

# Improving Inner-Core Turbulent Transport Parameterization for the Hurricane Analysis and Forecast System (HAFS)

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# Unique thermodynamic and turbulence structures in the eyewall of TCs

- Turbulence is commonly regarded as a flow feature pertaining to the boundary layer.
- In fair-weather conditions, the turbulent boundary layer is cleanly separated from the free atmosphere above by a capping inversion.
- In TC inner-core, turbulence can also be generated above the boundary layer by cloud processes.
- The characteristics of turbulence and vertical structure of thermodynamic fields in the eyewall and rainbands of a TC are in stark different from those in fair-weather conditions.

*“As the RMW is approached, the boundary layer becomes ill defined as air is pulled up into the active convection.”* (Shapiro, 1983)

Can the turbulent transport in the eyewall be treated in the same way as that in fair-weather conditions?

# HAFS's Eddy-Diffusivity-Mass-Flux (EDMF) TKE Scheme (Han & Bretherton 2019)

$$\begin{cases} K_m = l\sqrt{e}S_m \\ K_h = l\sqrt{e}S_h \end{cases}$$

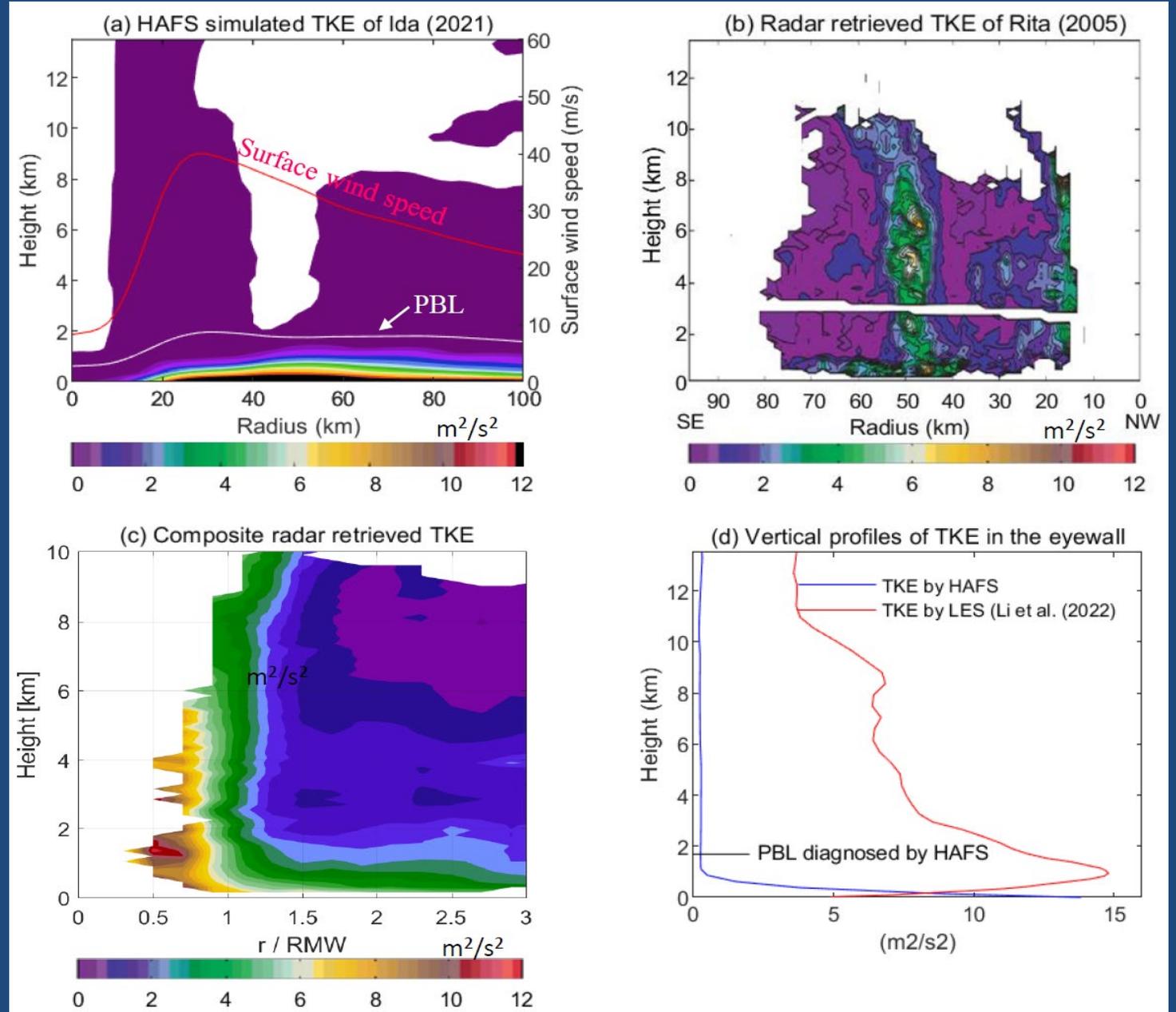
The EDMF TKE scheme does an excellent job in representing turbulent transport processes of CBL, MBL, and SBL.

OBS & LES:

- Large TKEs are seen above the PBL in the eyewall.

HAFS's EDMF TKE scheme:

- TKEs are mainly in the low part of the PBL.
- TKEs are negligible above the PBL in the eyewall.



# Likely reasons for the EDMF TKE scheme not capturing the observed structure of TKE in the eyewall

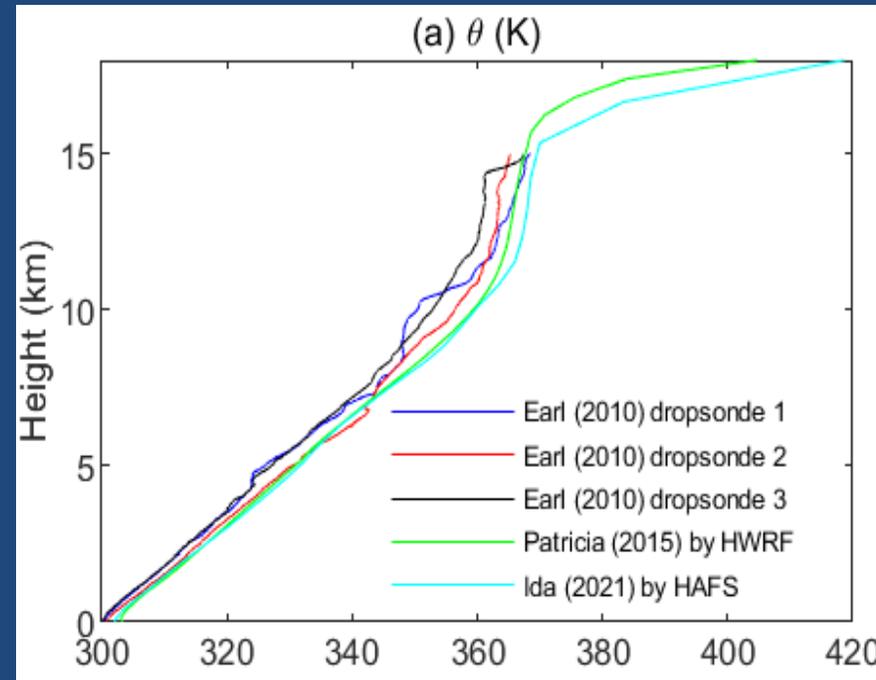
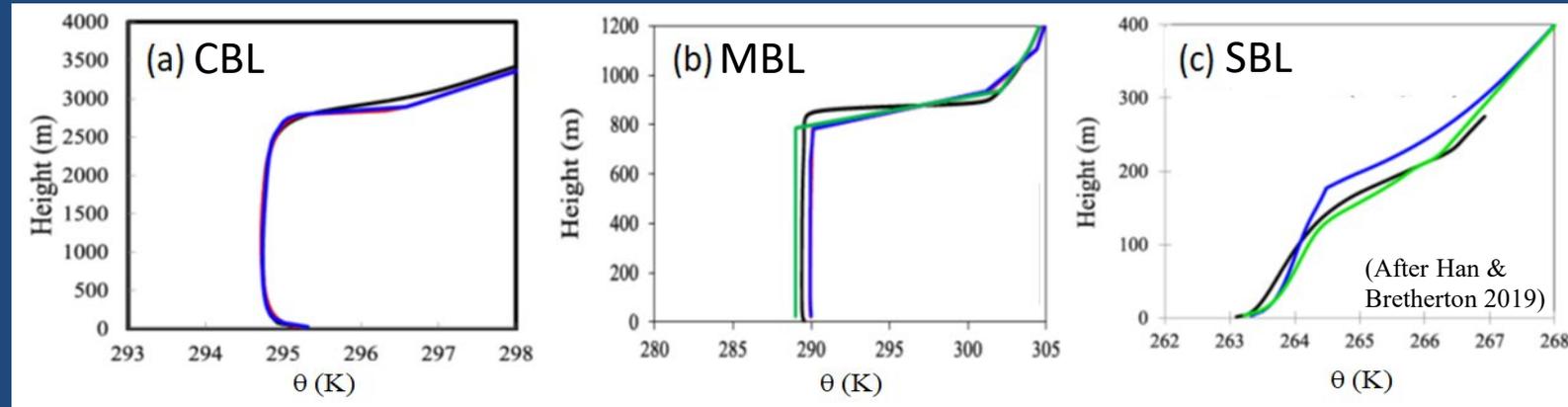
## 1. Separate turbulence parameterization below and above a diagnosed PBL height

$$h = R_c \frac{\theta_{va} |U(h)|^2}{g[\theta_v(h) - \theta_s]}$$

$h$  is generally below 2 km with the upper limit set to half of the model vertical levels.

The interconnected vertical turbulent transport in the eyewall requires a vertically integrated parameterization to represent the turbulence generated by the surface processes and cloud processes aloft as a whole.

A diagnosed PBL height is superfluous to the nature of the TKE methodology



Vertical profiles of  $\theta$  in the eyewall

2. Unphysical constraint set by the diagnosed PBL height on the lateral entrainment velocity used for parameterizing the eyewall buoyant updraft

$$\frac{\partial \psi_{up}}{\partial z} = -\varepsilon_{lat}(\psi_{up} - \bar{\psi}),$$

$\varepsilon_{lat}$ : lateral entrainment velocity, a key parameter that determines how the buoyant updraft is diluted as it arises.

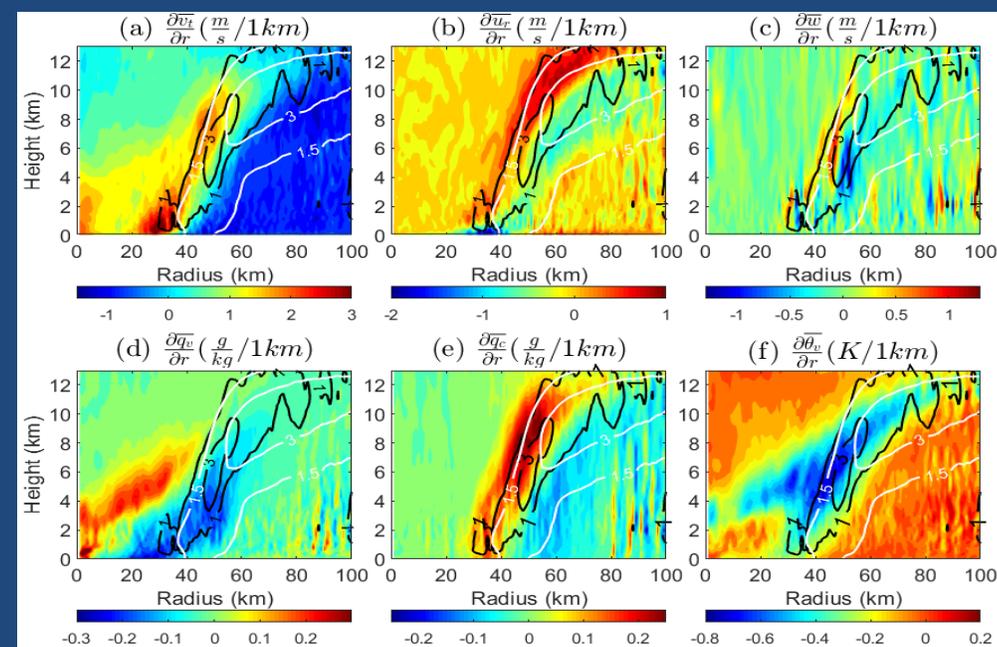
$$\varepsilon_{lat} = c_\varepsilon \left[ \frac{1}{z + \Delta z} + \frac{1}{(h - z) + \Delta z} \right] \quad \text{derived from the LESs of a dry CBL case (Siebesma et al. 2007)}$$

for  $z > h$ ,  $\varepsilon_{lat} < 0$ , Unphysical!

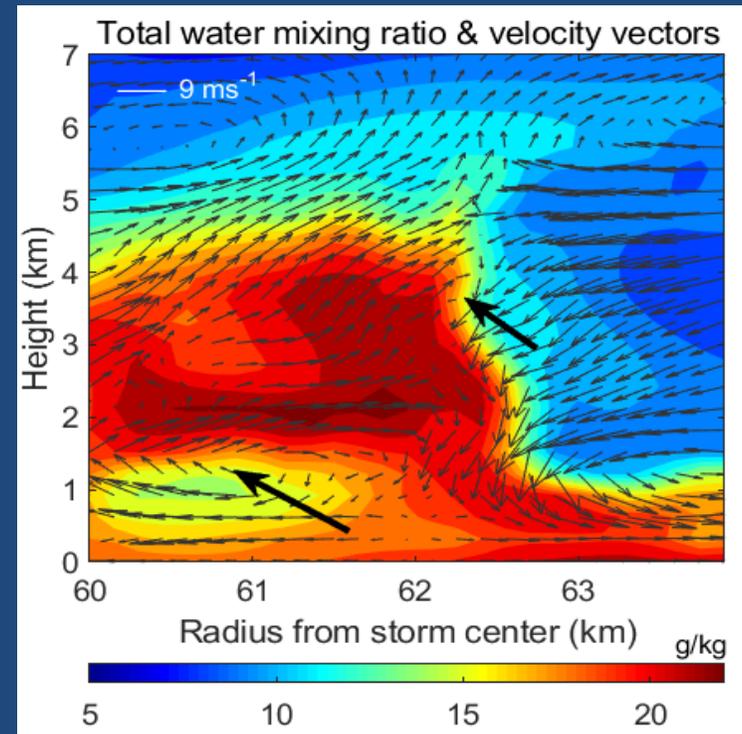
Lack of buoyant updrafts above the diagnosed PBL height is one of the reasons for the EDMF TKE scheme not producing the observed large TKE above the boundary layer in the eyewall.

### 3. Lateral turbulent mixing in TC inner-core

- For the typical CBL, MBL, and SBL, the horizontal gradients of variables in the boundary layer are much smaller than the corresponding vertical gradients. As a result, the lateral turbulent transport is much smaller than the vertical turbulent transport.
- In TC inner-core, large lateral gradient across the edge between eyewall and moat causes the lateral turbulent mixing to be comparable to the vertical turbulent mixing.
- Coherent eddy circulations generate large vertical and horizontal non-local transport
- Entraining moat air into eyewall and rainbands can result in lateral entrainment instability



Radial gradients of variables from a large eddy simulation of Hurricane Isabel (2002) by Li et al. (2022).

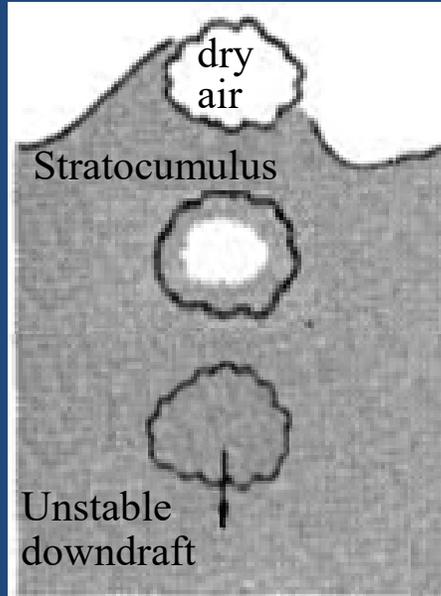


Outer edge of Hurricane Isabel (2002)'s eyewall from a large eddy simulation by Li et al. (2022).

## 4. Lateral entrainment instability and TKE generation in the eyewall

### Cloud-top entrainment instability

Deardorff (1980)  
Randall (1980)



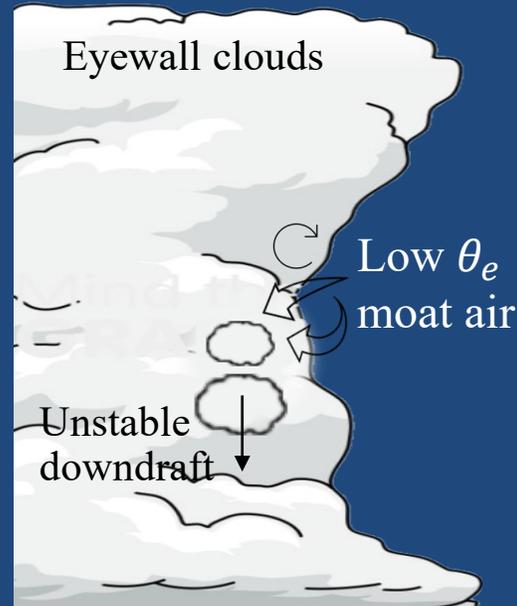
Cloud-top entrainment buoyancy flux:

$$\overline{(w'\theta'_v)}_{ctp\_ent} = w_{ctp}(-\alpha\Delta_{ctp}\theta_e + \bar{\theta}\Delta_{ctp}q_t)$$

Instability criterion:

$$\Delta_{ctp}\theta_e < (\Delta_{ctp}\theta_e)_{crit} = \bar{\theta}\Delta_{ctp}q_t/\alpha$$
$$\rightarrow \overline{(w'\theta'_v)}_{ctp\_ent} > 0$$

### Lateral entrainment instability



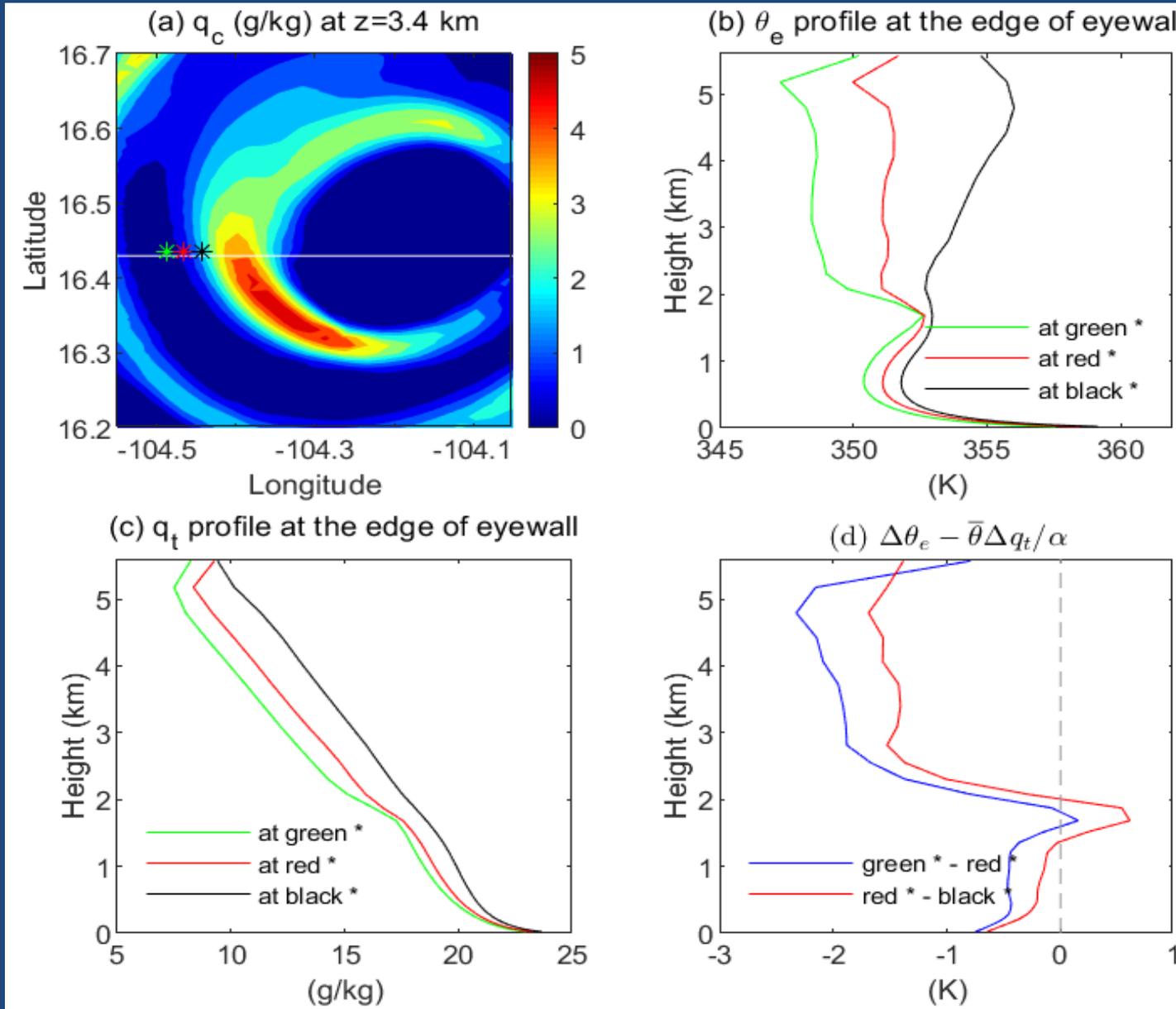
Lateral entrainment buoyancy flux:

$$\overline{(w'\theta'_v)}_{lat\_ent} = \varepsilon_{lat}(-\alpha\Delta_x\theta_e + \bar{\theta}\Delta_xq_t) + \varepsilon_{lat}(-\alpha\Delta_y\theta_e + \bar{\theta}\Delta_yq_t)$$

Instability criterion:

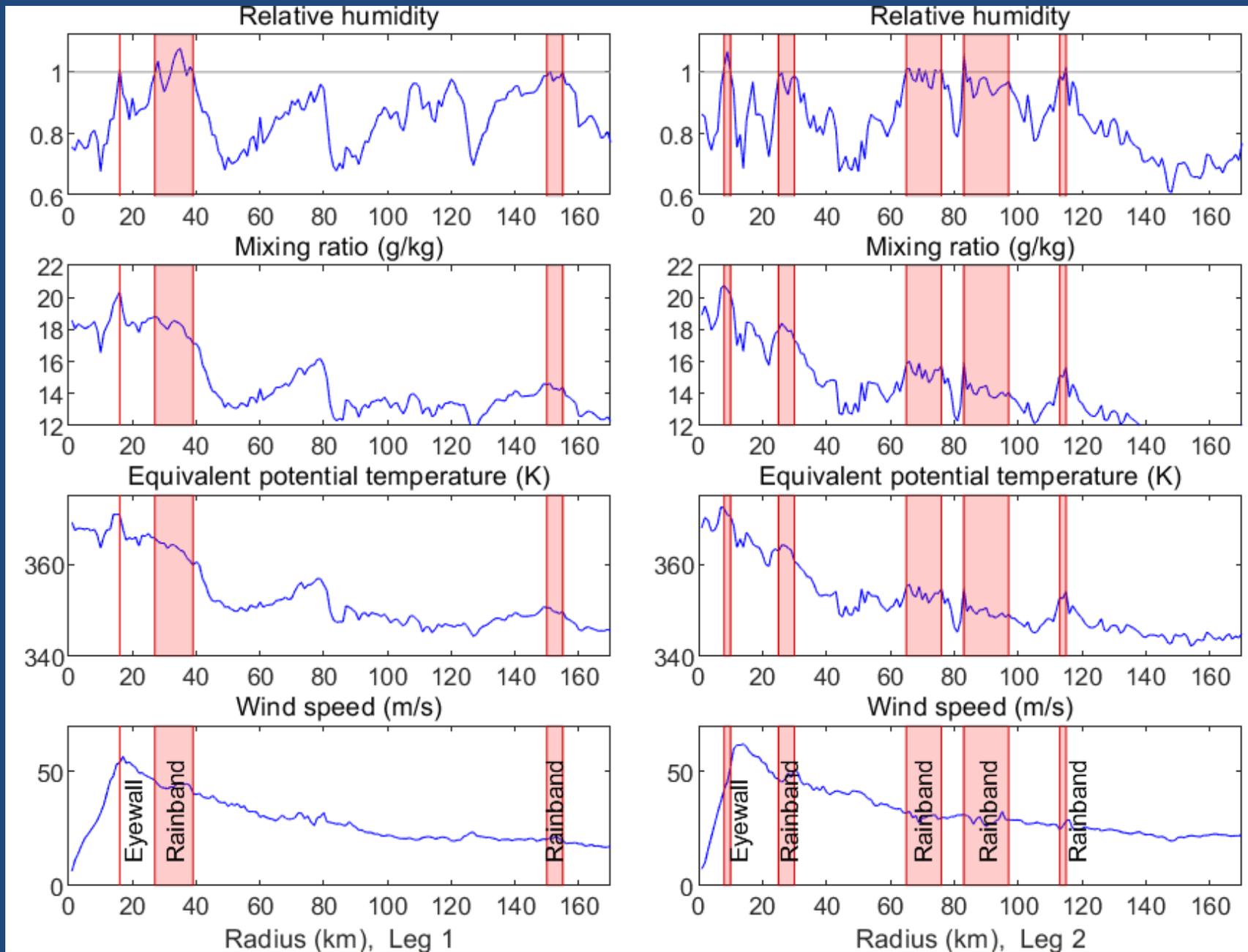
$$\Delta_{x,y}\theta_e < (\Delta_{x,y}\theta_e)_{crit} = \bar{\theta}\Delta_{x,y}q_t/\alpha$$
$$\rightarrow \overline{(w'\theta'_v)}_{lat\_ent} > 0$$

# Vertical profiles of $\theta_e$ and $q_t$ in the vicinity of eyewall and the associated instability parameter of Hurricane Patricia (2015) simulated by HWRF

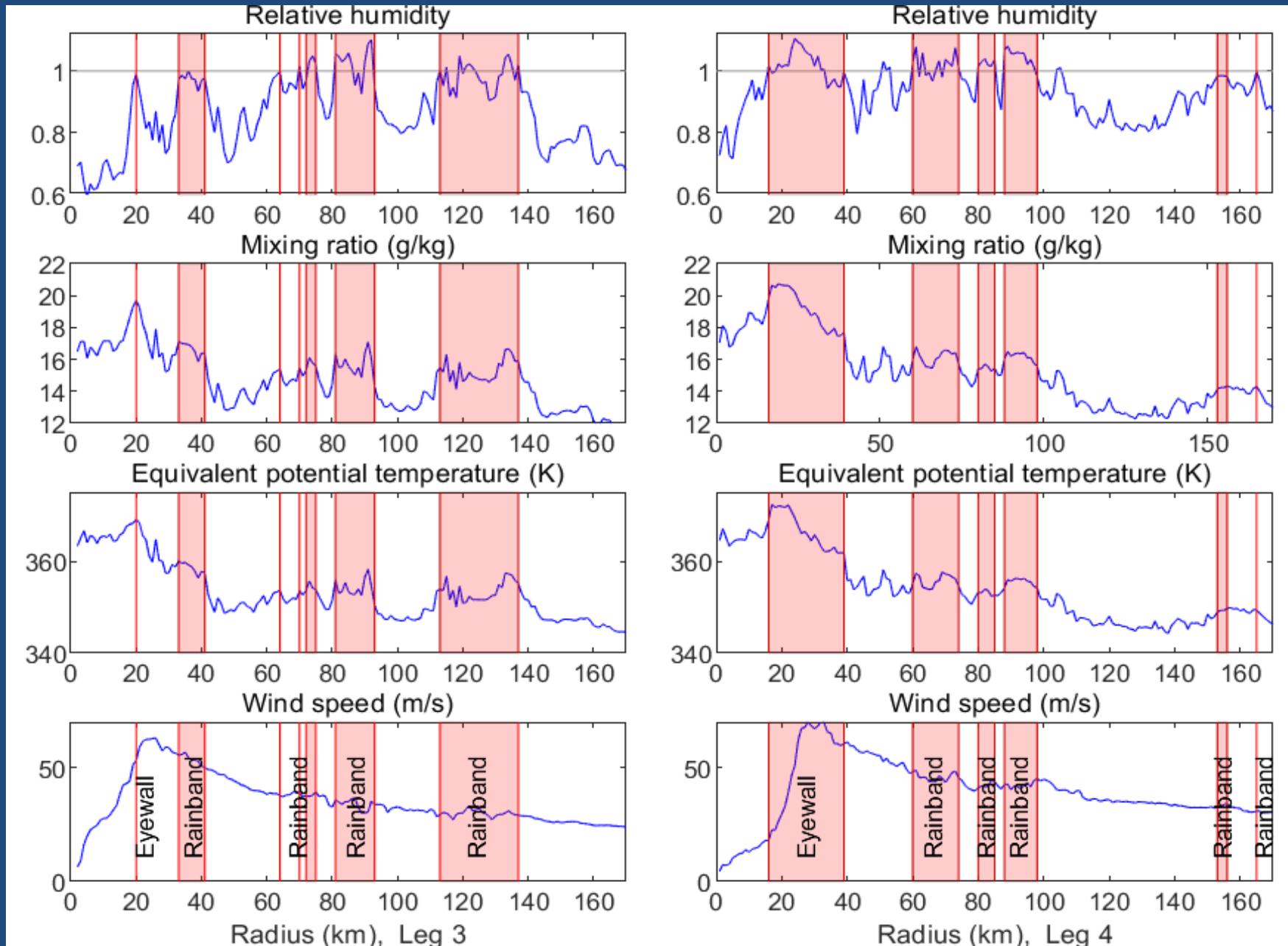


The instability parameter is negative and meets the instability criterion throughout the vertical column.

# In-situ aircraft measurements at $\sim 750$ hPa through Hurricane Michael (2018), legs 1 and 2

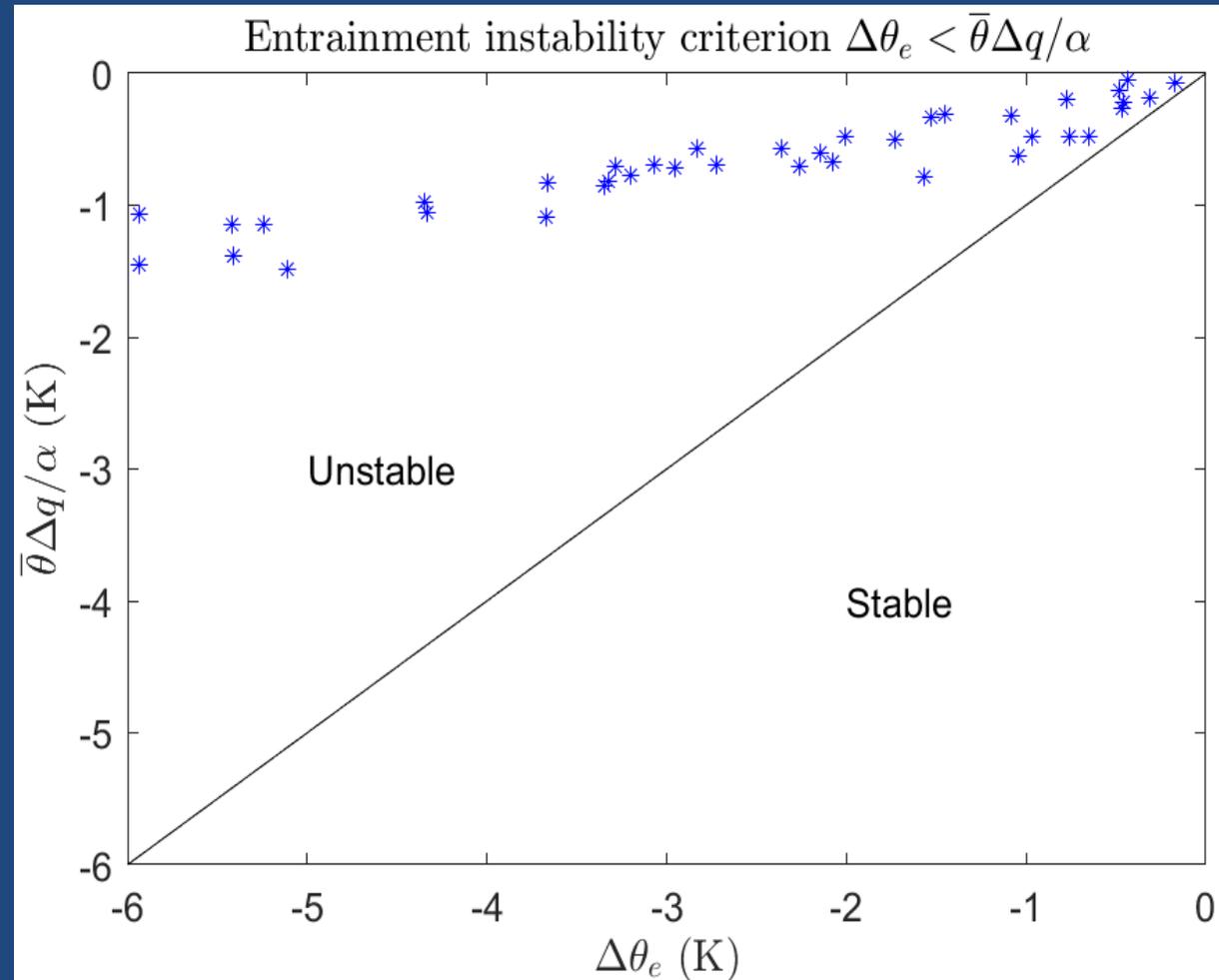


# In-situ aircraft measurements at $\sim 750$ hPa through Hurricane Michael (2018), legs 3 and 4



# Lateral entrainment instability parameters estimated from aircraft measurements

All estimated instability parameters fall into the unstable regime, indicating that the moist air has sufficiently low  $\theta_e$  to meet the instability criterion when it is entrained into the eyewall and rainbands.



Lateral entrainment buoyancy flux,  $(\overline{w'\theta'_v})_{lat\_ent} = \varepsilon_{lat}(-\alpha\Delta_x\theta_e + \bar{\theta}\Delta_x q_t) + \varepsilon_{lat}(-\alpha\Delta_y\theta_e + \bar{\theta}\Delta_y q_t)$ , needs to be included in the buoyancy production of TKE in the TKE budget equation.

## 5. Parameterization of horizontal non-local turbulent transport in TC inner-core

### Parameterization of vertical turbulent fluxes

- MY (1974), Zhang et al. (2018):

$$\overline{w'\psi'} = \underbrace{-K_{vert}^{\psi} \frac{\partial \bar{\psi}}{\partial x_j}}_{\text{Local}} + \underbrace{\overline{w'\psi'}^{NL}}_{\text{non-local}}$$

- Mass-flux approach:

$$\overline{w'\psi'}^{NL} \approx M_z(\psi_c - \bar{\psi}), \quad M_z \approx \sigma w_c$$

- Entraining plume model:

$$\frac{\partial w_c^2}{\partial z} = -b_1 \varepsilon_{lat} w_c^2 + b_2 g \frac{\theta_{v,c} - \bar{\theta}_v}{\bar{\theta}_v}$$

$$\frac{\partial \vec{V}_c}{\partial z} = -\varepsilon_{lat} (\vec{V}_c - \bar{\vec{V}}) + d_e \frac{\partial \bar{\vec{V}}}{\partial z}$$

$$\frac{\partial \psi_c}{\partial z} = -\varepsilon_{lat} (\psi_c - \bar{\psi})$$

### Parameterization of horizontal turbulent fluxes

- Split horizontal fluxes into local and non-local parts

$$\overline{u'v'} = -K_{hori}^m (\partial \bar{u} / \partial x + \partial \bar{v} / \partial y) + \overline{u'v'}^{NL}$$

$$\overline{u'\psi'} = -K_{hori}^{\psi} \partial \bar{\psi} / \partial x + \overline{u'\psi'}^{NL}$$

$$\overline{v'\psi'} = -K_{hori}^{\psi} \partial \bar{\psi} / \partial y + \overline{v'\psi'}^{NL}$$

- Horizontal mass fluxes

$$M_x \approx \sigma u_c \quad M_y \approx \sigma v_c$$

- Mass fluxes satisfy mass conservation

$$\frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y} + \frac{\partial M_z}{\partial z} = \frac{\partial u_{up}}{\partial x} + \frac{\partial v_{up}}{\partial y} + \frac{\partial w_{up}}{\partial z} = 0$$

- Horizontal non-local fluxes

$$\begin{cases} \overline{u'v'}^{NL} \approx M_x(v_c - \bar{v}) + M_y(u_c - \bar{u}) \\ \overline{u'\psi'}^{NL} \approx M_x(\psi_c - \bar{\psi}) \\ \overline{v'\psi'}^{NL} \approx M_y(\psi_c - \bar{\psi}) \end{cases}$$

# Summary

The EDMF TKE scheme provides an attractive framework for parameterizing turbulence generated by different processes in a unified manner. But it needs to be revised to reflect the unique thermodynamic and turbulence structure in TC inner-core and take into account the processes important to TKE generation in the TC eyewall.

## Ongoing and Future Work

Performing single-column model simulations using the soundings and forcing conditions collected in TC inner-core and evaluate the scheme and revisions by comparing simulations with observations including the radar retrieved TKE.