Updates on Improvement of HAFS Turbulent Mixing Schemes and Understanding of the Pathway to Rapid Intensification

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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.

- 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 stability (Brunt-Väisälä Frequency, BVF) correction in HAFS-B

Testing BVF correction and a new TKE scheme in HAFS-A

Two new options added in the latest 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.

Tested storms in 2018-2020 seasons in the Atlantic basin using HAFS-A:

CAT 3 – 5

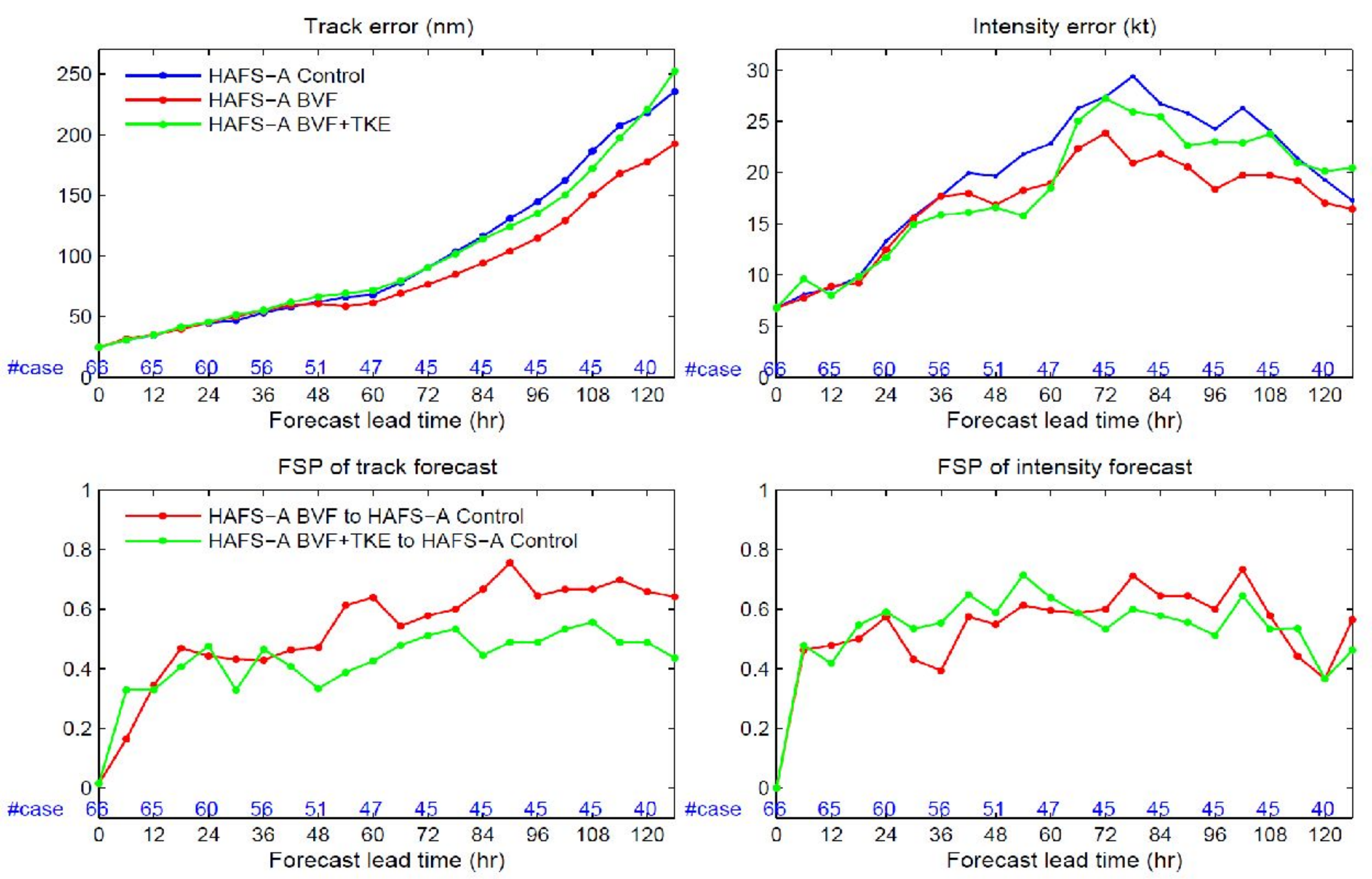
Delta 2020 (3); Dorian 2019 (7); Florence 2018 (4);
Humberto 2019 (2); Iota 2020 (3); Laura 2020 (5);
Michael 2018 (2); Teddy 2020 (2);

TS, CAT 1 – 2

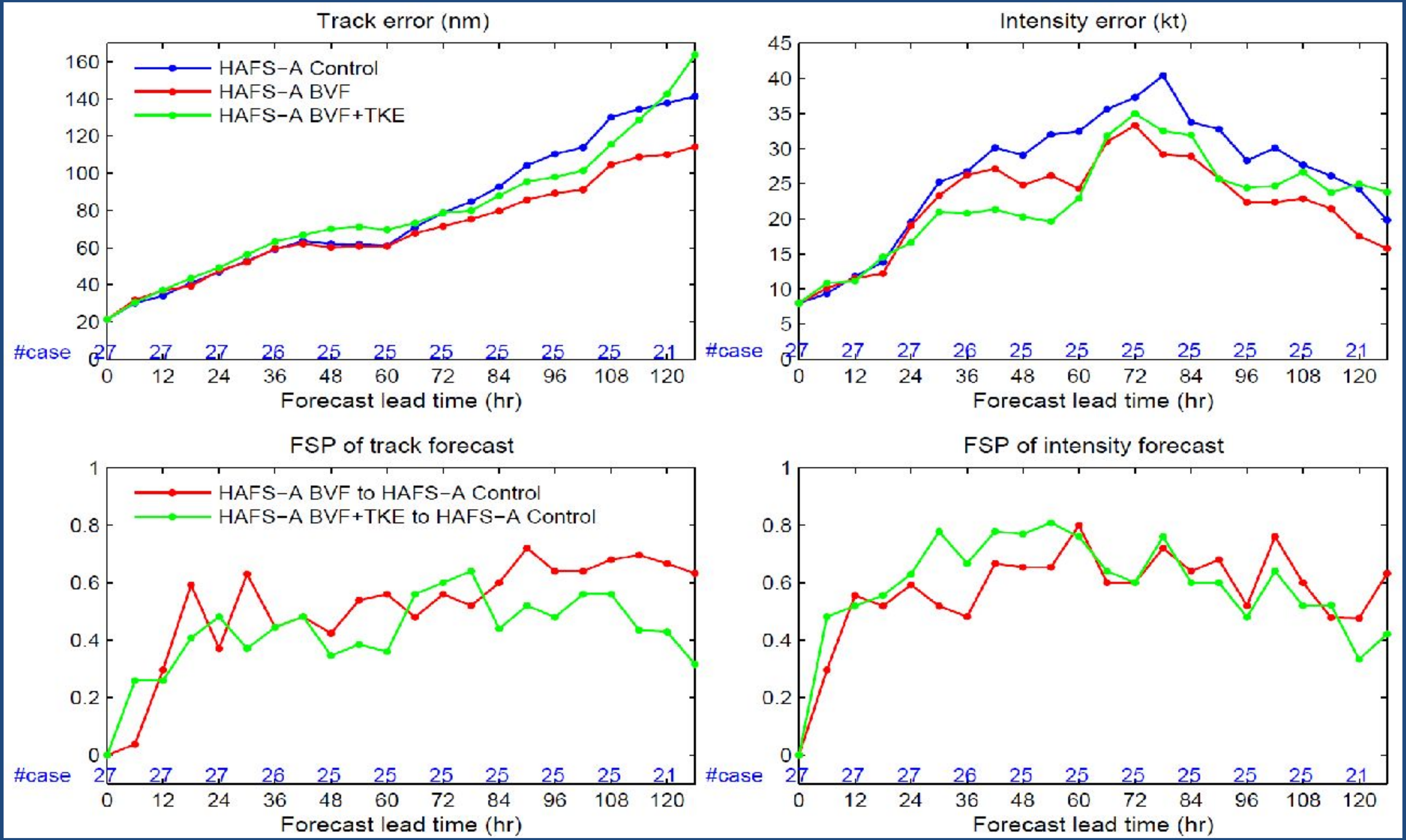
Erin 2019 (7); Gamma 2020 (3); Helene 2018 (2);
Imelda 2019 (2); Isaac 2018 (4); Isaias 2020 (3);
Jerry 2019 (2); Leslie 2018 (2); Marco 2020 (5);
Paulette 2020 (2); Rene 2020 (2); Sally 2020 (2);
Theta 2020 (3)

In total 68 cycles

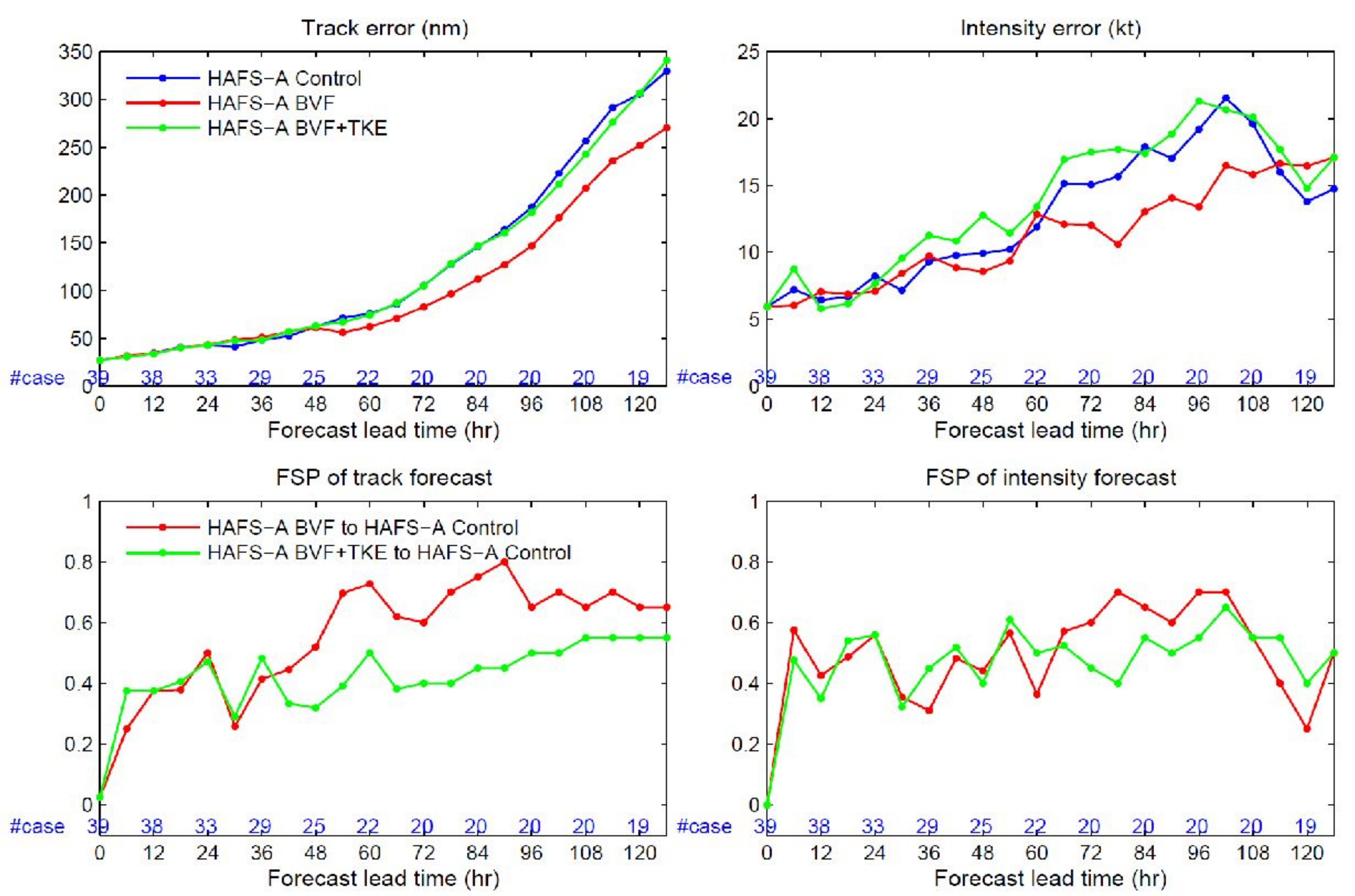
Model Forecast Verification (HAFS-A) for North Atlantic Basin 2018-2020



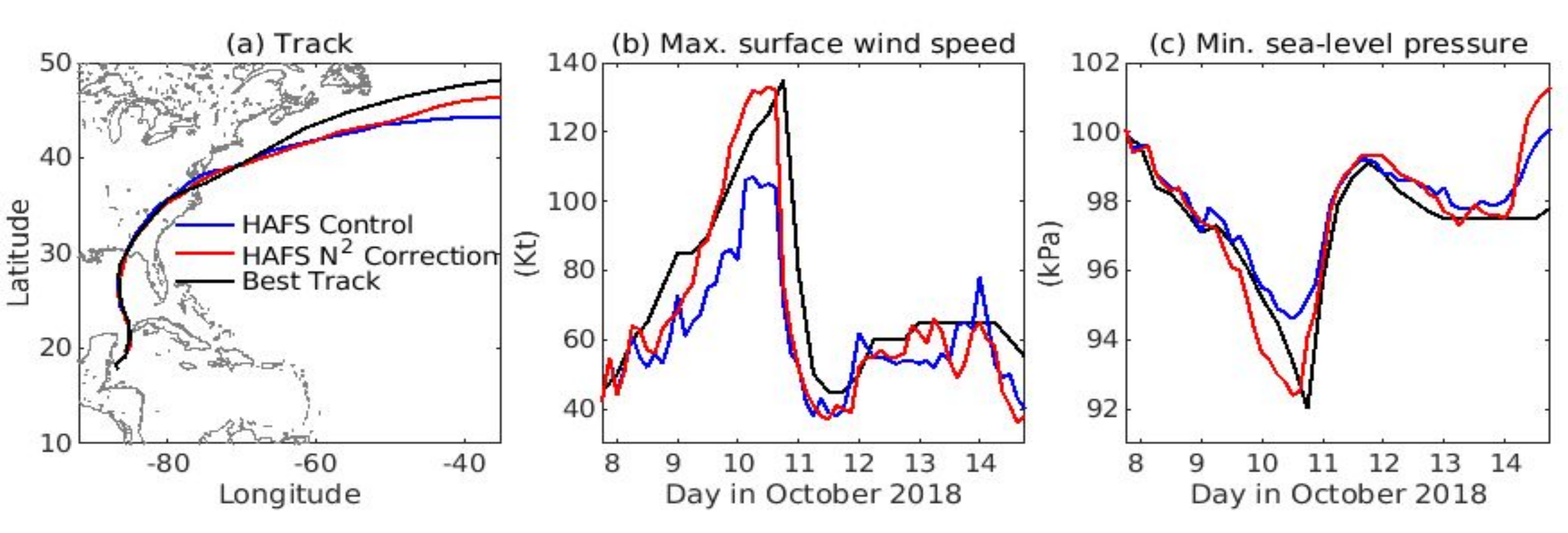
Model Forecast Verification for CAT 3-5 Storms



Model Forecast Verification for TS and CAT 1-2 Storms

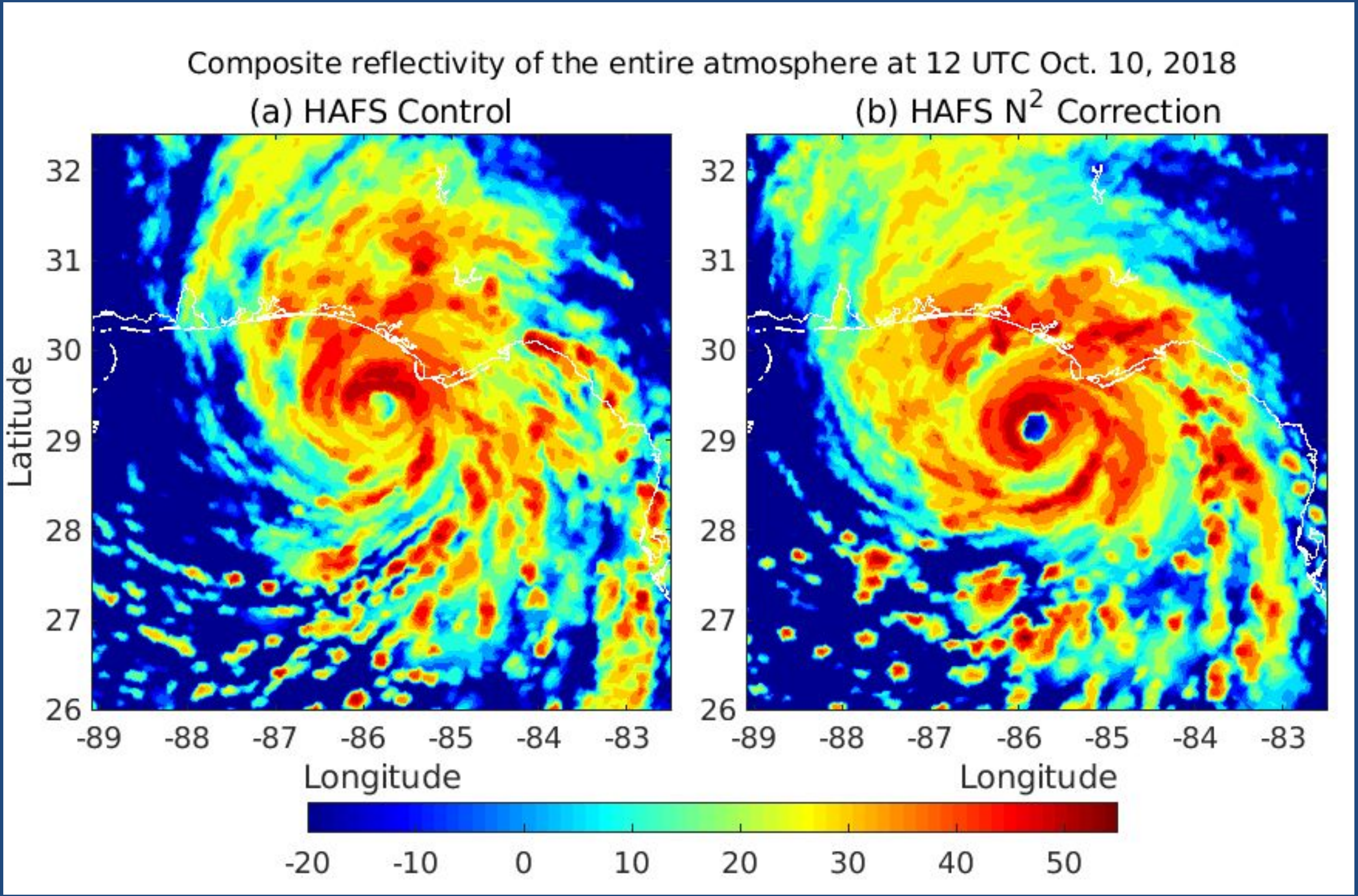


Pathway to TC Intensification

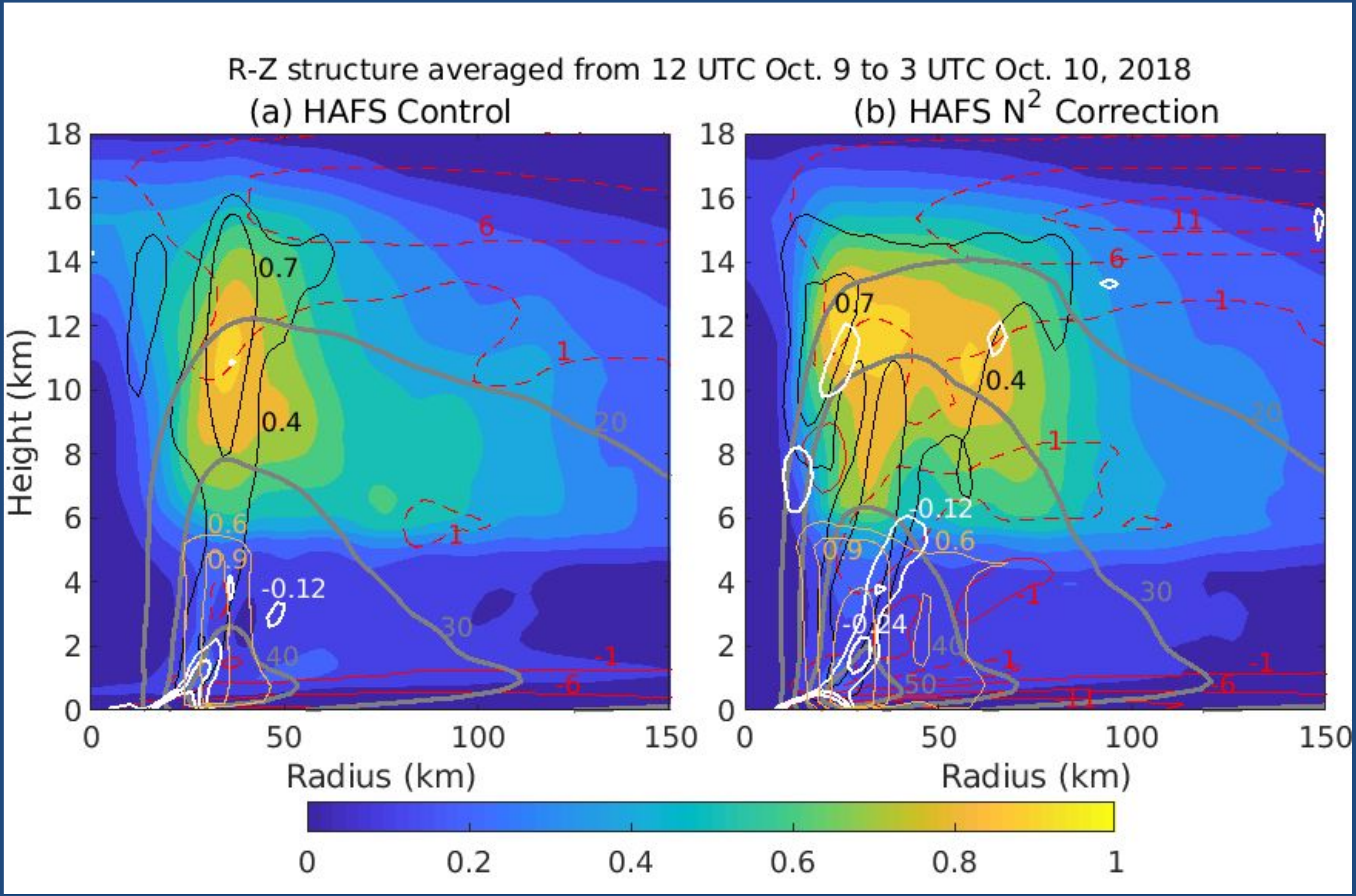


Hurricane Michael (2018) simulated by HAFS-B

- Why does Michael fail to reach the observed peak intensity in the default HAFS-B?
- What triggers and causes the RI of Michael in the modified HAFS-B?



Composite reflectivity of the entire atmosphere at 12 UTC Oct. 10, 2018
(a) HAFS Control
(b) HAFS N2 Correction
Latitude
32
31
30
29
28
27
26
Longitude
-89
-88
-87
-86
-85
-84
-83
-20
-10
0
10
20
30
40
50



Hydrometeor mixing ratio (shades); tangential wind (thick gray contours); radial inflow (red solid contours); radial outflow (red dashed contours); radial flow convergence (white contours); precipitation mixing ratio (brown contours)

Azimuthal-mean tangential wind budget

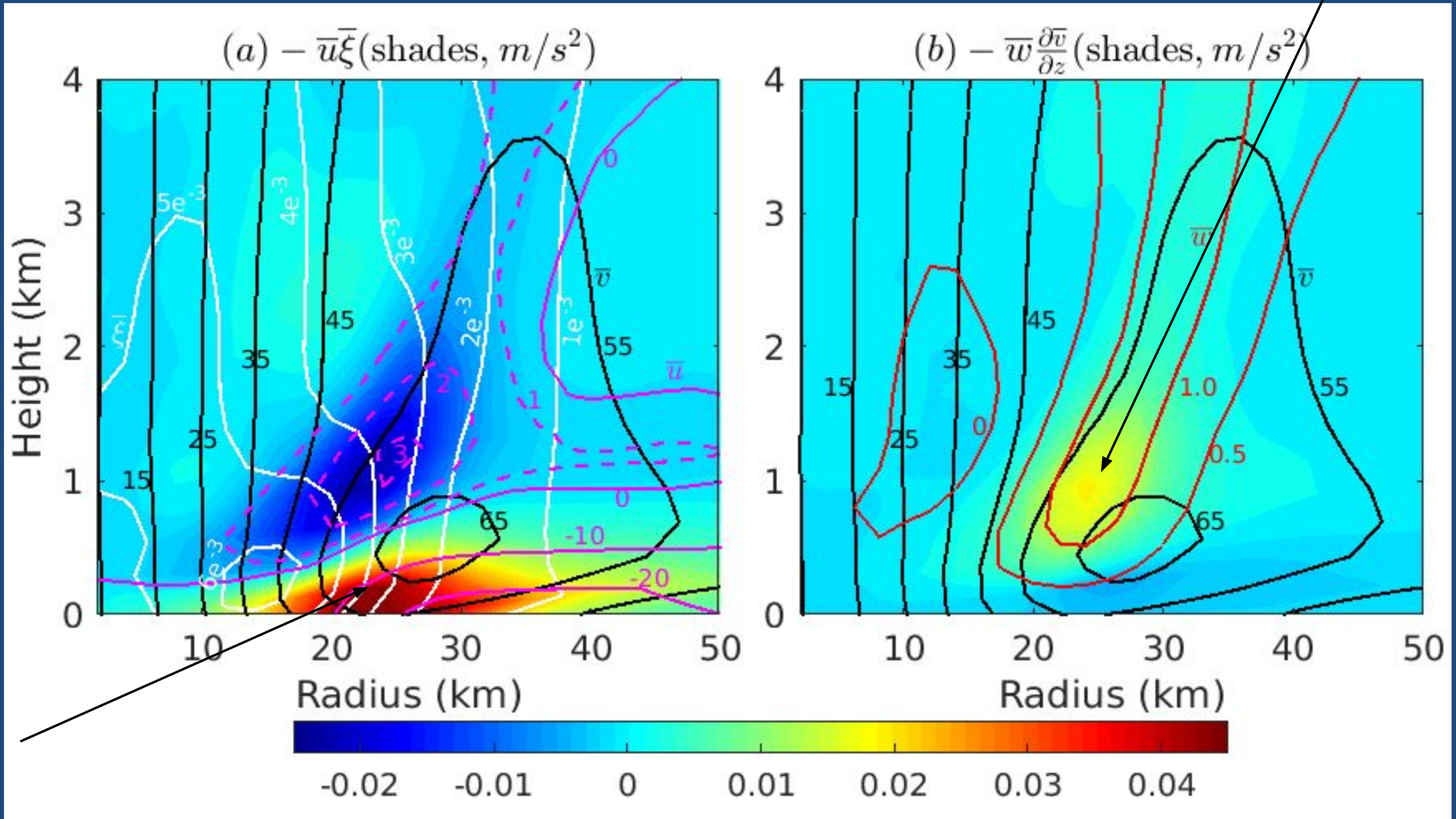
$$\frac{\partial \bar{v}}{\partial t} = -\bar{u}\bar{\xi} - \bar{w}\frac{\partial \bar{v}}{\partial z} - \overline{u'\zeta'} - \overline{v'\frac{\partial v'}{r\partial \lambda}} - \overline{w'\frac{\partial v'}{\partial z}} + D_{sgs\_\lambda},$$

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

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

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

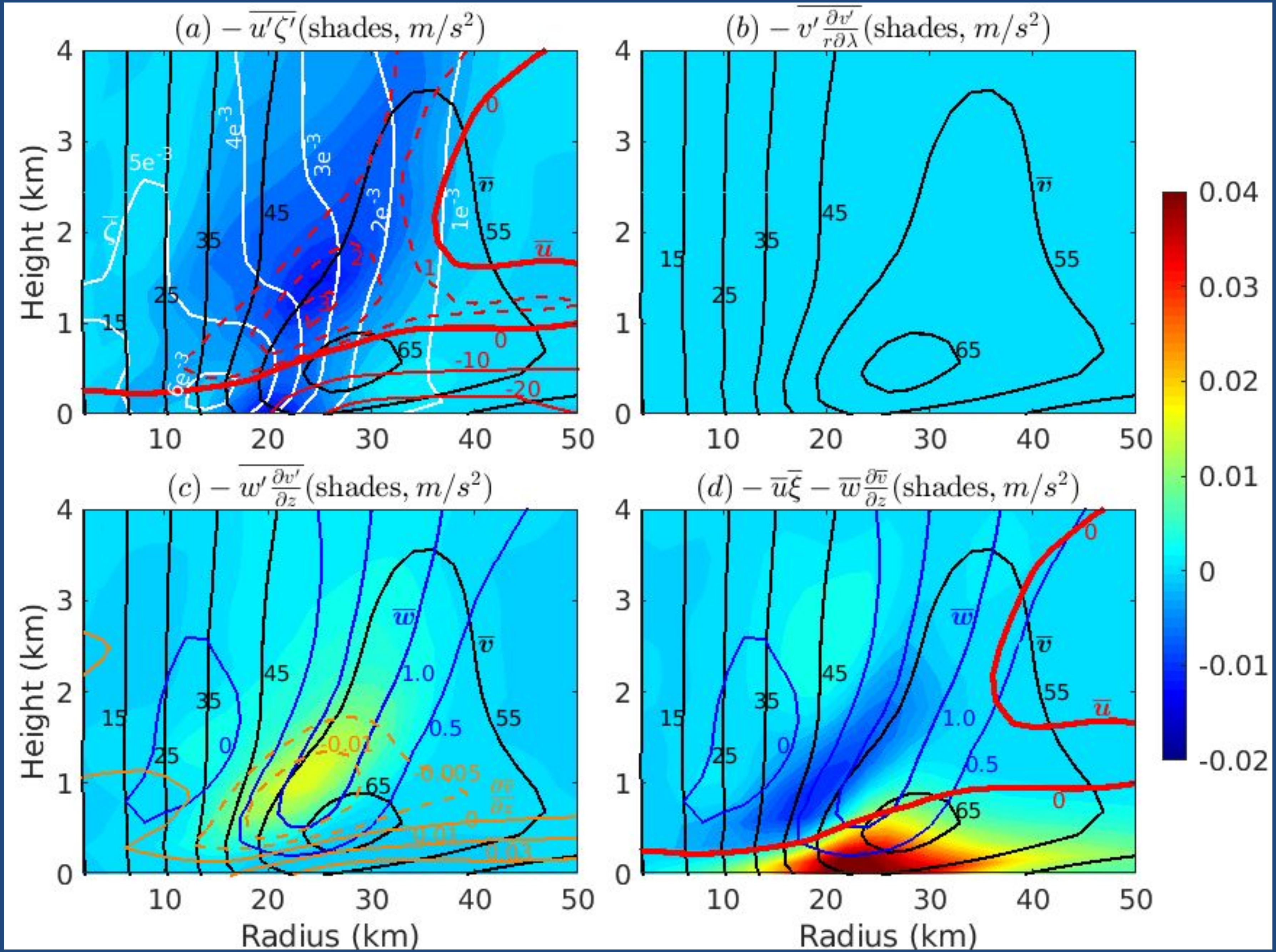
$-\bar{u}\bar{\xi}$ (inward transport of mean absolute vorticity) accelerates the tangential winds inside the inflow layer.

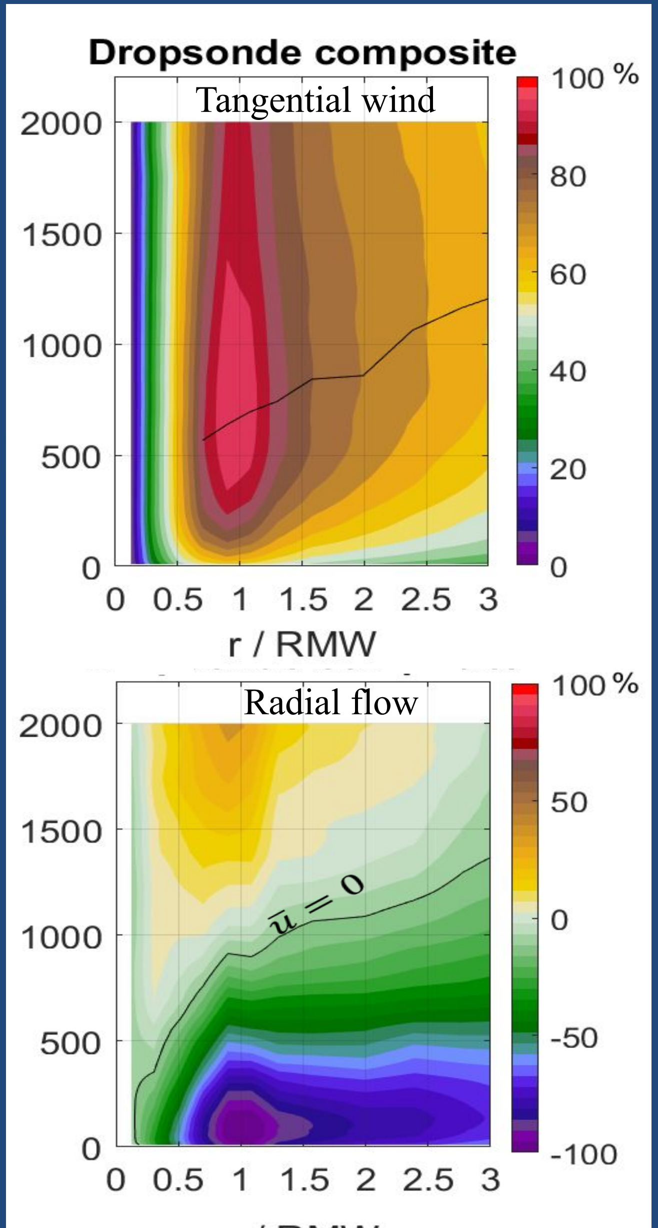


$\bar{u} < 0, \bar{\xi} > 0 \rightarrow -\bar{u}\bar{\xi} > 0$

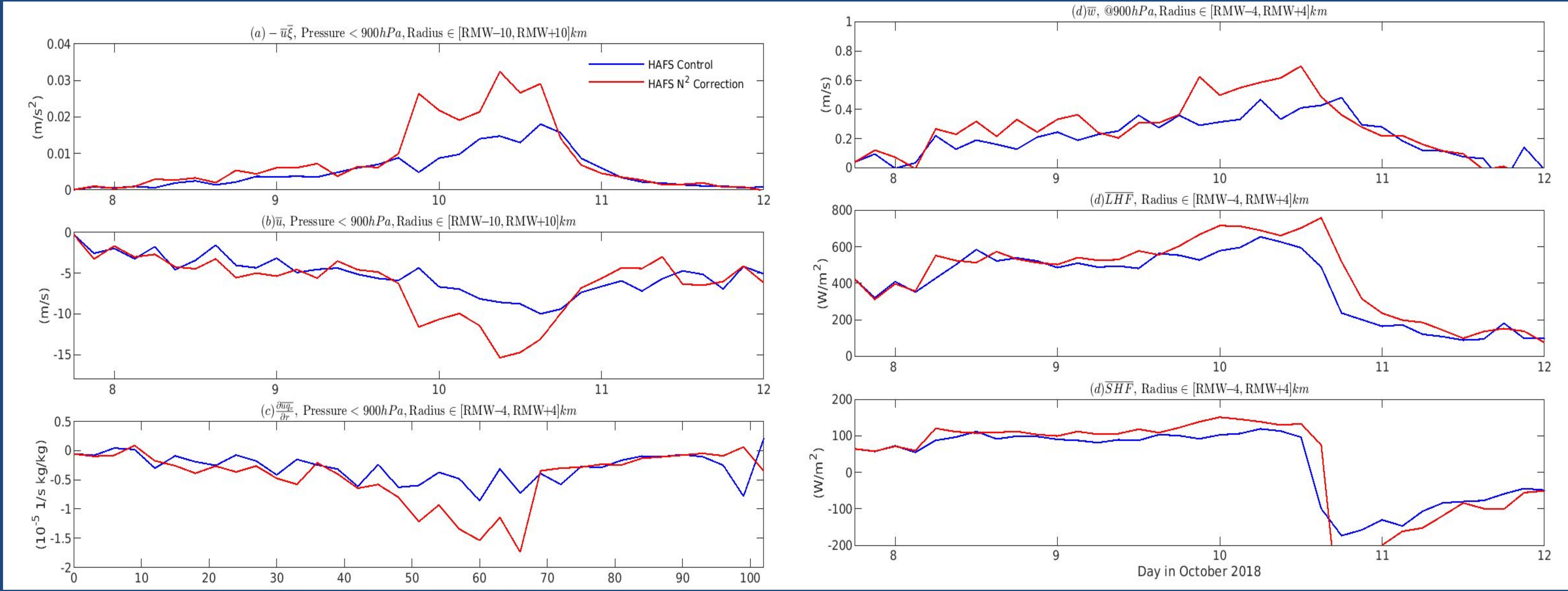
Eddy forcing terms

~ 800 dropsondes in 13 TCs





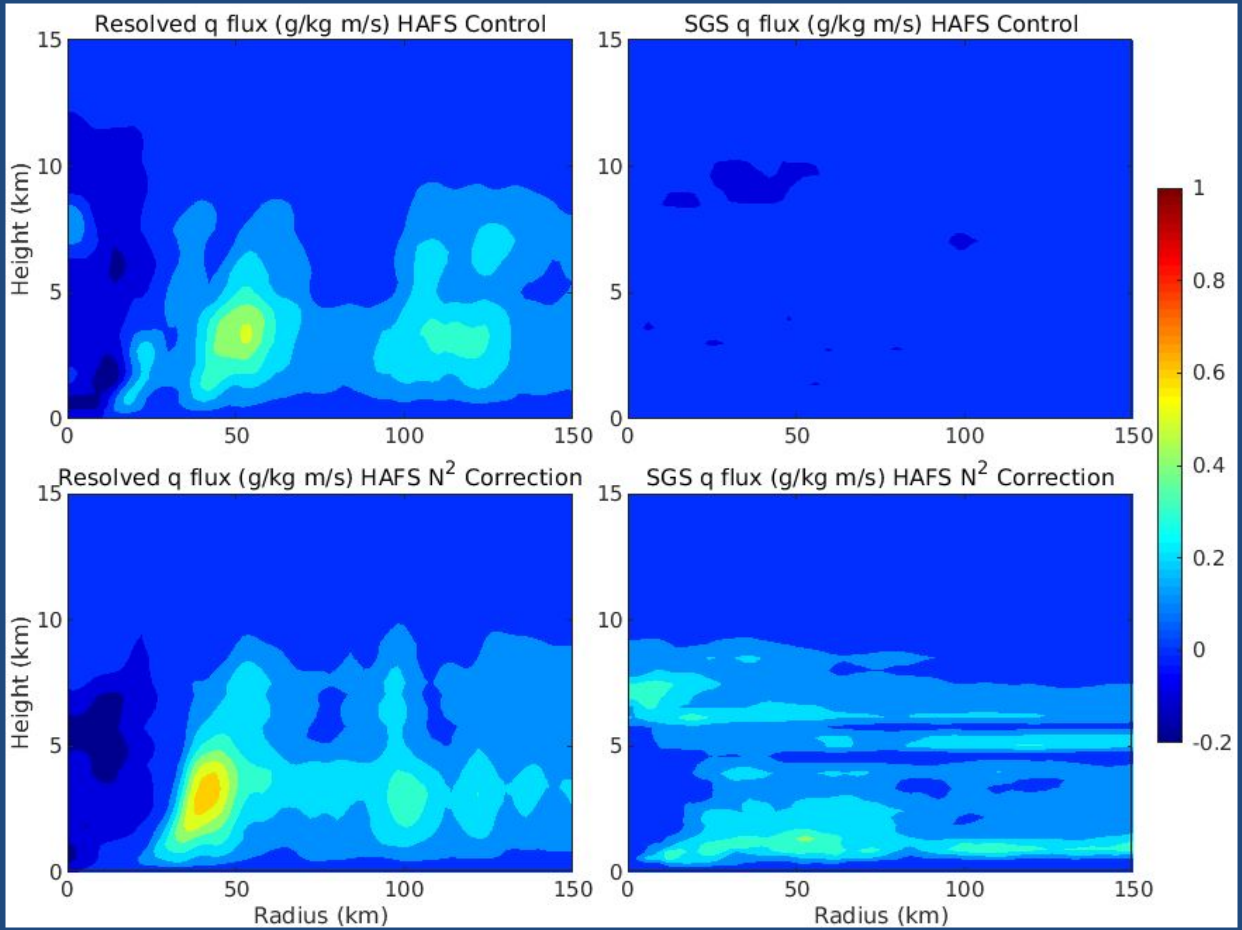
Zhang et al. (2020)

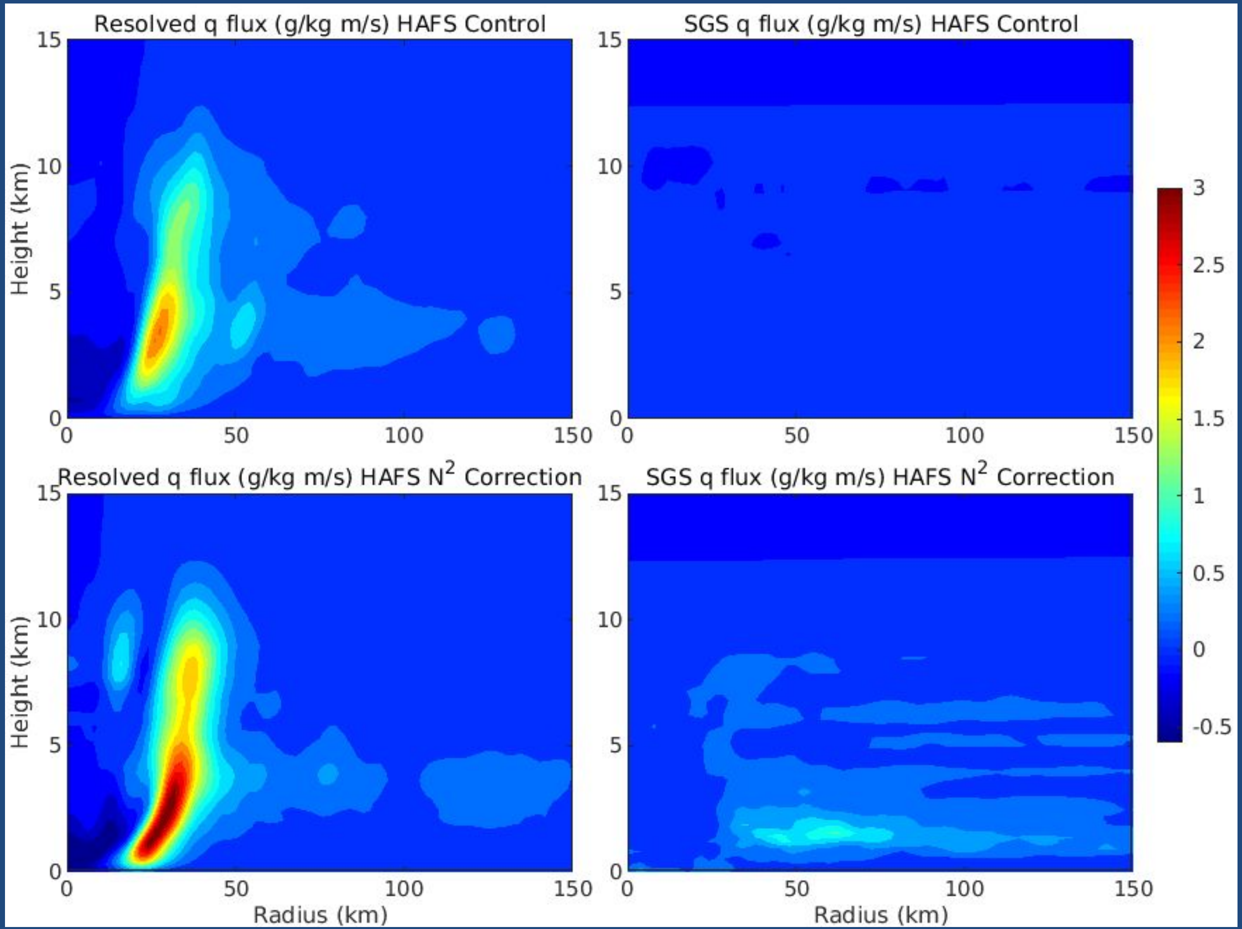


Eyewall convection must exceed a critical level. Below this level, the convection cannot generate sufficiently large inward transport of absolute vorticity to overcome the friction dissipation and other deceleration processes.

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. The static stability correction in the eyewall by including the effects of liquid- and ice-phase hydrometeors improves HFAS's skill in predicting TC track and intensity, in particular, for RI storms.

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.