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

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# Outline

- Parameterization of turbulent transport and hydrometeor sedimentation in the eyewall.
- Pathway to rapid intensification (RI).

# 1. Turbulent processes in the eyewall and their parameterization

- Turbulence can be generated by the buoyancy production in eyewall clouds.
- There is no physical interface to separate it from the turbulence in the boundary layer.

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

- HWRF and HAFS use $N^2 = \frac{g}{\theta_v}\frac{\partial \theta_v}{\partial z}$ to calculate static stability, but it provides a very poor estimate of the real stability in the eyewall.

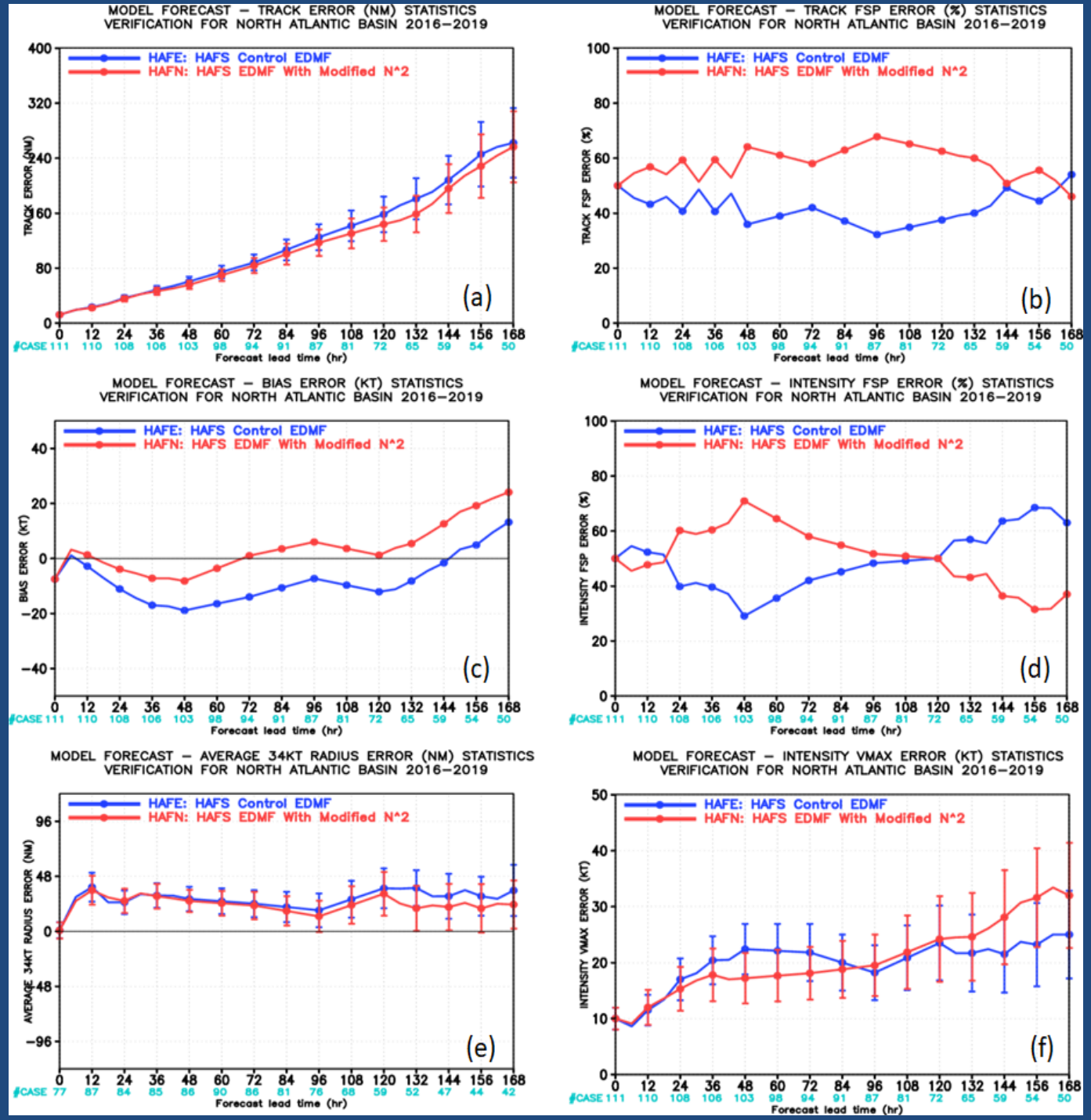
- For the saturated atmosphere containing mixed-phase clouds:

$$N^2 \approx g\left\{\left(1+\frac{l_m q_s^e}{R_d T^e}\right)\frac{1}{T^e}\left(\frac{\partial T^e}{\partial z}+\Gamma_m\right)-\frac{1}{1+q_t^e}\frac{\partial q_t^e}{\partial z}\right\}$$

$$\Gamma_m = -\frac{\partial T^p}{\partial z} = \frac{g}{C_{pd}}\cdot\frac{(1+q_t^e)\left(1+\frac{l_s q_s^p}{R_d T^p}\right)+\frac{l_f}{g}\frac{\partial q_w^p}{\partial z}}{1+\frac{C_{pv}q_s^p+C_w q_w^p+C_i q_i^p}{C_{pd}}+\frac{(\epsilon+q_s^p)l_s l_m q_s^p}{C_{pd}R_d T^{p2}}}, \quad l_m = \frac{\delta E_w l_v+(1-\delta)E_i l_s}{E}$$

- For eyewall clouds, it is important to consider the effects of multi-phase water (moisture, liquid, and solid) on static stability.

# Testing the stability correction in Global-nested HAFS (HAFS-B)



# Combining stability correction with Mellor & Yamada level 2 TKE scheme

The scheme has been implemented in the latest HAFS-SAR (HAFS-A)

Two new options in the HEDMF physics suite:

- Option-1 "bvf_pbl" activates the stability correction but retains the default HEDMF PBL scheme.
- Option-2 "bvftke_pbl" activates the TKE scheme plus static stability correction.

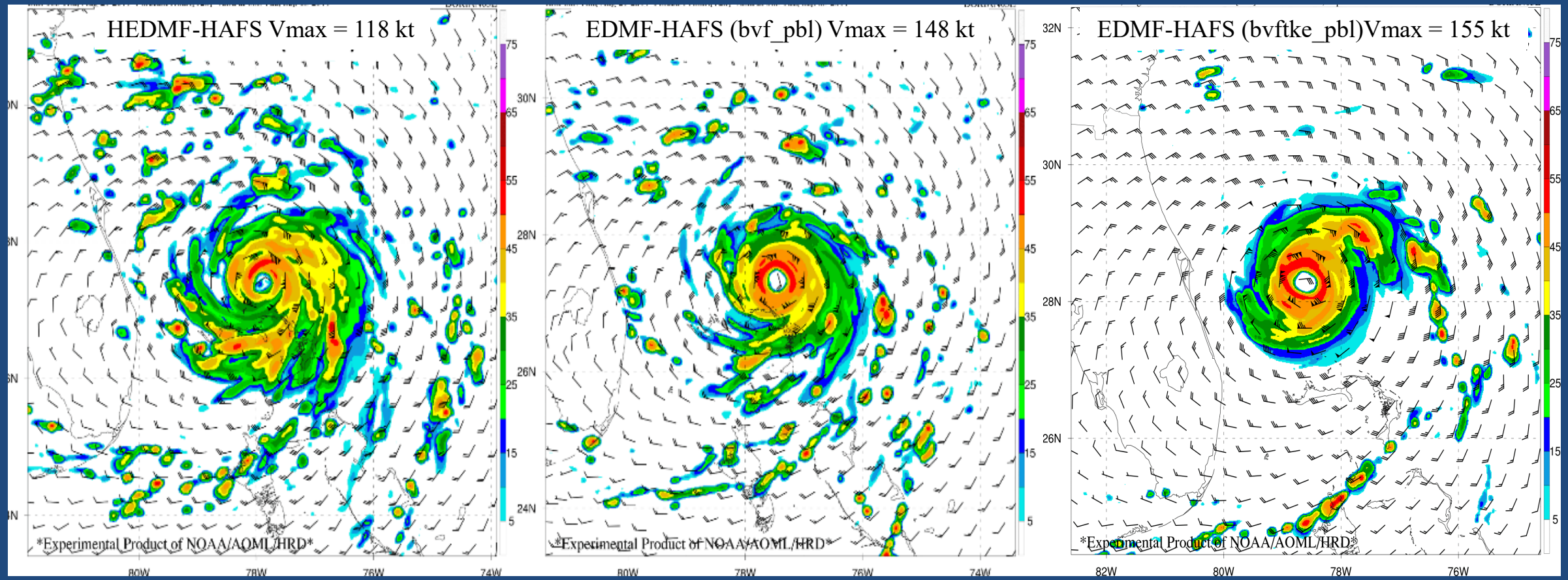
# Testing the new schemes in the latest HAFS-SAR (HAFS-A)

2019082900 (Hurricane Dorian):

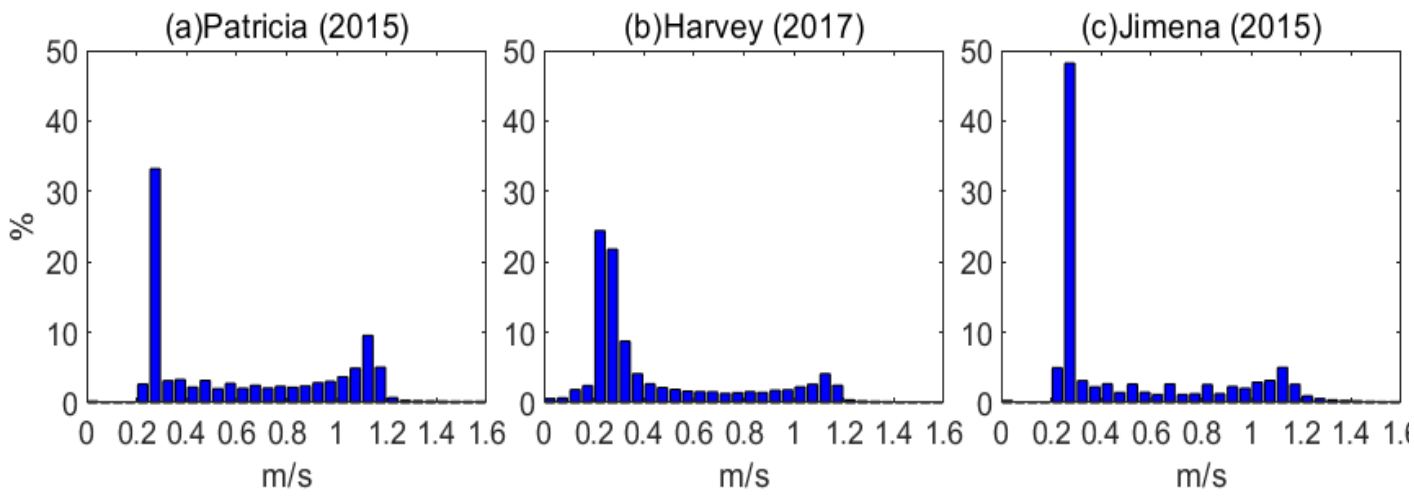
| | | |
|---|---|---|
| HEDMF: | 118 kt, | 943 hPa |
| HEDMF (bvf_pbl): | 148 kt, | 923 hPa |
| HEDMF (bvftke_pbl): | 155 kt, | 918 hPa |
| Best-track: | 160 kt, | 910 hPa |

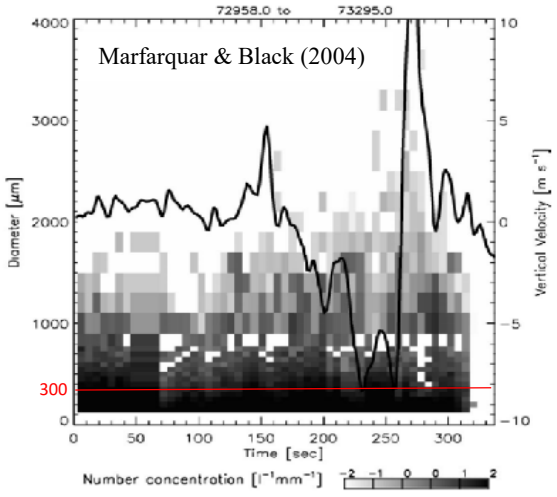
2020082406 (Hurricane Laura):

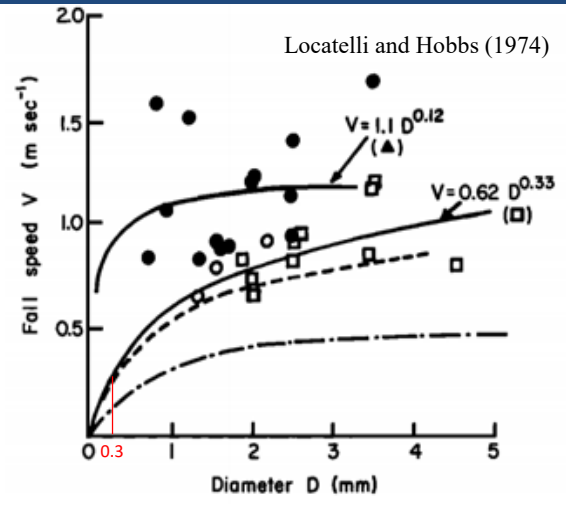
| | | |
|---|---|---|
| HEDMF: | 117 kt, | 948 hPa |
| HEDMF (bvf_pbl): | 133 kt, | 933 hPa |
| HEDMF (bvftke_pbl): | 120 kt, | 945 hPa |
| Best-track: | 130 kt, | 937 hPa |

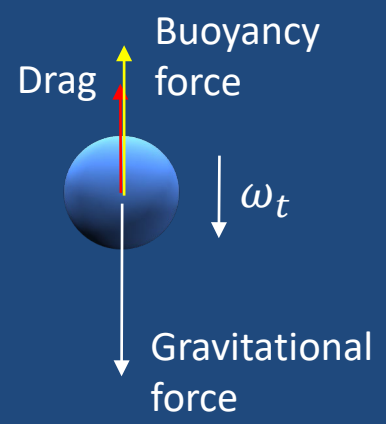


# 2. Hydrometeor sedimentation in the eyewall and its parameterization




**Quiescent condition**

$$\frac{1}{2}\rho_e C_D A_h \omega_t^2 = V_h(\rho_h - \rho_e)g,$$

$C_D = f(R_e)$, $R_e = \frac{\omega_t d_n}{\nu}$: Reynolds number

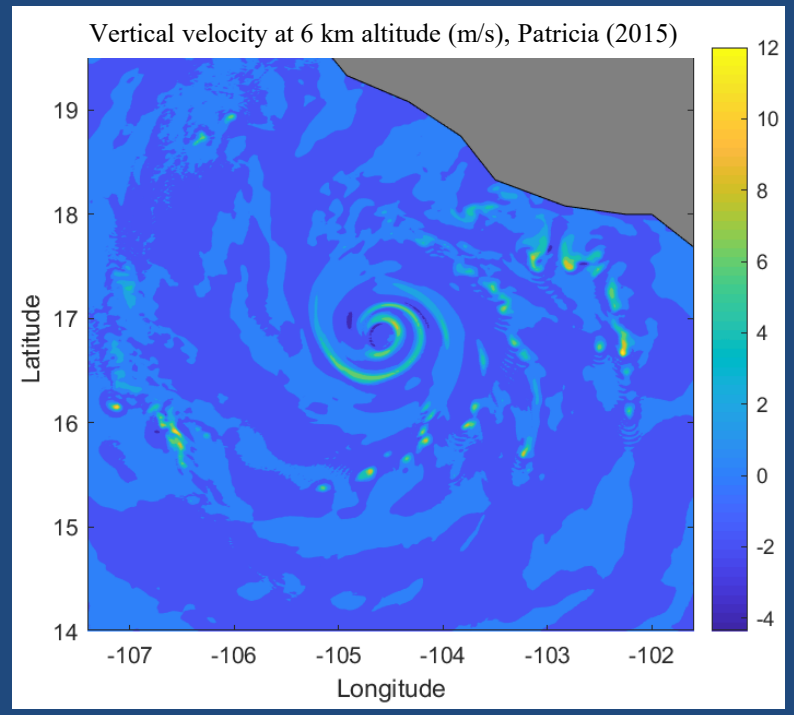
Assume: $R_e(X) = aX^b$, Mitchell (1996)

$X = C_D R_e^2$: Davies number

$\rho_h V_h = \alpha d_n^\beta$, $A_h = \gamma d_n^\varepsilon$.

$\omega_t = E_v d_n^{F_v}$, $d_n$: equivalent diameter

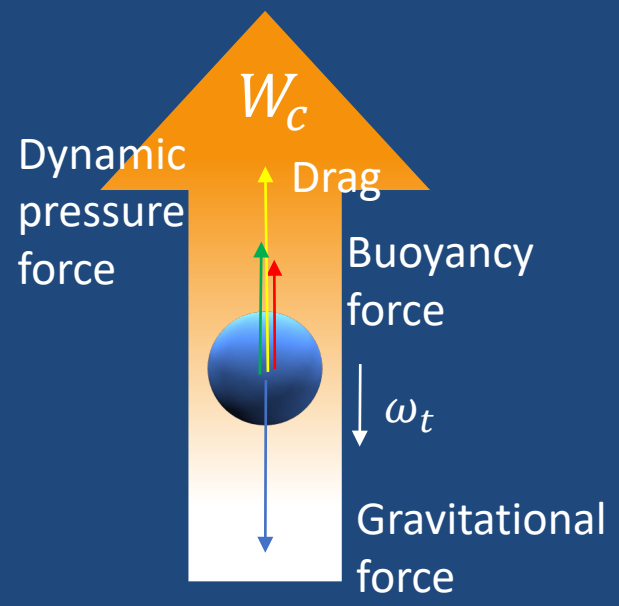
$E_v = a\nu^{1-2b}[\frac{2\lambda g}{\gamma}(\frac{\rho_h}{\rho_e} - 1)]^b$ and $F_v = (\beta - \varepsilon)b + 2b - 1$




Quiescent condition is NOT valid in the eyewall!

# Hydrometeor Particle Fall Speed in a non-quiescent condition

Particle fall speed is governed by a four-force balance among the gravitational, buoyancy, drag, and dynamic pressure force resulting from the convective currents.




$$\frac{1}{2}\rho_e C_D A_h (W_c - \omega_t)^2 + \frac{1}{2}\rho_e A_h (W_c - \omega_t)^2 = V_h(\rho_h - \rho_e)g$$

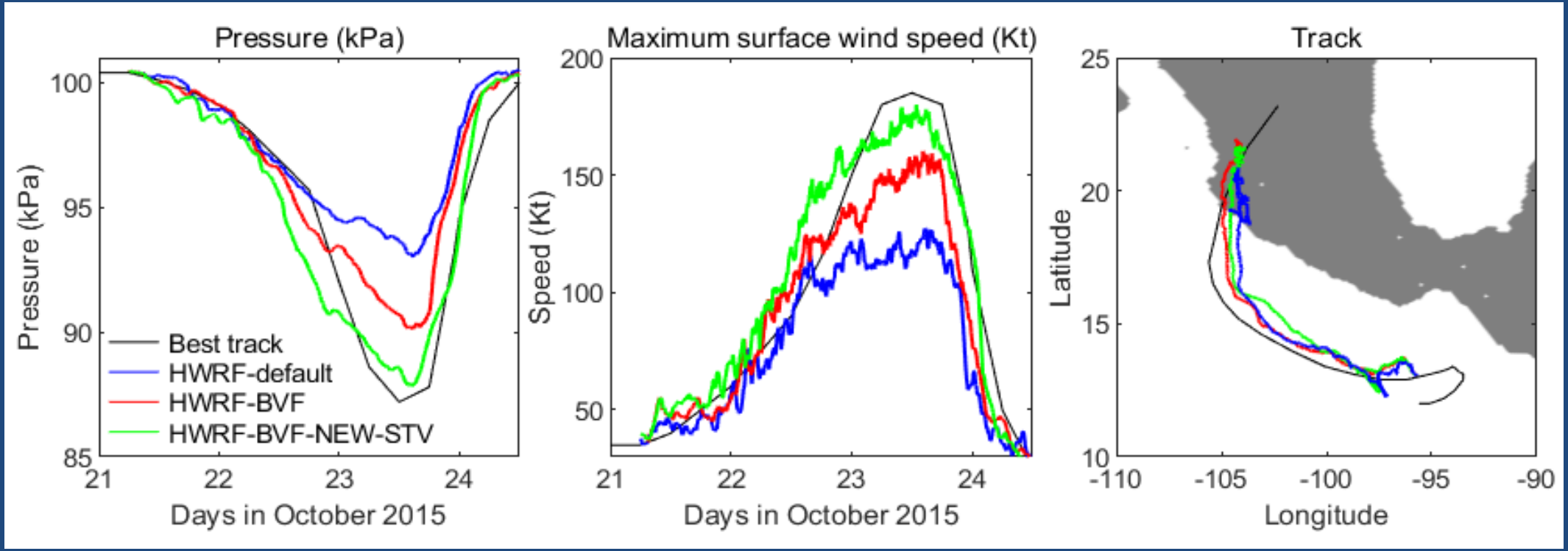
$$(W_c - \omega_t)^2 = \frac{2V_h(S-1)g}{(C_D+1)A_h} = \frac{4(S-1)g}{3(C_D+1)} d_n, \qquad S = \frac{\rho_h}{\rho_e}, \qquad d_n = (V_h)^{1/3}$$

$$C_D = f(R_e), \qquad R_e = \frac{|W_c - \omega_t| d_n}{\nu}$$

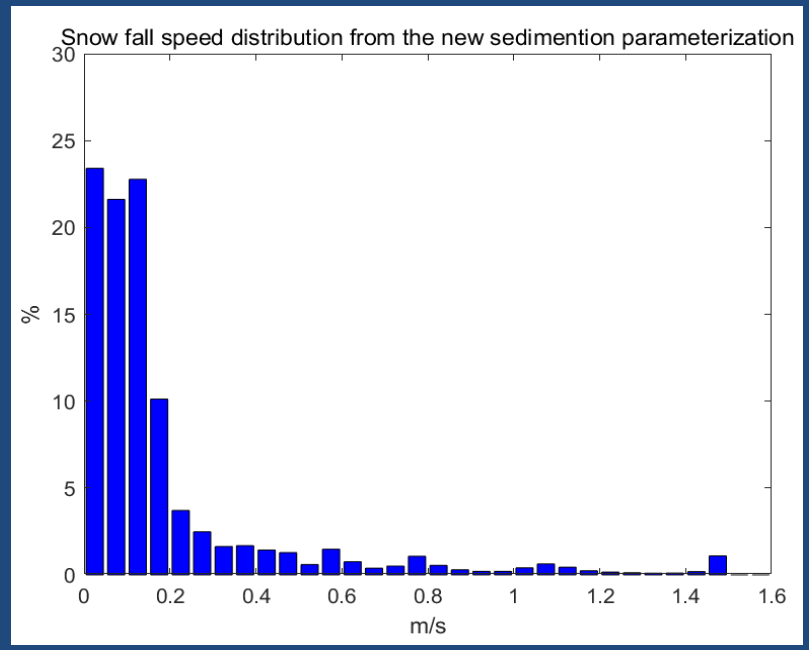
$$C_D = \left[(M/R_e)^{1/\xi} + N^{1/\xi}\right]^{\xi} \text{ (Cheng, 1997)}, \quad \begin{cases} C_D = M/R_e, & R_e \to 0 \\ C_D = N, & R_e \to \infty \end{cases} \quad \text{(Stokes, 1851)}$$

$$|W_c - \omega_t| = \frac{M\nu}{N d_n}\left[\sqrt{\frac{1}{4} + \left(\frac{4N}{3M^2} D_*^3\right)^{1/\xi}} - \frac{1}{2}\right]^{\xi}, \qquad D_* = d\left[\frac{(S-1)g}{\nu^2}\right]^{1/3}$$

$M = 32$ (Raudkivi, 1990; Cheng, 1997), $N = 2.1$ (Camenen B. 2007), and $\xi = 2.0$ (Dallavalle, 1948).



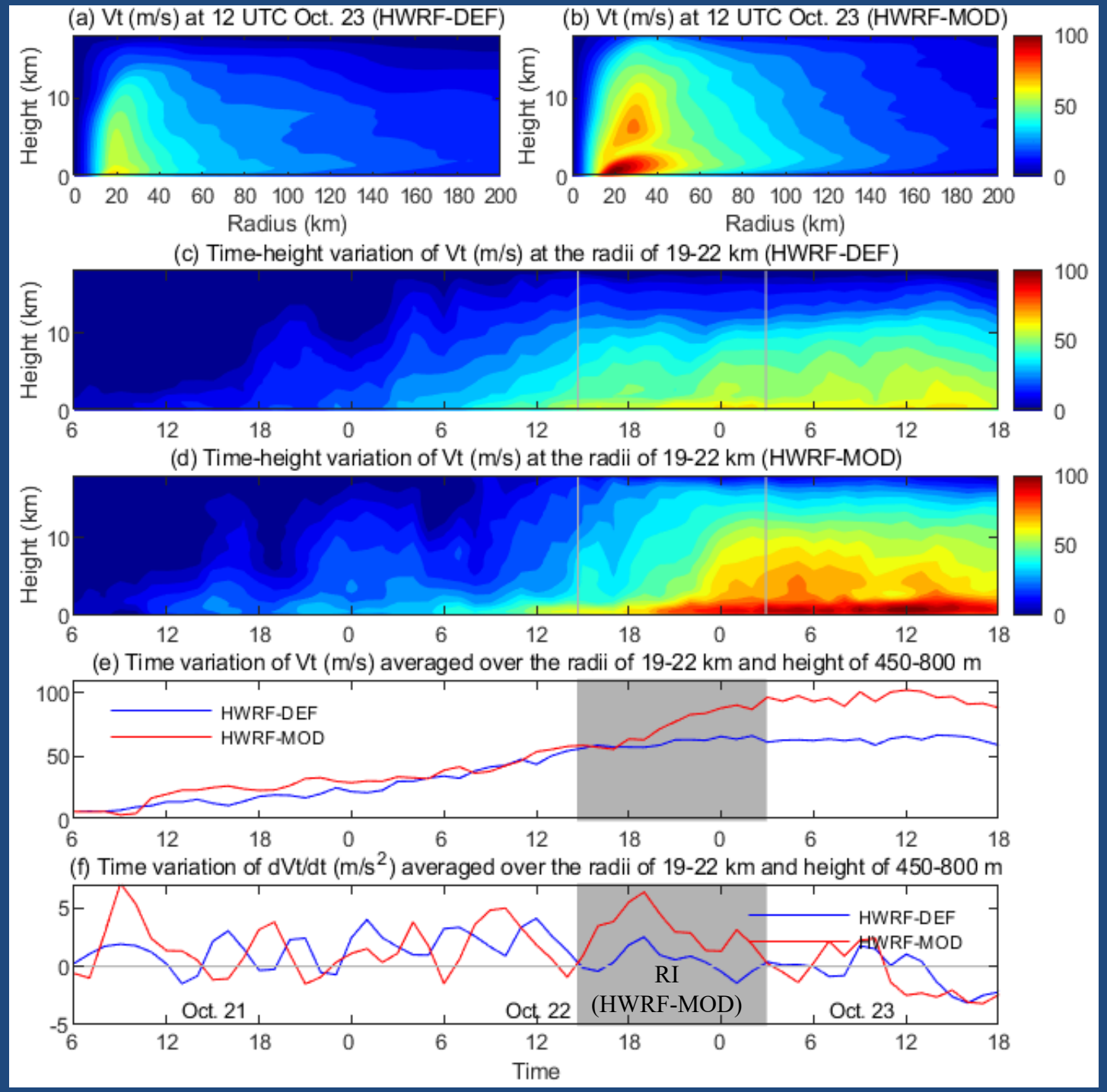

Storm sea-level central pressure, maximum surface wind speed, and track of Patricia (2015) simulated by the default HWRF, the modified HWRF with the BVF correction alone, and the modified HWRF with the new particle fall speed parameterization plus stability correction compared with the NHC best-track data.




Histogram of hydrometeor fall speeds ($ms^{-1}$) from the HWRF simulation of Patricia (2015)

# 3. Pathway to TC Intensification

- Why does Patricia stop intensifying in the default HWRF simulation?
- What triggers and causes the RI of Patricia in the modified HWRF simulation?



# Azimuthal-mean tangential wind budget

$$\frac{\partial \bar{v}}{\partial t} = -\bar{u}\frac{\partial \bar{v}}{\partial r} - \bar{w}\frac{\partial \bar{v}}{\partial z} - \bar{u}\left(f + \frac{\bar{v}}{r}\right) - \overline{u'\frac{\partial v'}{\partial r}} - \overline{v'\frac{\partial v'}{r\partial \lambda}} - \overline{w'\frac{\partial v'}{\partial z}} - \frac{\overline{u'v'}}{r} + D_{sgs\_\lambda}.$$

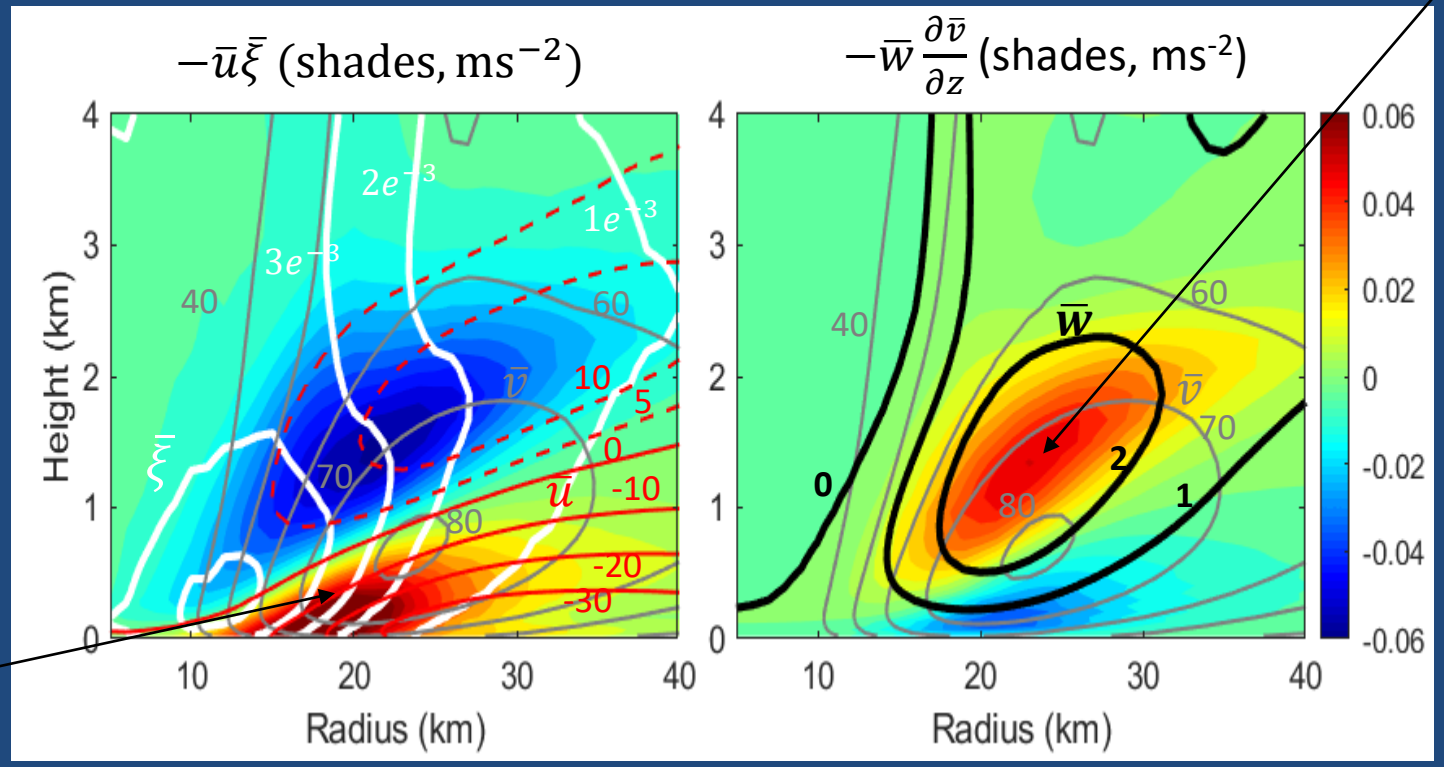
Relative vorticity: $\zeta = \frac{\partial v}{\partial r} + \frac{v}{r}$; Absolute vorticity: $\xi = \frac{\partial v}{\partial r} + \frac{v}{r} + f$

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

$\bar{w} > 0, \frac{\partial \bar{v}}{\partial z} < 0 \rightarrow -\bar{w}\frac{\partial \bar{v}}{\partial z} > 0$

$-\bar{u}\bar{\xi}$ (inward transport of mean absolute vorticity) accelerates the tangential winds inside the inflow layer.

$\bar{u} < 0, \bar{\xi} > 0 \rightarrow -\bar{u}\bar{\xi} > 0$



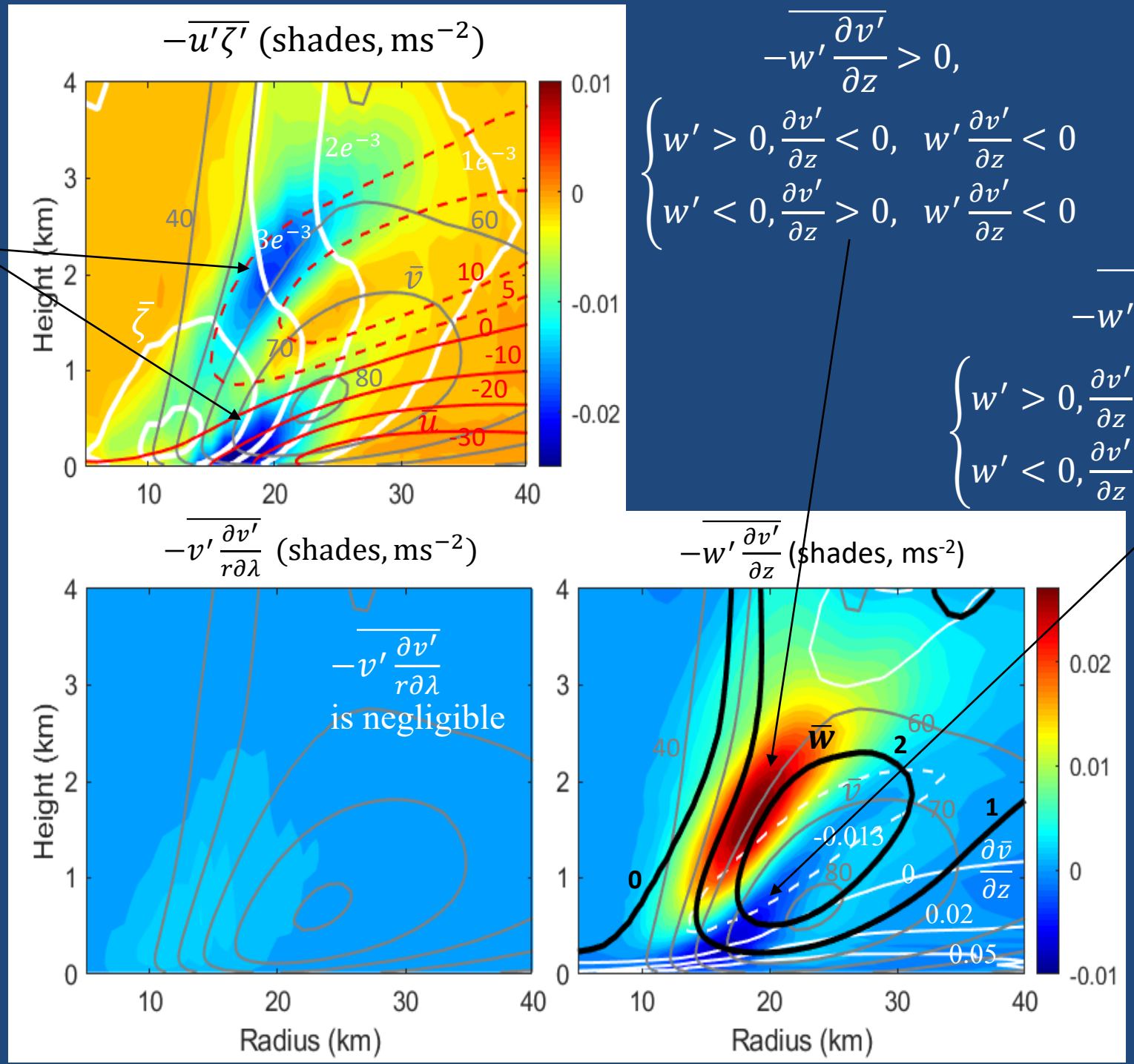

Averaged over 15 UTC, 22 – 3 UTC, 23 Oct. from the HWRF-MOD

# Eddy forcing terms

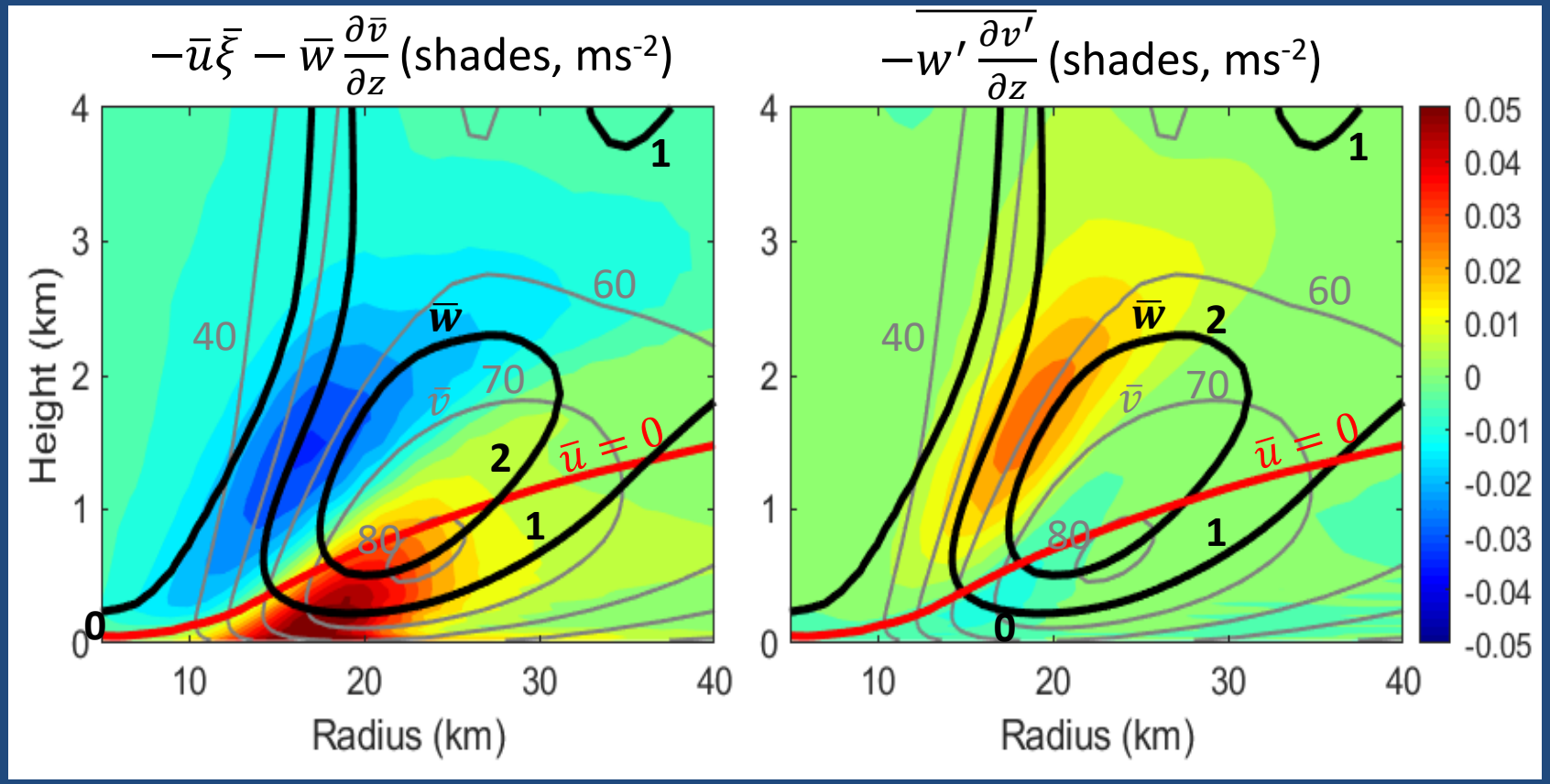
$$-\overline{u'\zeta'} < 0,$$
$$\begin{cases} u' > 0, \zeta' > 0, \quad u'\zeta' > 0 \\ u' < 0, \zeta' < 0, \quad u'\zeta' > 0 \end{cases}$$

$$-\overline{w'\frac{\partial v'}{\partial z}} > 0,$$
$$\begin{cases} w' > 0, \frac{\partial v'}{\partial z} < 0, \quad w'\frac{\partial v'}{\partial z} < 0 \\ w' < 0, \frac{\partial v'}{\partial z} > 0, \quad w'\frac{\partial v'}{\partial z} < 0 \end{cases}$$

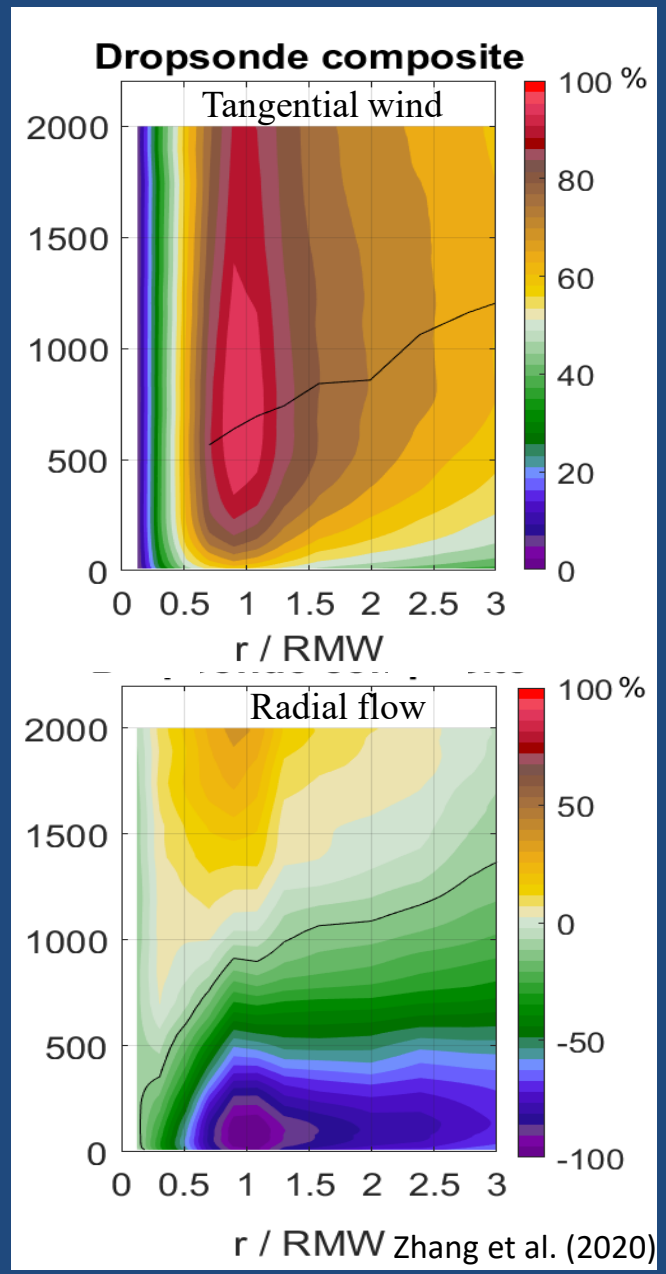
$$-\overline{w'\frac{\partial v'}{\partial z}} < 0,$$
$$\begin{cases} w' > 0, \frac{\partial v'}{\partial z} > 0, \quad w'\frac{\partial v'}{\partial z} > 0 \\ w' < 0, \frac{\partial v'}{\partial z} < 0, \quad w'\frac{\partial v'}{\partial z} > 0 \end{cases}$$




$-\overline{w'\frac{\partial v'}{\partial z}}$ is the main eddy forcing term that may lead to the acceleration of tangential winds.

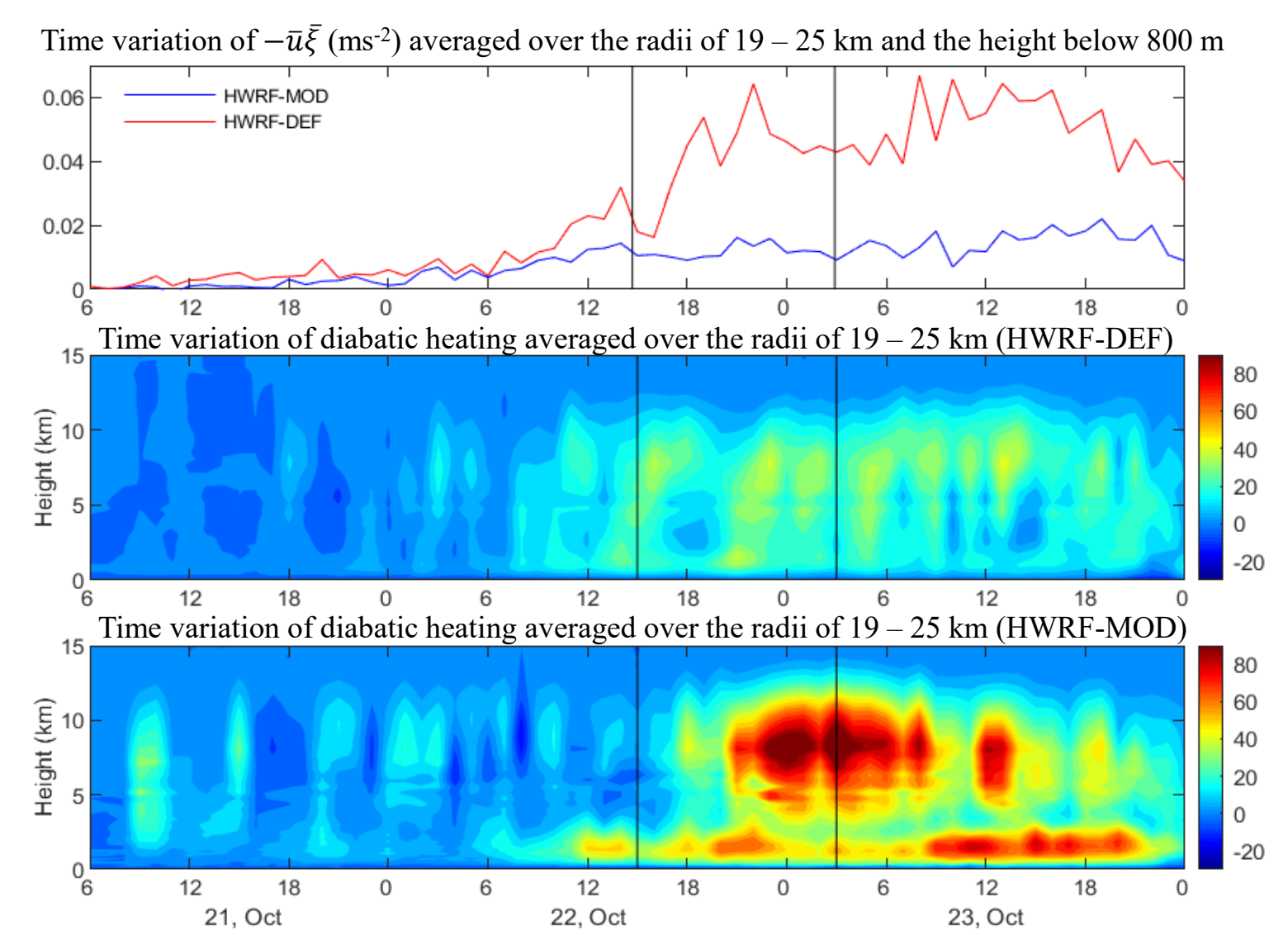



~ 800 dropsondes in 13 TCs




Zhang et al. (2020)

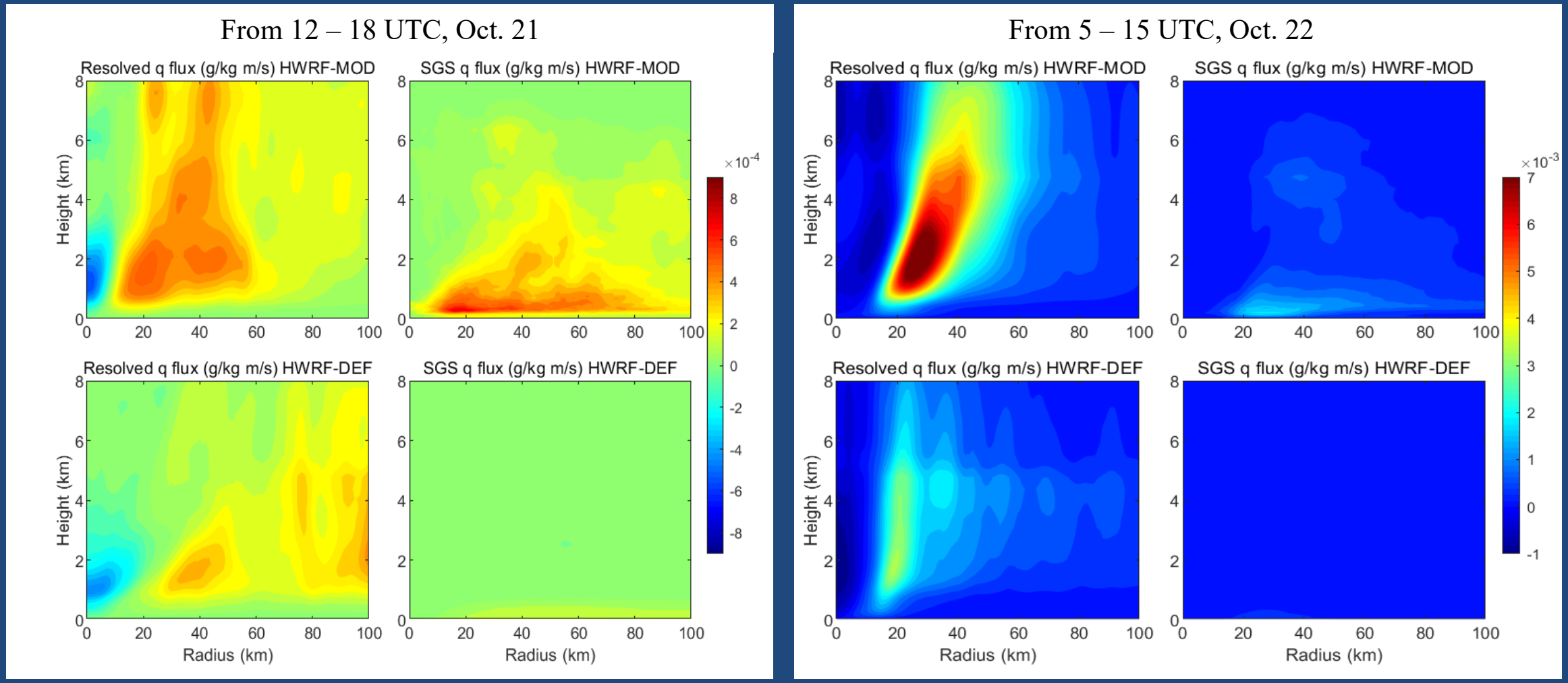
The acceleration induced by $-\overline{w'\frac{\partial v'}{\partial z}}$ above the inflow layer is overwhelmed by the deceleration caused by $-\bar{u}\bar{\xi}$. This leaves the inward transport of absolute vorticity inside the inflow layer to be the only driving force for acceleration of tangential winds, suggesting the importance of the mean secondary circulation induced by eyewall convection to TC intensification.




Eyewall convection must exceed a critical level. Below this level, the convection cannot generate sufficiently large inward transport of absolute vorticity to overcome the friction dissipation and other deceleration processes.

# Importance of SGS turbulent mixing to initiation of TC intensification

## Vertical moisture transport by the resolved and SGS processes




A successful simulation of an RI requires a robust interaction between the resolved and parameterized processes. The latter plays an important role in helping initiate the WISHE-like positive feedback underlying the RI.

# Summary

1. Our work focuses on building a robust interaction between physics modules and model-resolved fields. The static stability calculation in the PBL module now includes the input of liquid- and ice-phase hydrometeors from the microphysics module, and the hydrometeor sedimentation parameterization now includes the input of model-resolved convective currents. Such a direct link at a model time step shows a promising result to improve HFAS and HWRF's skill in predicting TC intensity.

2. Eyewall convection must exceed a critical level to generate sufficiently large inward transport of absolute vorticity to overcome friction dissipation and other deceleration processes. This requires a robust interaction between the resolved and parameterized SGS processes, the latter plays an important role in initiating the WISHE-like positive feedback leading to RI.