UIFCW 2023

A Scale-Aware Three-Dimensional TKE Turbulent Mixing Parameterization for the Hurricane Analysis and Forecast System (HAFS)

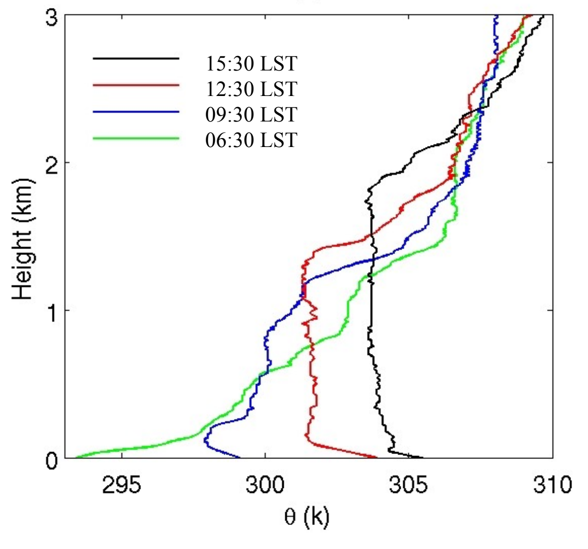
Ping Zhu[1], Jun Zhang[2,3], Xuejing Zhang[3], Jianwen Bao[4], Zhan Zhang[5]

[1]Florida International University (FIU)
[2]Cooperative Institute for Marine & Atmospheric Studies (CIMAS), University of Miami (UM)
[3]AOML/Hurricane Research Division (HRD), NOAA
[4]Physical Sciences Laboratory (PSL), NOAA
[5]Environmental Modeling Center (EMC), NOAA

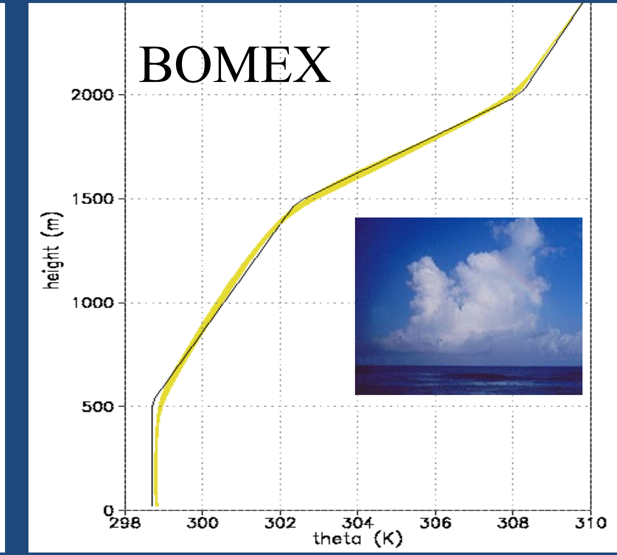
07/25/2023

Background

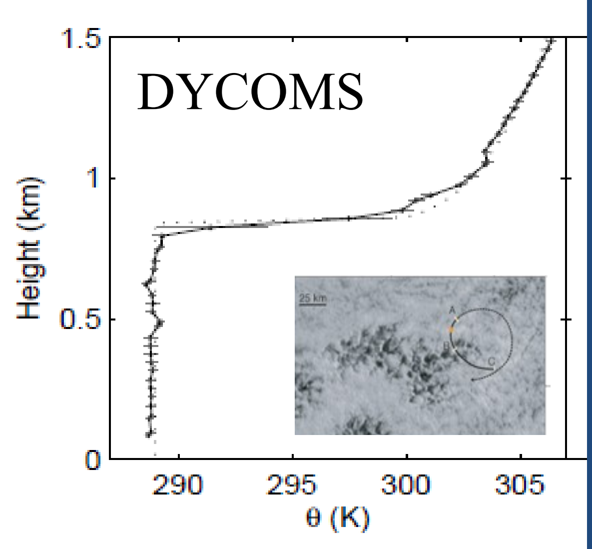
Boundary layer and turbulence parameterization



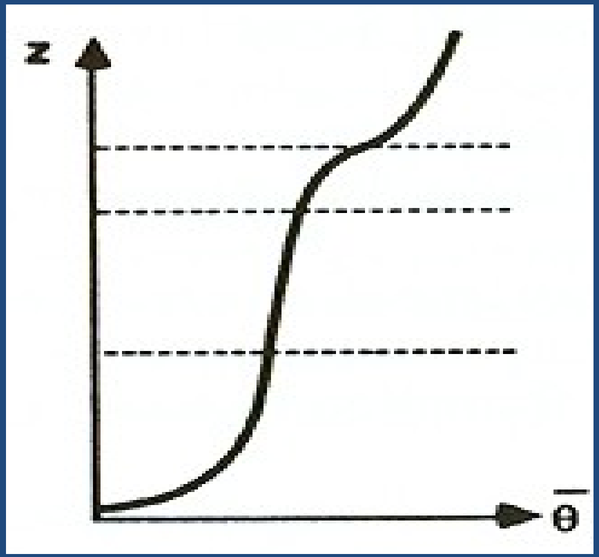
Southern Great Plains Typical CBL



Subtropical trade-wind MBL



Stratocumulus-topped MBL

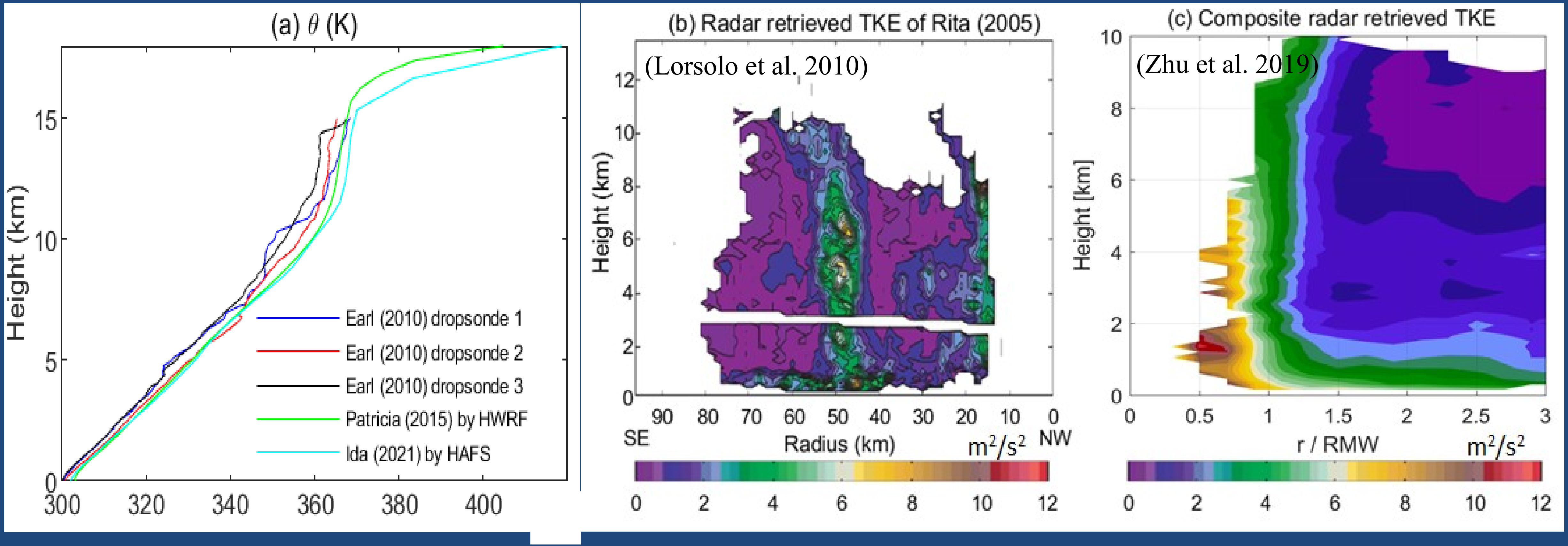


Typical SBL

- The turbulent BL is cleanly separated from the free atmosphere above by a capping inversion.
- Vertical turbulent mixing is much stronger than the horizontal turbulent mixing.
- In MS and LS models, horizontal and vertical turbulent mixing is treated separately. The former is handled in a model's dynamic solver, whereas the latter is treated as a standalone one-dimensional module in a model's physics package.

Background

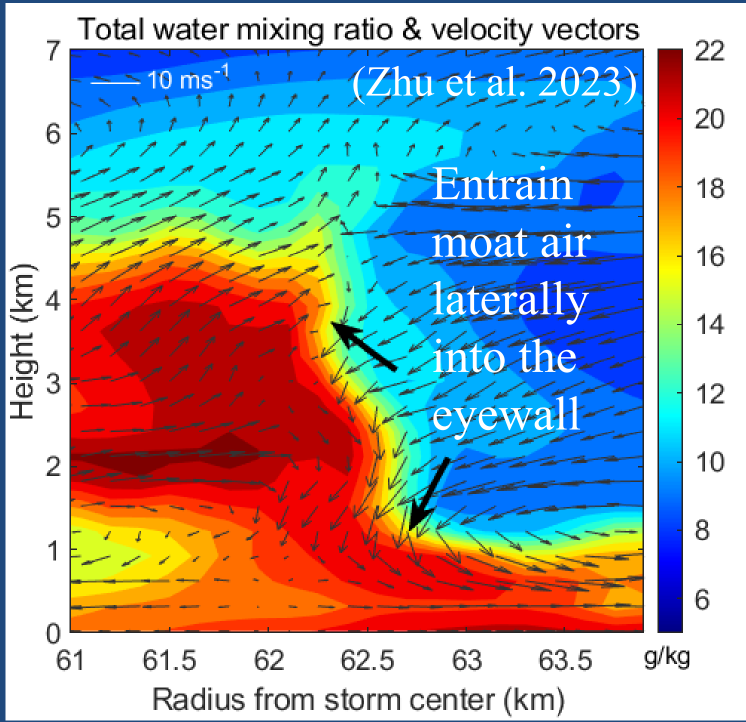
Observed thermodynamic and turbulence structure in the eyewalls of tropical cyclones (TCs)

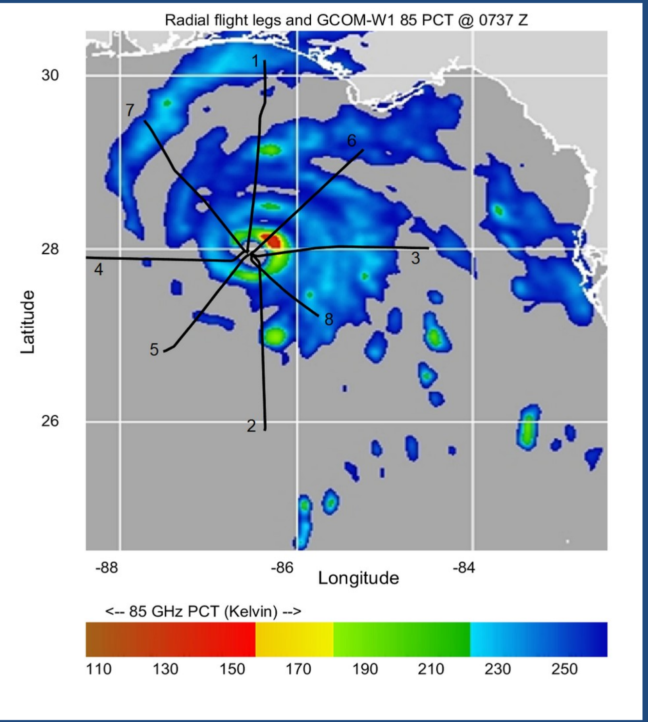


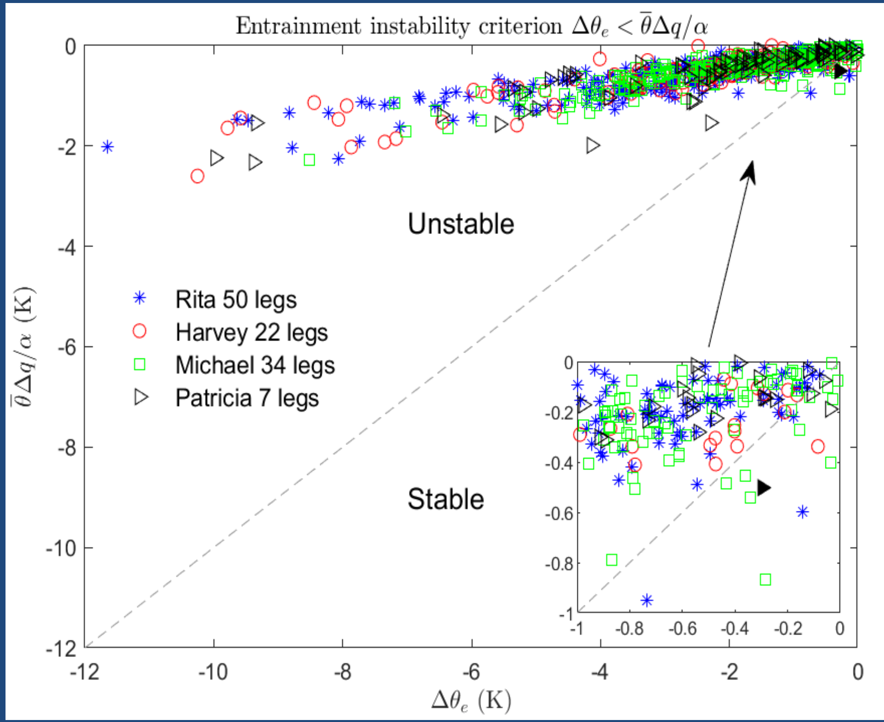
- No inversion exists to separate the BL from the free atmosphere above in the eyewall.
- Large Turbulent kinetic energy (TKE) is seen in the eyewall throughout troposphere.
- Traditional PBL concept does not apply to the eyewall.

Background

Horizontal turbulent mixing and lateral entrainment instability in the inner core of TCs



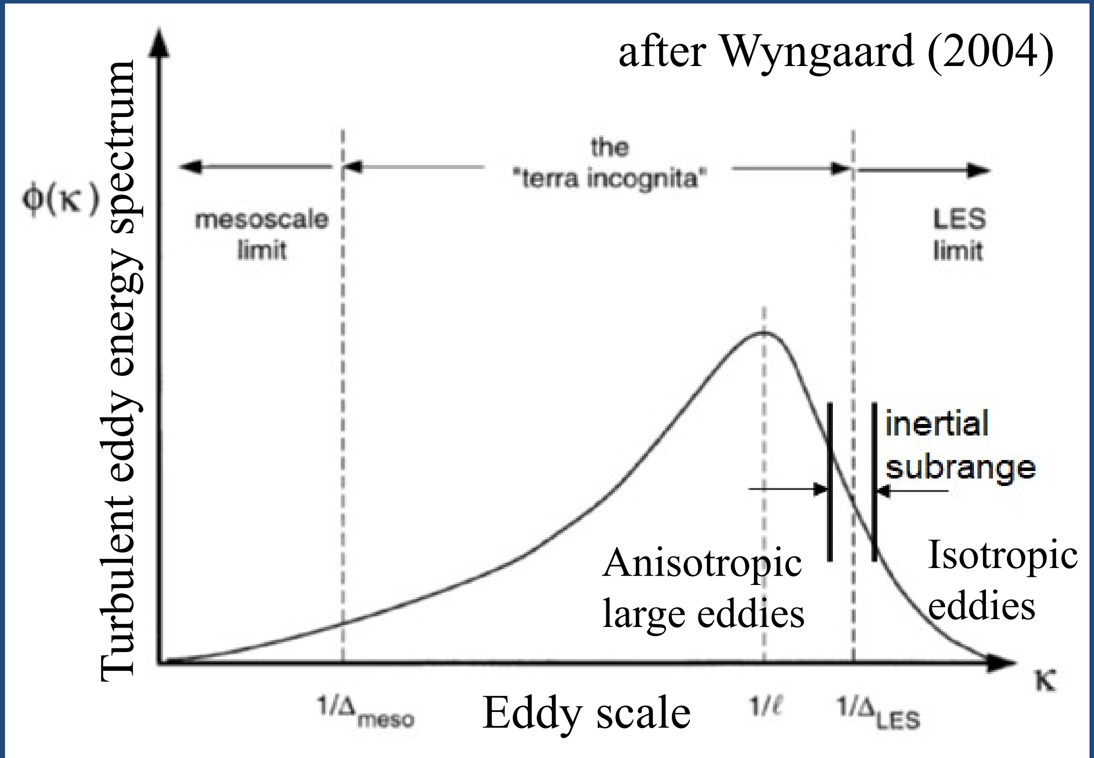




- Turbulent eddies experience large lateral contrast across the edge of the eyewall to generate inter-connected comparable horizontal and vertical turbulent mixing.
- The later entrainment instability promotes the TKE generation in the eyewall, which ensue causes more low-θ_e moat air to be entrained into the eyewall.
- The unique turbulent transport in the TC inner core poses a problem for the separated vertical and horizontal turbulence parameterization.

Background

Parameterization of turbulent mixing in the gray zone



- Large eddies are generated by the instabilities of the mean flow and fundamentally anisotropic.
- Eddies smaller than inertial subrange are isotropic.
- In large-eddy simulations (LES), the unresolved small-scale turbulence needs to be treated three dimensionally under the isotropic assumption.
- In mesoscale simulations (MS), the large anisotropic turbulence is currently handled by the separated vertical and horizontal turbulence schemes.

- What about turbulent mixing when model grid resolution falls in the gray zone? The purely 1D column parameterization framework becomes a problem.
- The physics-dynamics coupling becomes important as model resolution falls in the gray zone. The "separation" between physics and model dynamics becomes an obstacle to model development.

A scale-aware (SA) 3D TKE turbulence scheme bridging the gap between the LES and MS limits

(a) 3D TKE budget equation

$$\frac{de}{dt} = -\overline{u_i'u_j'}\frac{\partial \bar{u}_i}{\partial x_j} + \delta_{i3}\frac{g}{\overline{\theta_v}}\overline{u_i'\theta_v'} - \frac{\partial \overline{u_i'\left(e+\frac{p'}{\bar{\rho}}\right)}}{\partial x_i} - \varepsilon$$

Shear production | Buoyancy production | 3D TKE trans. & Press. Corr. | TKE dissipation

In 1D PBL scheme,

$$\frac{de}{dt} = -\overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \overline{v'w'}\frac{\partial \bar{v}}{\partial z} + \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \frac{\partial \overline{w'\left(e+\frac{p'}{\bar{\rho}}\right)}}{\partial z} - \varepsilon$$

(b) Turbulence closure in a TKE scheme

$$\overline{u_i'u_j'} = -K_{ij}^M\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) + \overline{u_i'u_j'}^{NL}; \quad \overline{u_i'\varphi'} = -K_i^H\frac{\partial \bar{\varphi}}{\partial x_i} + \delta_{i3}\overline{u_i'\varphi'}^{NL};$$

NL: nonlocal mixing

$$K_{m,ij} = c_m l_{ij}\sqrt{e};\ K_{h,i} = c_h l_i\sqrt{e};$$

(c) LES limit ($\Delta \ll l_e$), $\overline{u_i'u_j'}^{NL} \to 0;\quad \overline{u_i'\varphi'}^{NL} \to 0;\ K_{m,ij} \to K_{m,LES} = c_{LES}l_{LES}\sqrt{e};\ K_{h,i} \to K_{h,LES} = c_{LES}l_{LES}\sqrt{e}$

(d) MS limit ($\Delta \gg l_e$),

V:

$$\overline{u'w'}\left(\overline{v'w'}\right) = -K_{m,MS}^V\frac{\partial \bar{u}}{\partial z}\left(\frac{\partial \bar{v}}{\partial z}\right) + \overline{u'w'}^{NL}\left(\overline{v'w'}^{NL}\right),$$

$$\overline{w'\theta_v'} = -K_{h,MS}^V\frac{\partial \overline{\theta_v}}{\partial z} + \overline{w'\theta_v'}^{NL},\ K_{mh,MS}^V = S_m(S_h)l\sqrt{e}$$

H:

$$\overline{u_i'u_j'} = -K_{m,MS}^H\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right), i,j = 1,2$$

$$\overline{u'\theta_v'}\left(\overline{v'\theta_v'}\right) = -K_{h,MS}^H\frac{\partial \overline{\theta_v}}{\partial x}\left(\frac{\partial \overline{\theta_v}}{\partial y}\right),\ K_{mh,MS}^H = C_m(C_h)l\sqrt{e}$$

(e) Transitioning a 3D TKE scheme from the LES limit to the MS limit. Defining a partition function $P_L(\Delta/z_i)$ for local fluxes (Zhang et al. 2018), where z_i is the diagnosed BL height and Δ grid spacing, such that

$$\text{at the LES limit } (\Delta \ll z_i), \qquad P_L(\Delta/z_i) = 0;$$

$$\text{at the MS limit } (\Delta \gg z_i), \qquad P_L(\Delta/z_i) = 1.$$

$P_L(\Delta/z_i)$, then, is used to blend the horizontal and vertical eddy exchange coefficients for a model in the gray zone,

$$\begin{cases} K^V_{m,ij,\Delta} = K^V_{m,MS} P_L(\Delta/z_i) + K_{m,LES}\,[1 - P_L(\Delta/z_i)] \\ K^V_{h,ij,\Delta} = K^V_{h,MS} P_L(\Delta/z_i) + K_{h,LES}[1 - P_L(\Delta/z_i)] \end{cases}, \qquad \begin{cases} K^H_{m,ij,\Delta} = K^H_{m,MS} P_L(\Delta/z_i) + K_{m,LES}\,[1 - P_L(\Delta/z_i)] \\ K^H_{h,ij,\Delta} = K^H_{h,MS} P_L(\Delta/z_i) + K_{h,LES}[1 - P_L(\Delta/z_i)] \end{cases}.$$

Similar blending method is applied to the non-local fluxes by defining a partition function $P_{NL}(\Delta/z_i)$ such that at the LES ($\Delta \ll z_i$) and MS ($\Delta \gg z_i$) limits, $P_{NL}(\Delta/z_i) = 0$ and 1, respectively. Then, the non-local flux for a model in the gray zone may be expressed as,

$$\overline{w'\varphi'}^{\Delta,NL} = \overline{w'\varphi'}^{NL} P_{NL}(\Delta/z_i), \qquad \overline{w'\vec{V}'}^{\Delta,NL} = \overline{w'\vec{V}'}^{NL} P_{NL}(\Delta/z_i).$$

The non-local fluxes $\overline{w'\varphi'}^{NL}$ and $\overline{w'\vec{V}'}^{NL}$ at the MS limit are determined by the mass-flux approach.

(f) Implementation of the SA 3D TKE scheme in HAFS.

The main body of the SA 3D TKE scheme is placed in the CCPP, but the TKE shear production tensor and 3D TKE transport are calculated in the dynamic solver and transferred to the CCPP.

(e) Transitioning a 3D TKE scheme from the LES limit to the MS limit by defining a partition function $P_L(\Delta/z_i)$ for local fluxes (Zhang et al. 2018), where z_i is the diagnosed BL height, such that

at the LES limit ($\Delta \ll z_i$), $\quad P_L(\Delta/z_i) = 0;$

at the MS limit ($\Delta \gg z_i$), $\quad P_L(\Delta/z_i) = 1.$

$P_L(\Delta/z_i)$, then, is used to blend the horizontal and vertical eddy exchange coefficients for a model in the gray zone,

$$\begin{cases} K^M_{ij,\Delta} = K^M_{MS,z} P_L\,(\Delta/z_i) + K^M_{LES}[1 - P_L(\Delta/z_i)] \\ K^H_{ij,\Delta} = K^H_{MS,z} P_L(\Delta/z_i) + K^H_{LES}[1 - P_L(\Delta/z_i)] \end{cases}.$$

Similar blending method can be applied to the non-local fluxes by defining a partition function $P_{NL}(\Delta/z_i)$ such that at the LES ($\Delta \ll z_i$) and MS ($\Delta \gg z_i$) limits, $P_{NL}(\Delta/z_i) = 0$ and 1, respectively. Then, the non-local flux for a model with grid spacing Δ in the gray zone may be expressed as,

$$\overline{w'\varphi'}^{\Delta,NL} = \overline{w'\varphi'}^{NL} P_{NL}(\Delta/z_i), \qquad \overline{w'\vec{V}'}^{\Delta,NL} = \overline{w'\vec{V}'}^{NL} P_{NL}(\Delta/z_i).$$

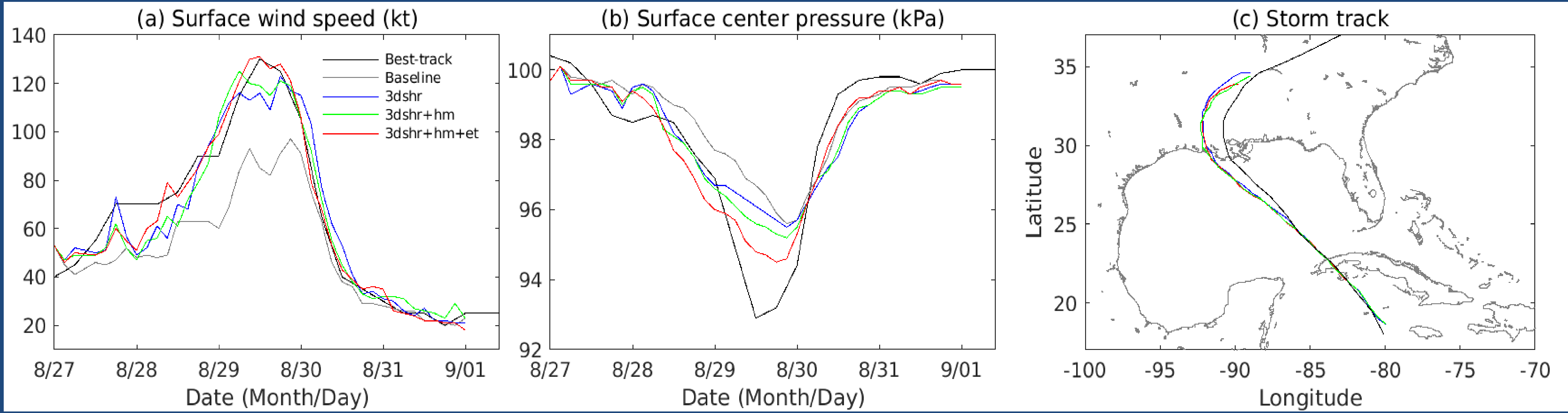
The non-local fluxes $\overline{w'\varphi'}^{NL}$ and $\overline{w'\vec{V}'}^{NL}$ at the MS limit are determined by the mass-flux approach.

(f) Implementation of the scale-aware 3D TKE scheme in HAFS.

The main body of the scale-aware 3d TKE scheme in the CCPP, but the TKE shear production tensor and 3D TKE transport will be calculated in the dynamic solver and transfer them to CCPP.

Initial results

HAFS's simulated track and intensity of Hurricane Ida (2021) compared with observations



Black line: the best-track; Gray line: baseline HAFS simulation; Blue line: HAFS simulation that considers 3D TKE shear production only; Green line: HAFS simulation that considers 3D TKE shear production and horizontal mixing parameterized using the predicted TKE;

Red line: HAFS simulation that considers 3D TKE shear production, TKE based horizontal mixing, and 3D TKE transport and pressure correlation.

Summary

- The purely one-dimensional vertical column framework for parameterizing vertical turbulent mixing and the separated inconsistent horizontal and vertical turbulence parameterization pose an obstacle for a realistic representation of the three-dimensional turbulent transport in the TC inner core.
- A scale-aware 3D TKE scheme shows a promising result to improve HAFS's skill in predicting TC intensity.

Future Work

- Conducting sensitivity tests to evaluate the scale-aware 3D turbulence scheme for various resolution settings, and further refining and tuning the scheme.
- Validating the HAFS simulations of historical hurricane cases against observations.
- Performing real-time TC forecasts during the Atlantic hurricane seasons.