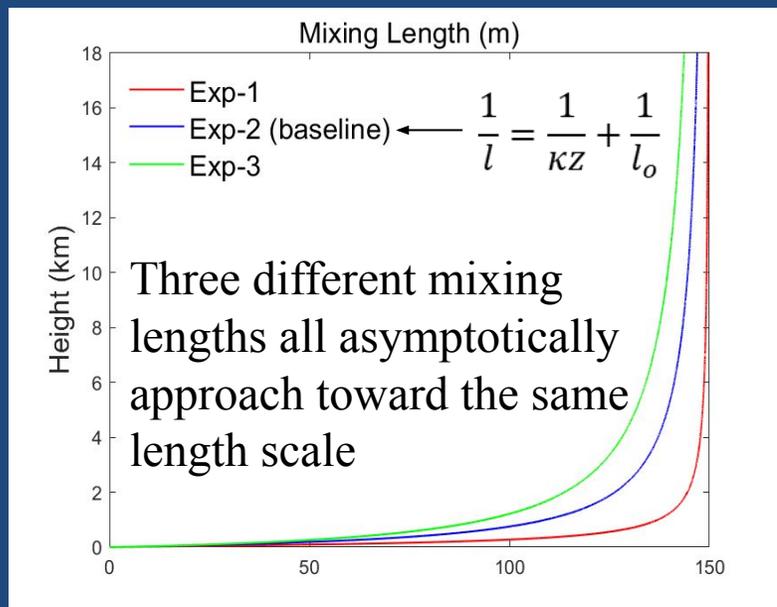


$$K_m = P_m l q = l^2 S P_m \sqrt{b_1 (P_m - P_h R_i)}$$

$$K_h = P_h l q = l^2 S P_h \sqrt{b_1 (P_m - P_h R_i)}$$

(Galperin et al. 1988)

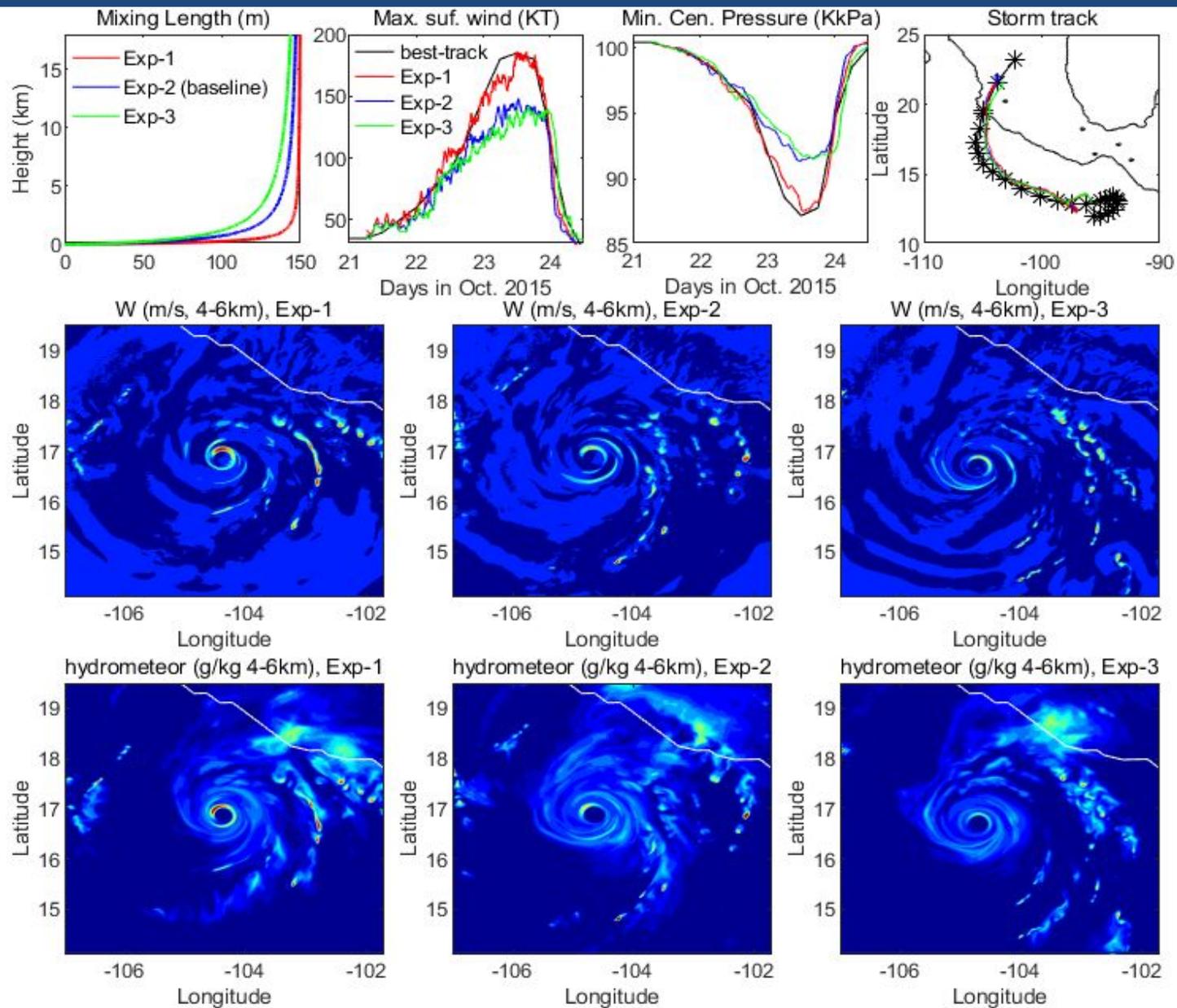
4.1 Idealized HWRF simulations



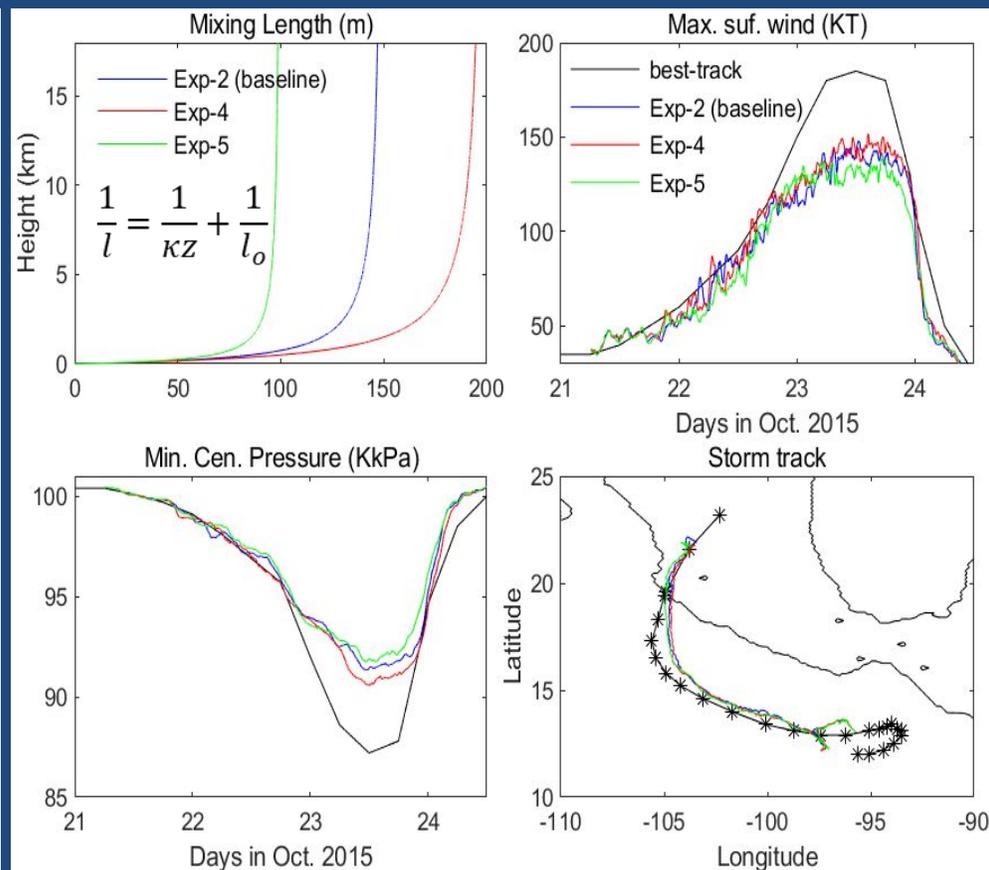
Different vertical profile of the mixing length leads to different TC intensification

4.2 HWRF real-case simulations of Hurricane Patricia (2015)

Sensitivity to the mixing length slope



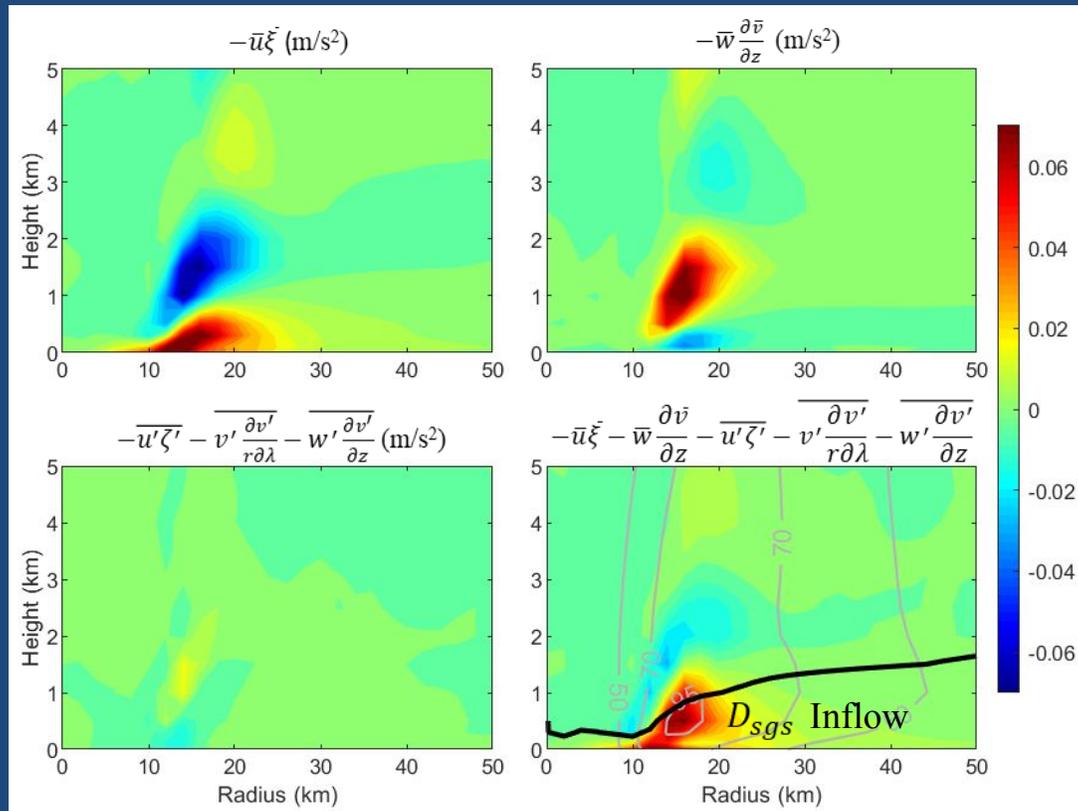
Sensitivity to the asymptotic length scale



Why is TC intensification so sensitive to the mixing length slope from the boundary layer to mid troposphere?

5. TC intensification in numerical simulations

$$\frac{\partial \bar{v}}{\partial t} = -\bar{u}\bar{\xi} - \bar{w}\frac{\partial \bar{v}}{\partial z} - \overline{u'\zeta'} - \overline{v'\frac{\partial v'}{r\partial\lambda}} - \overline{w'\frac{\partial v'}{\partial z}} + D_{sgs}$$



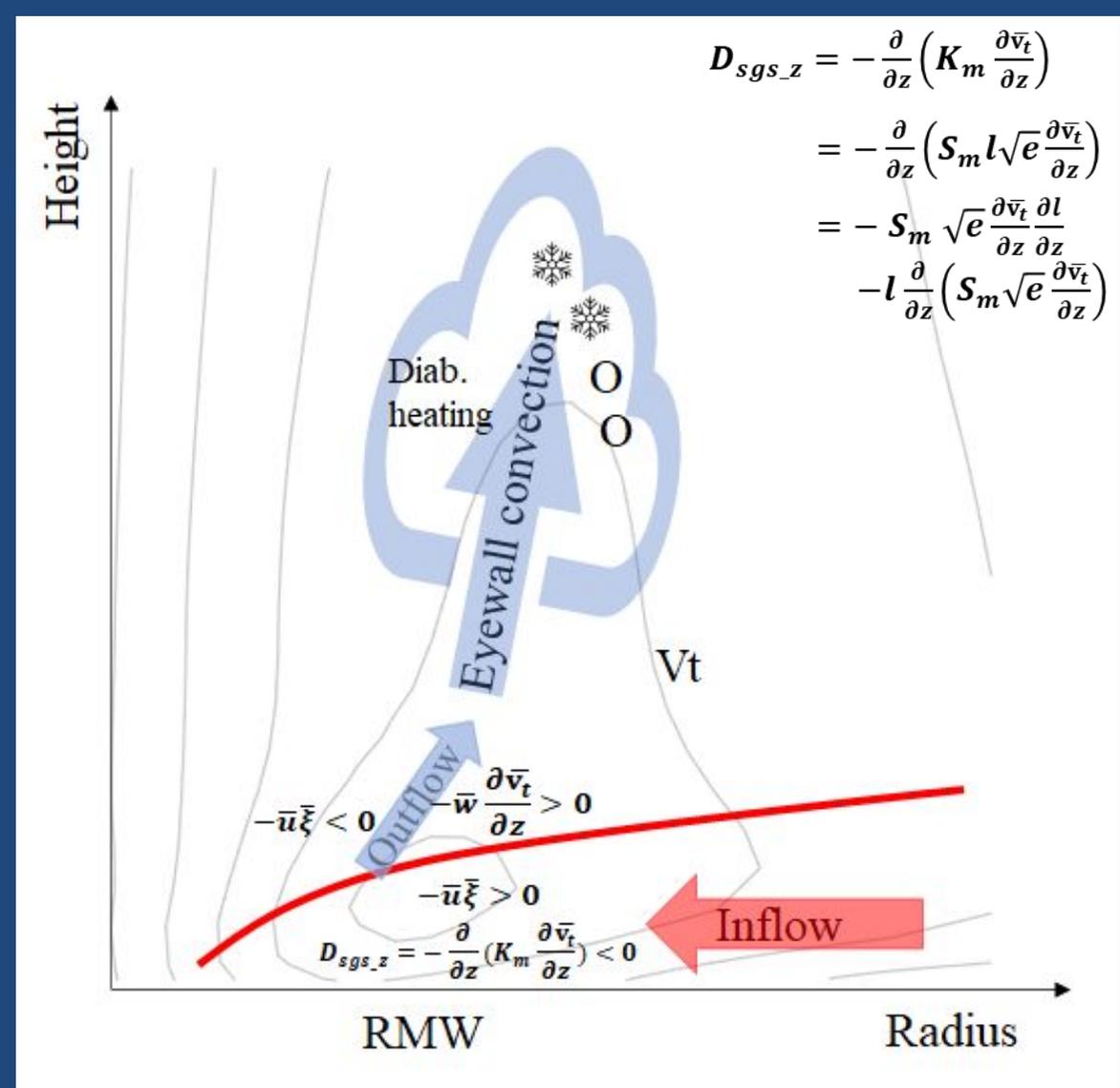
Turbulence plays triple roles in TC intensification:

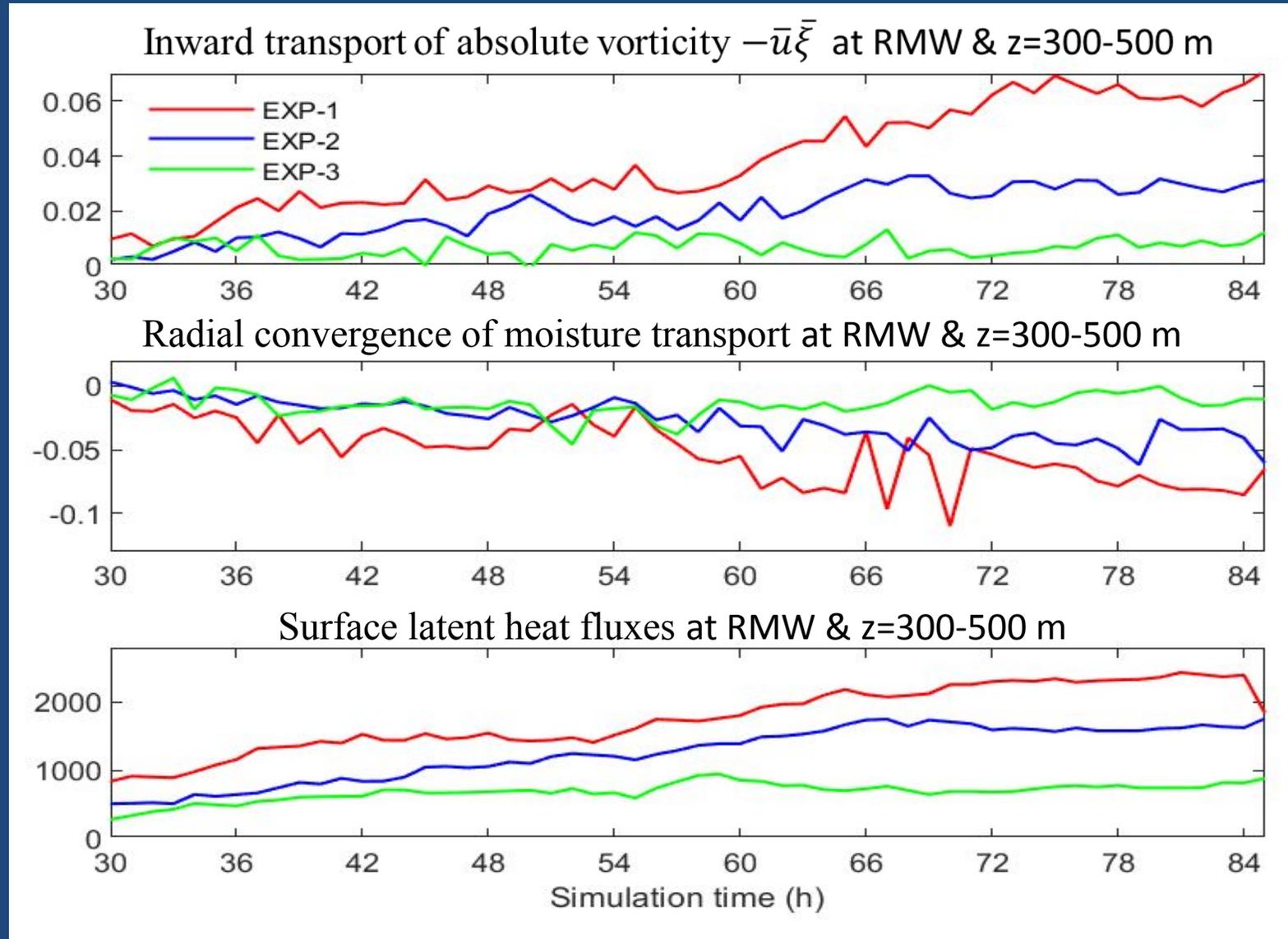
(a) It acts as the frictional force to slow down a TC vortex.

(b) It induces the inflow that accelerates the primary circulation via $-\bar{u}\bar{\xi}$.

(c) It transports moisture upward to foster eyewall convection, which further accelerates the vortex in the inflow layer via $-\bar{u}\bar{\xi}$.

The large cancellation among different acceleration and deceleration processes causes the maximum acceleration to occur at the RMW just below the interface between inflow and outflow.

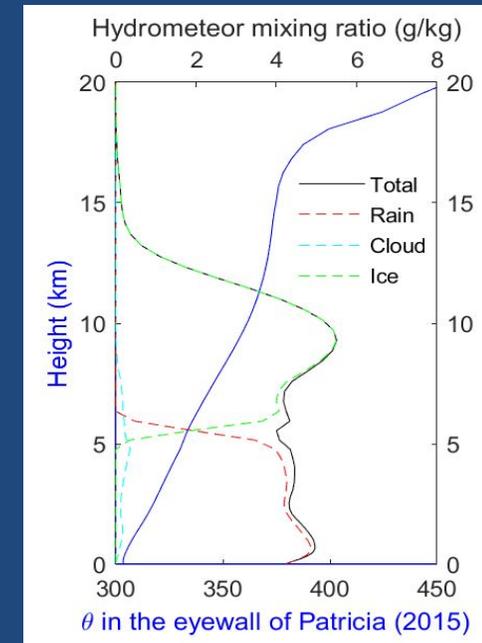
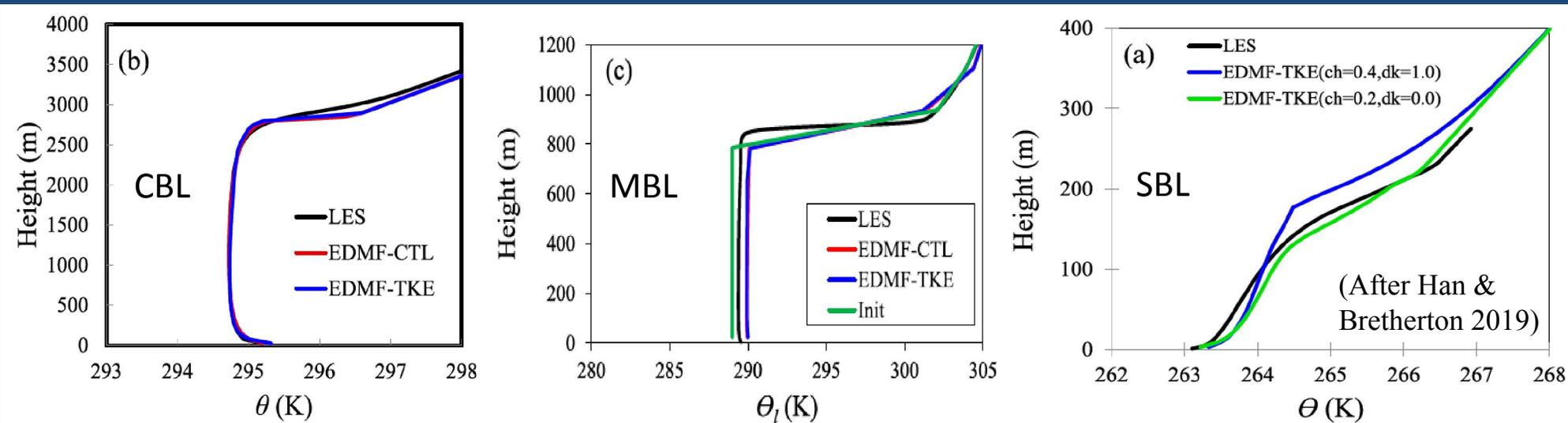




In EXP-1, the turbulent transport is able to kick off a positive feedback among vortex acceleration via $-\bar{u}\bar{\xi}$, radial convergence of moisture, and surface evaporation. But in EXP-3, it is unable to generate sufficiently large $-\bar{u}\bar{\xi}$ to overcome the friction dissipation, and thus fail to initiate the positive feedback mechanism leading to vortex intensification.

6. TKE turbulence scheme for TC simulations

The EDMF TKE scheme used in HAFS (Han & Bretherton 2019) was validated for three cases of CBL, MBL topped by stratocumulus, and SBL, in which the turbulent BL is separated from the free atmosphere by an inversion. Because of this, the eddy exchange coefficients are separately parameterized based on a diagnostic PBL height in a similar way to the EDMF hybrid PBL scheme.



In the eyewall, no inversion exists to separate the turbulence generated by the surface processes and cloud processes aloft. Thus, an artificially separated treatment of eddy exchange coefficients is not physically sound.

Summary

1. Turbulent transport in the eyewall plays an important role in TC intensification. The stability correction by considering the cloud induced buoyancy allows the turbulence scheme to capture the vertical turbulent transport in the eyewall and generate robust dynamical-microphysical interaction in TC inner-core region, leading to the improvement of HFAS's skill in predicting TC intensity, in particular RI.
2. TC intensification in numerical simulations is sensitive to the slope of vertical profile of mixing length even with the same asymptotic length scale. Such a sensitivity results from the delicate acceleration/deceleration of a TC vortex involving a large cancellation among inward transport of absolute vorticity, vertical advection of tangential wind, and friction dissipation, which are all related to the turbulence parameterization.
3. The separate treatment of the interconnected turbulence in the eyewall by a diagnosed PBL height is not a physically sound method since no physical interface exists in the eyewall to separate the turbulence generated by the boundary layer processes and cloud processes aloft.