Evaluating the effect of model physics on hurricane rapid intensification forecasts in HWRF

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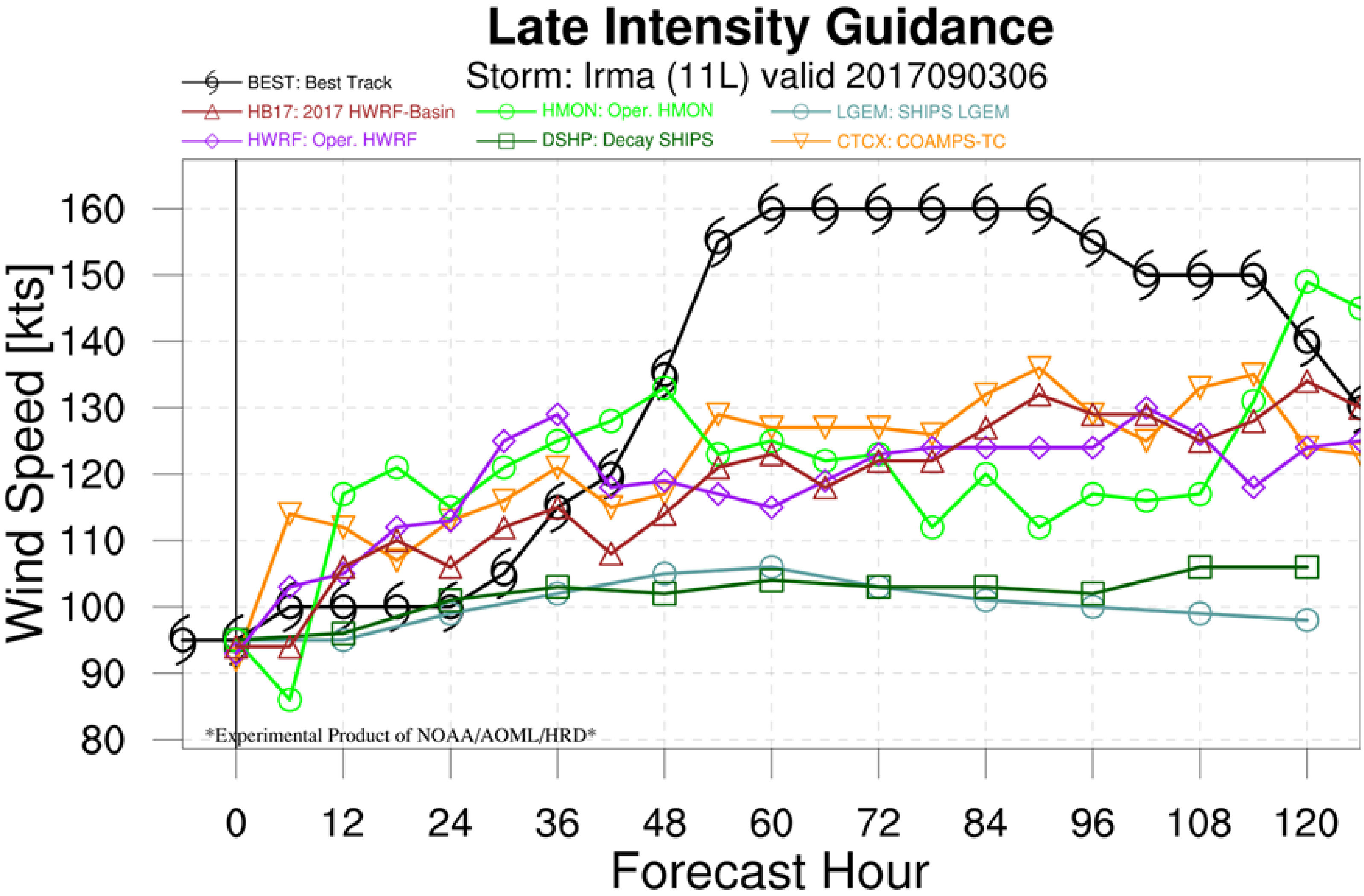
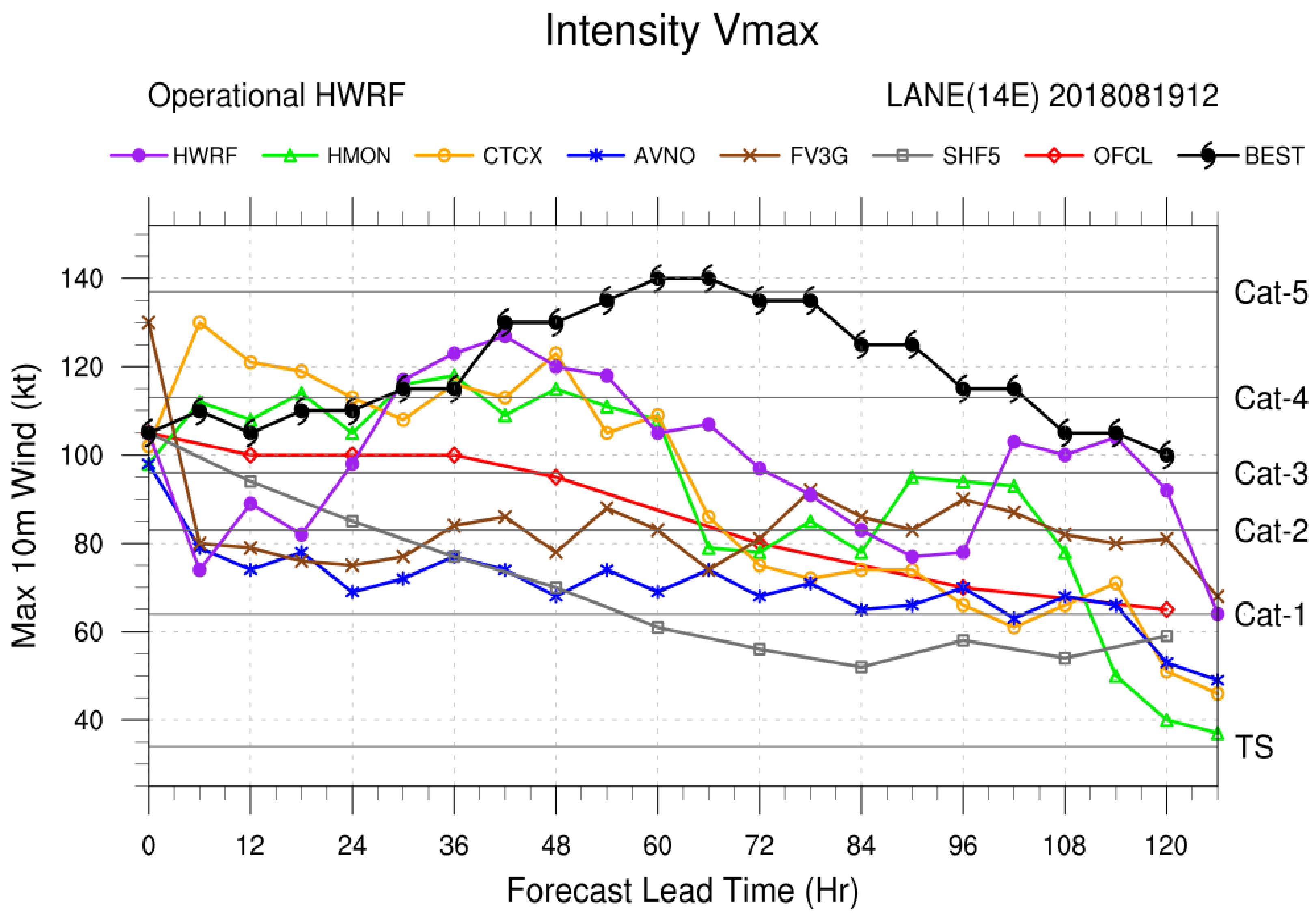
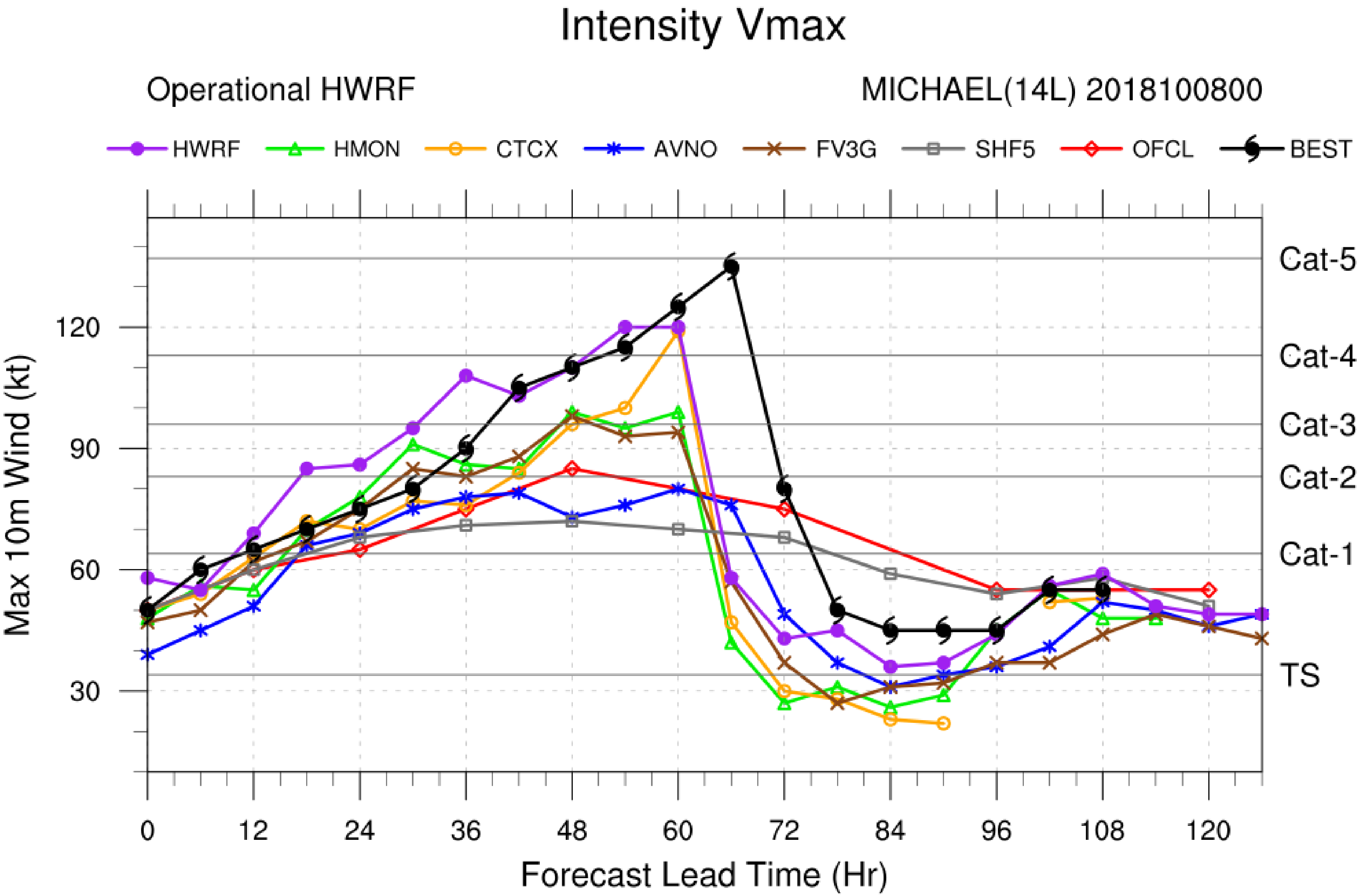
- Other collaborators: David Nolan, Ping Zhu

- Accurately forecasting hurricane rapid intensification (i.e., 24-h intensity increase by 30 kt and more) is a challenge.




Intensity Vmax
Operational HWRF
LANE(14E) 2018081912
HWRF
HMON
CTCX
AVNO
FV3G
SHF5
OFCL
BEST
Max 10m Wind (kt)
140
120
100
80
60
40
Cat-5
Cat-4
Cat-3
Cat-2
Cat-1
TS
0
12
24
36
48
60
72
84
96
108
120
Forecast Lead Time (Hr)


Intensity Vmax
Operational HWRF
MICHAEL(14L) 2018100800
HWRF
HMON
CTCX
AVNO
FV3G
SHF5
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BEST
Max 10m Wind (kt)
120
90
60
30
Cat-5
Cat-4
Cat-3
Cat-2
Cat-1
TS
0
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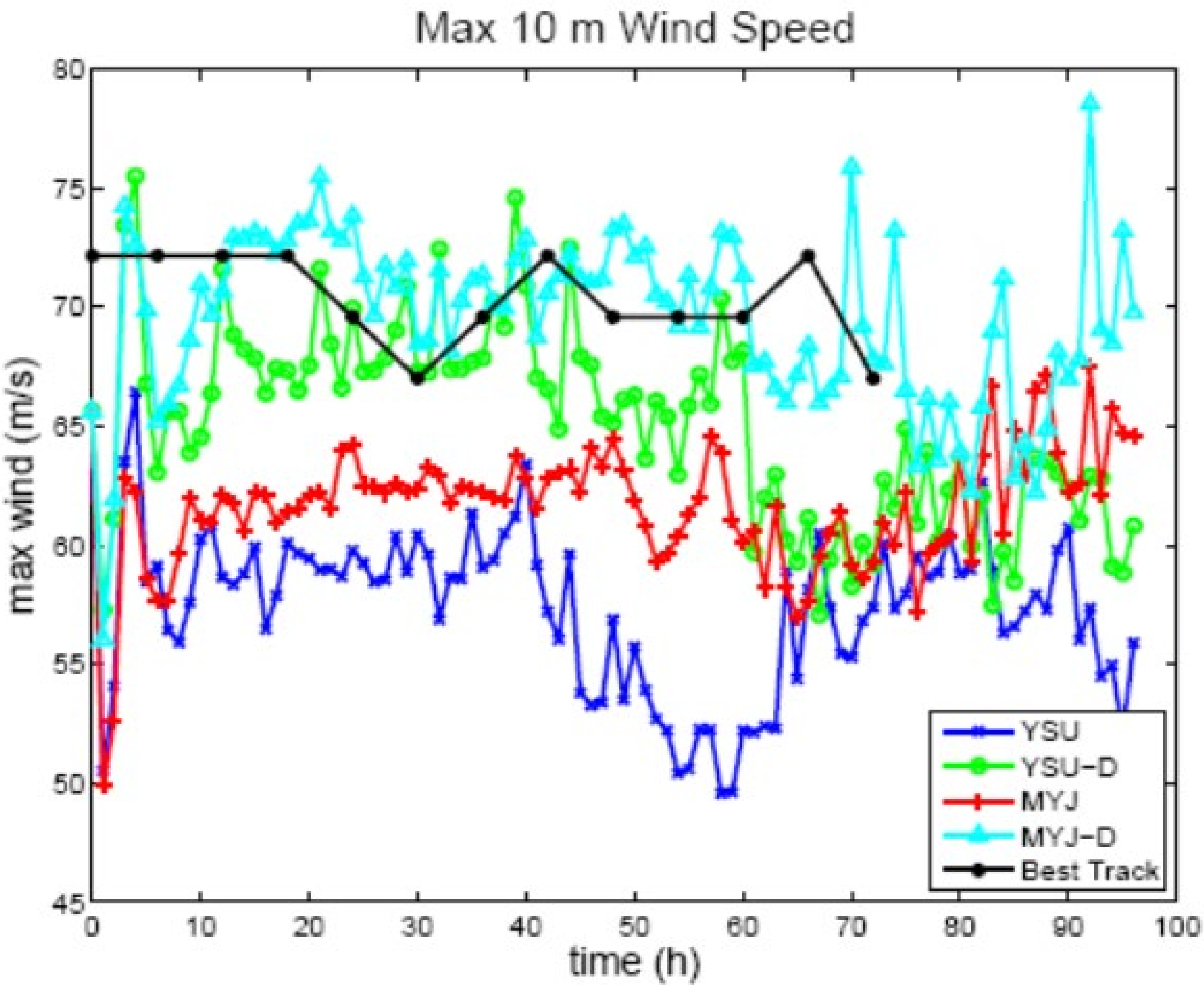
24
36
48
60
72
84
96
108
120
Forecast Lead Time (Hr)

Sensitivity of simulated hurricane intensity to model physics



WRF simulations of Hurricane Isabel (2003)

(Nolan et al. 2009a, b)

Sensitivity to boundary-layer and surface-layer parameterizations

Objectives

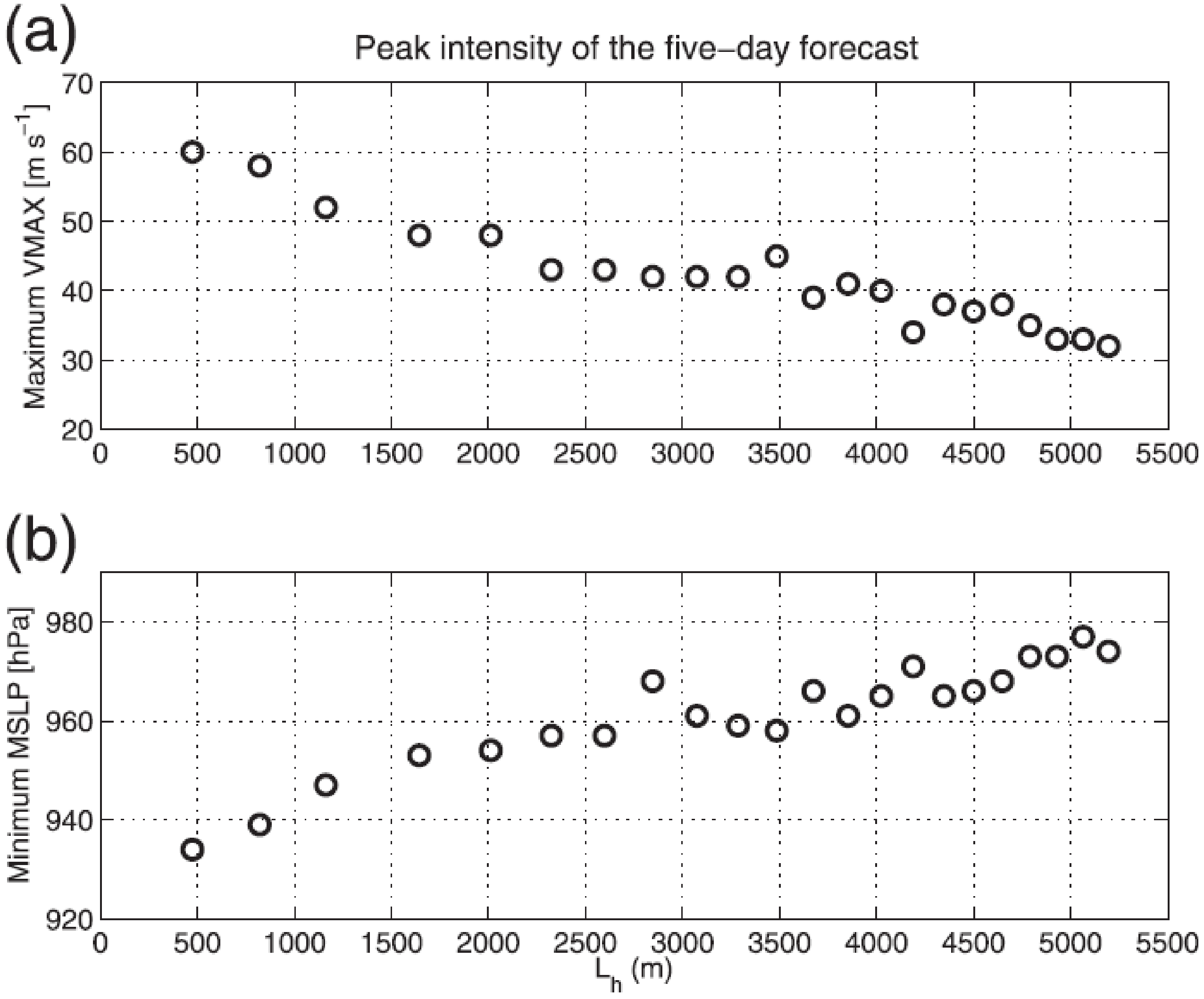
- To evaluate the impact of model physics in HWRF on hurricane RI forecasts.

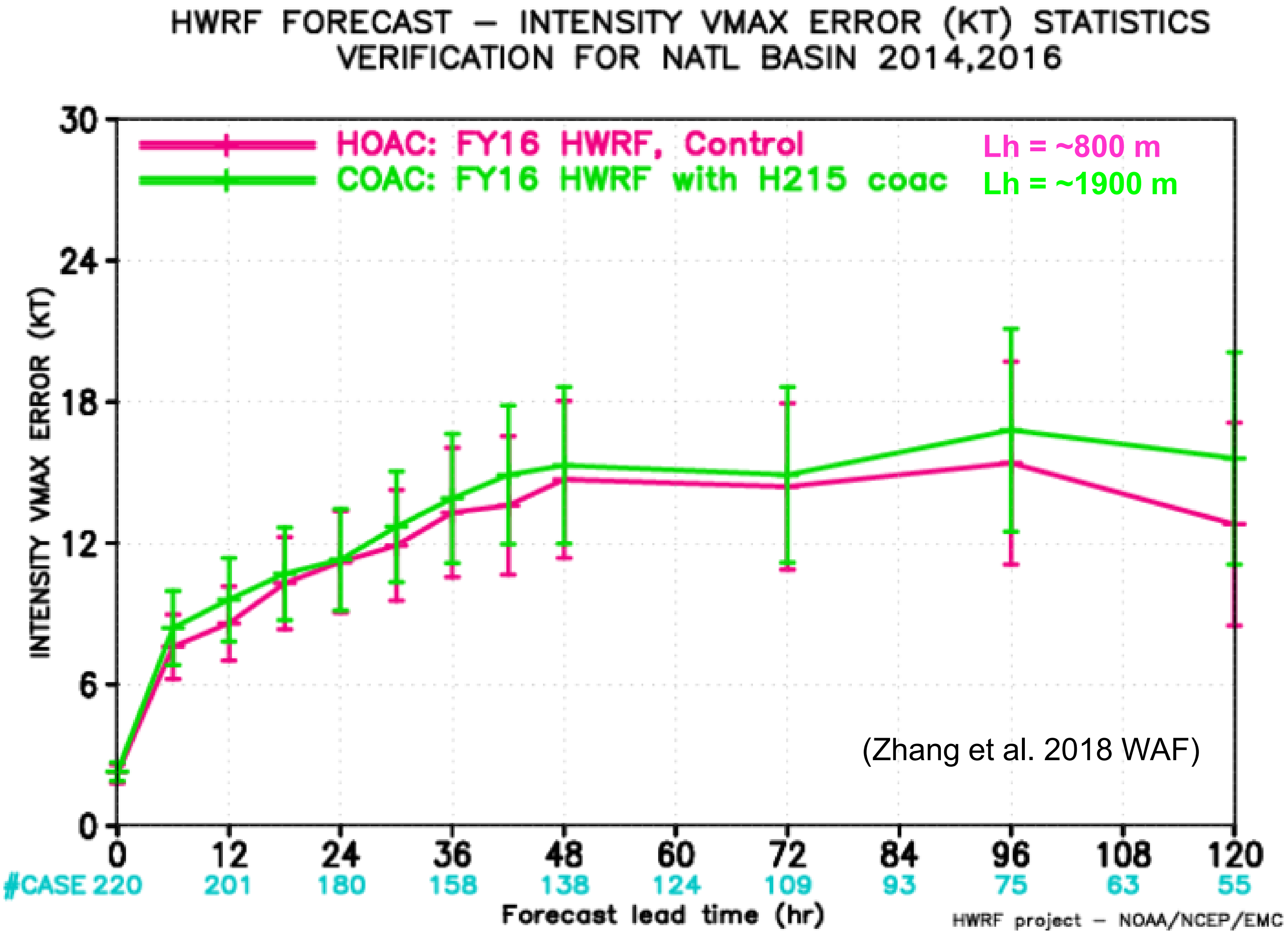
We focus on three types of model physics:

1. Horizontal-diffusion parameterization
2. Cumulus parameterization
3. Boundary-layer parameterization

Effects of horizontal diffusion on hurricane intensity in idealized HWRF simulations

(Zhang and Marks 2015)

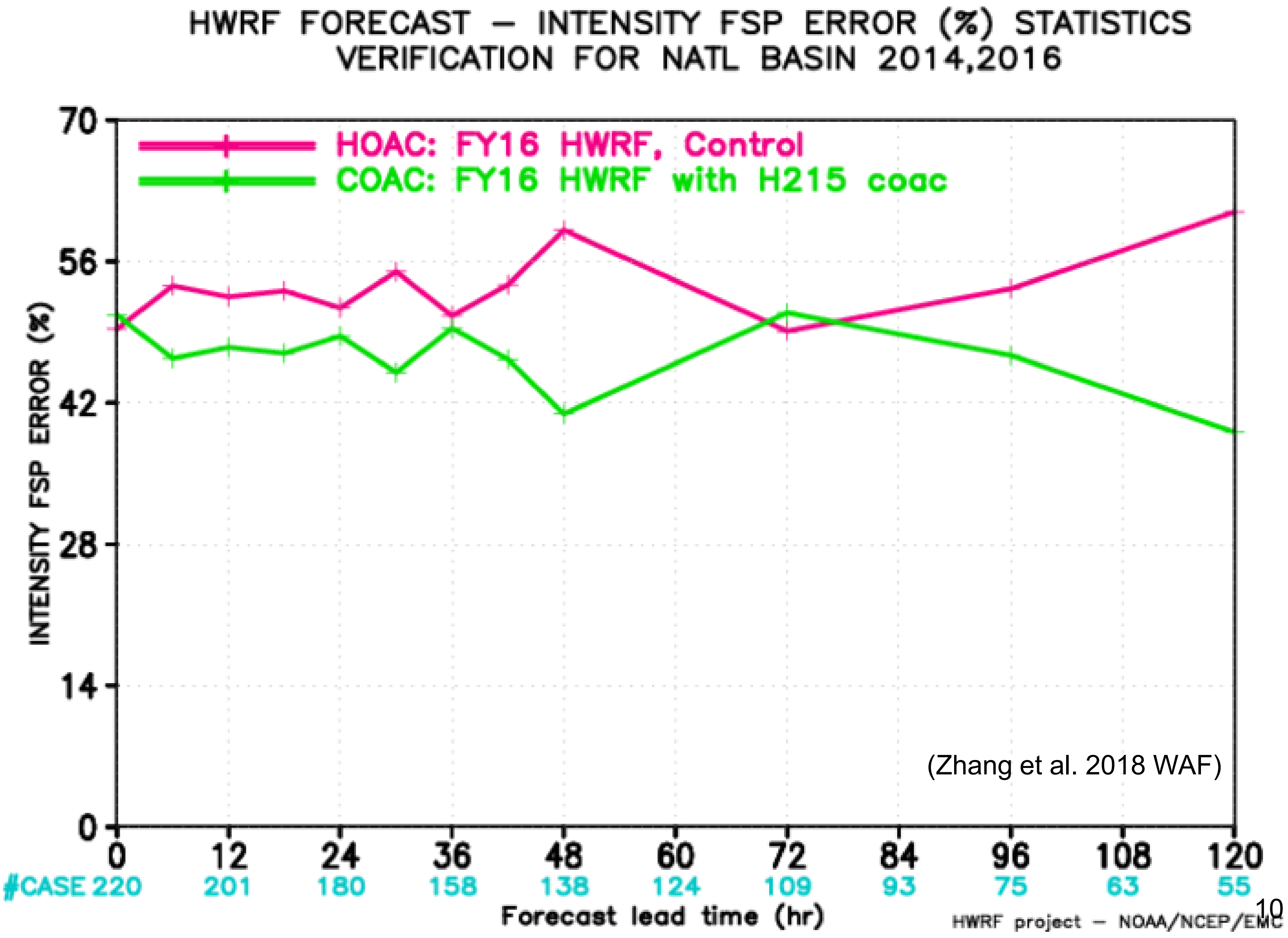




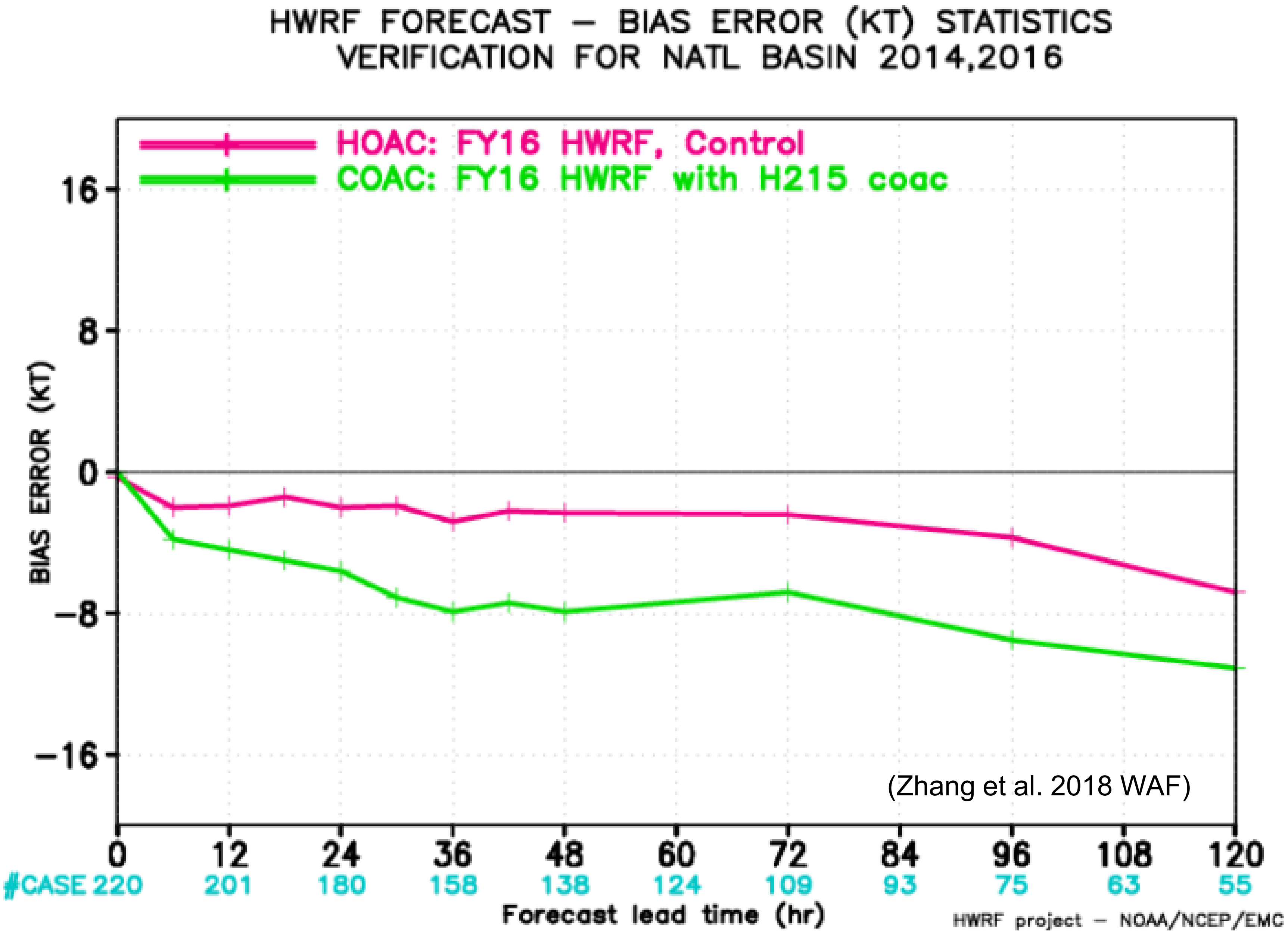
Lh = ~800 m
Lh = ~1900 m

(Zhang et al. 2018 WAF)

- The horizontal mixing length (Lh) was reduced in H216 to be close to observational estimates given by Zhang and Montgomery (2012).



(Zhang et al. 2018 WAF)

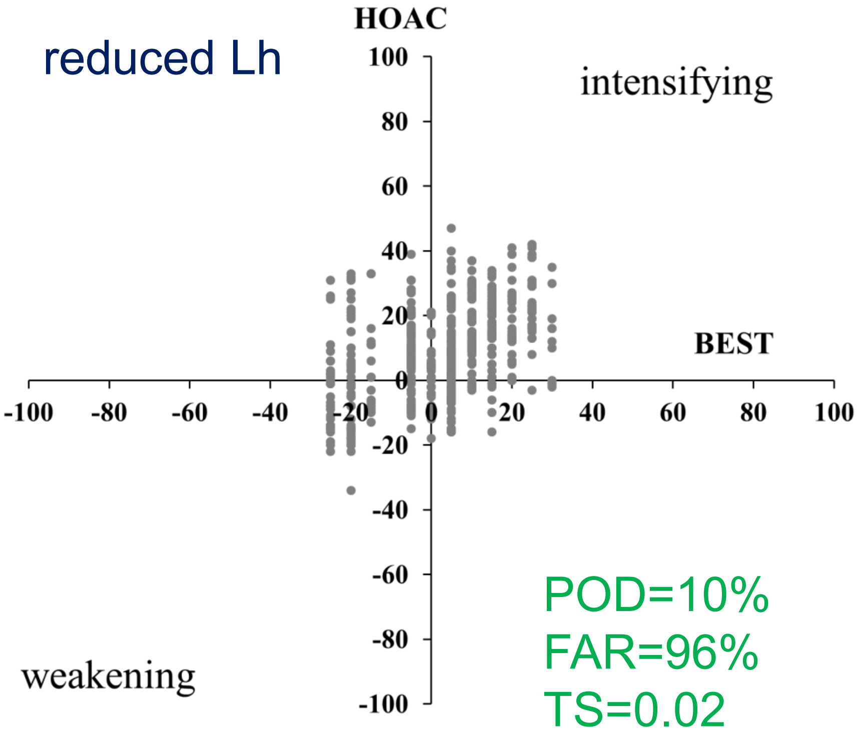


HWRF FORECAST – BIAS ERROR (KT) STATISTICS
VERIFICATION FOR NATL BASIN 2014,2016

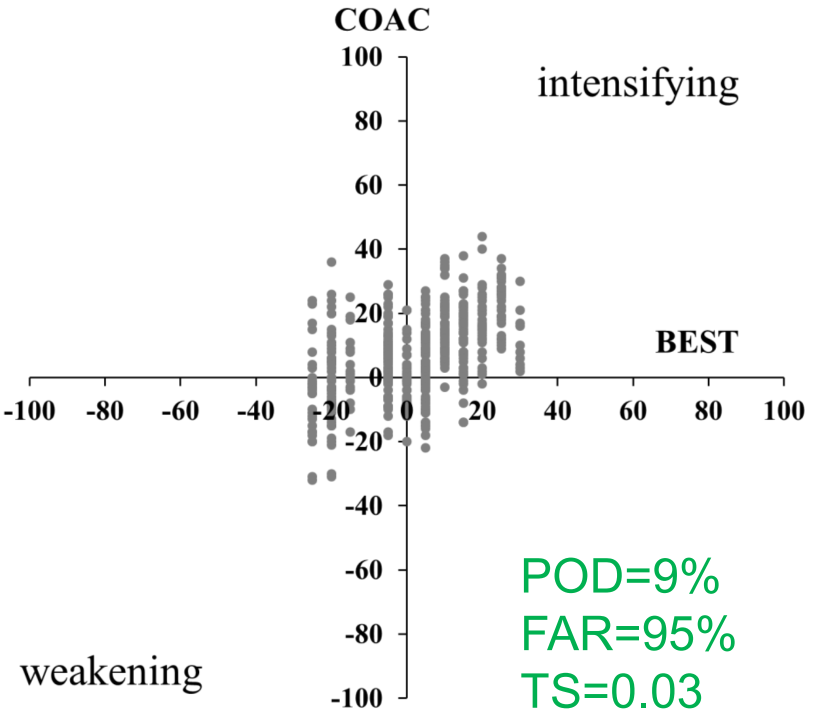
(Zhang et al. 2018 WAF)

Impact of horizontal diffusion parameterization on RI forecasts in HWRF

reduced Lh



POD=10%
FAR=96%
TS=0.02



POD=9%
FAR=95%
TS=0.03

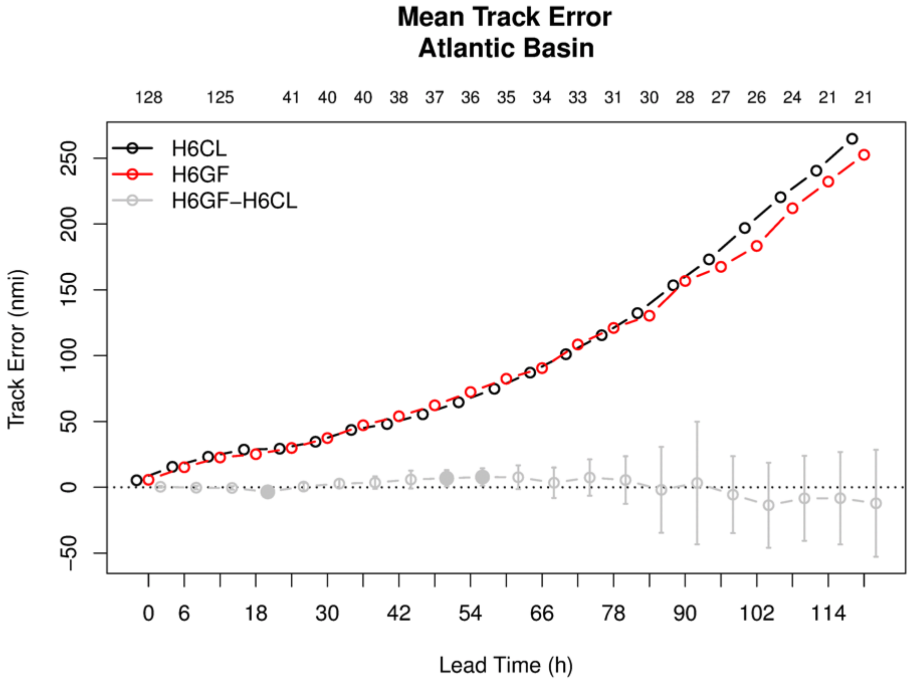
OBS HOAC	Yes	No
Yes	1	41
No	9	422

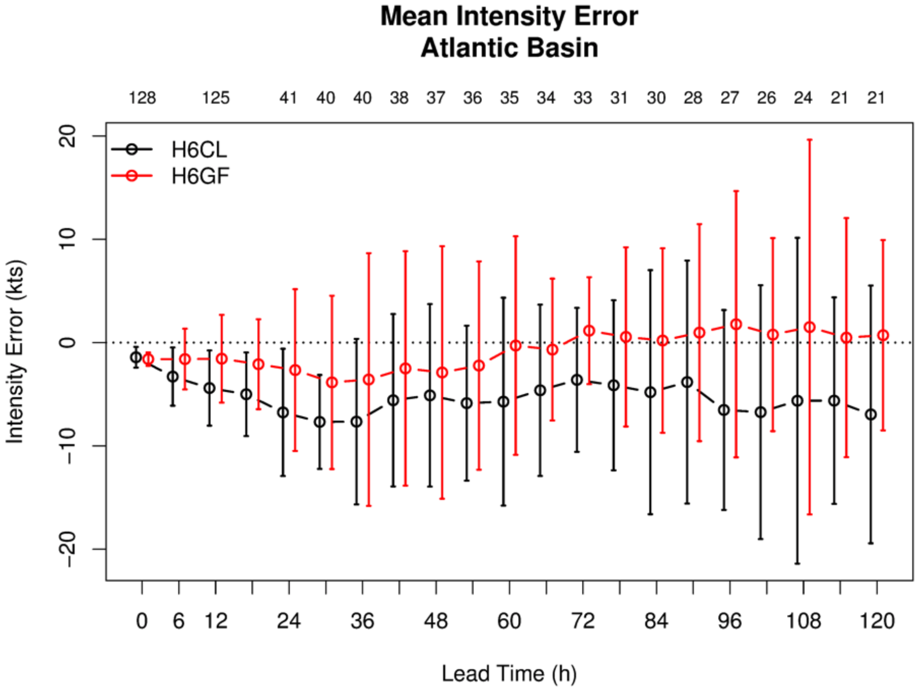
POD – Probability of detection
FAR- False alarm rate
TS – total success index

OBS COAC	Yes	No
Yes	1	19
No	10	442

- Reducing Lh has a small impact on RI forecasts in HWRF (H216).

HWRF forecasts with SAS vs GF cumulus schemes





H6CL - SAS scheme (Arakawa and Schubert, 1974; Grell, 1983, Han and Pan 2011)

H6GF - GF scheme (Grell and Freitas 2014) – scale-aware cumulus scheme

(Biswas et al. 2020, in press)

Impact of cumulus parameterization on RI forecasts

Control

		Observation	
		RI	***No RI***
Model Forecast	***RI***	**28**	13
	No RI	52	472

POD=35.0%
FAR=31.7%
TS= 0.30

POD – Probability of detection
FAR- False alarm rate
TS – total success index

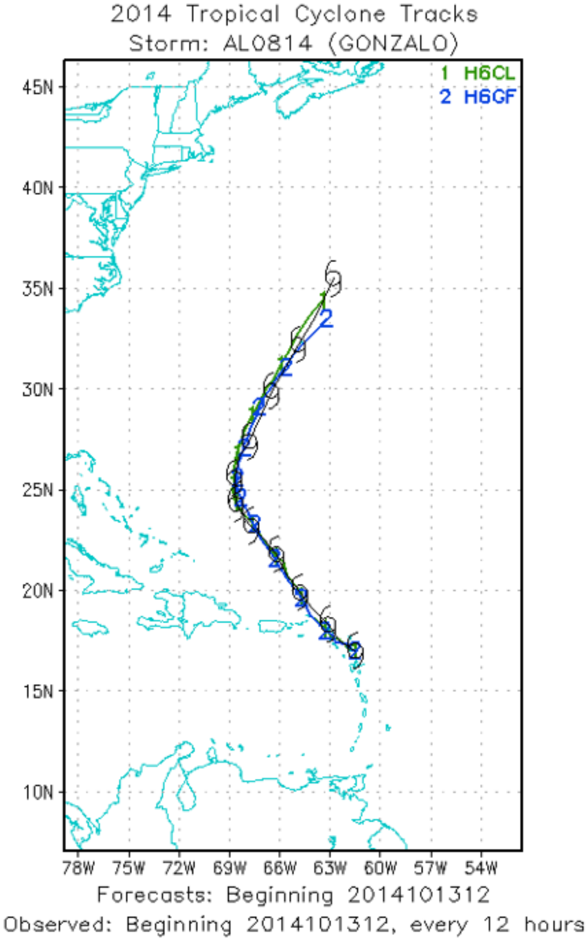
GF

		Observation	
		RI	***No RI***
Model Forecast	***RI***	**38**	26
	No RI	42	459

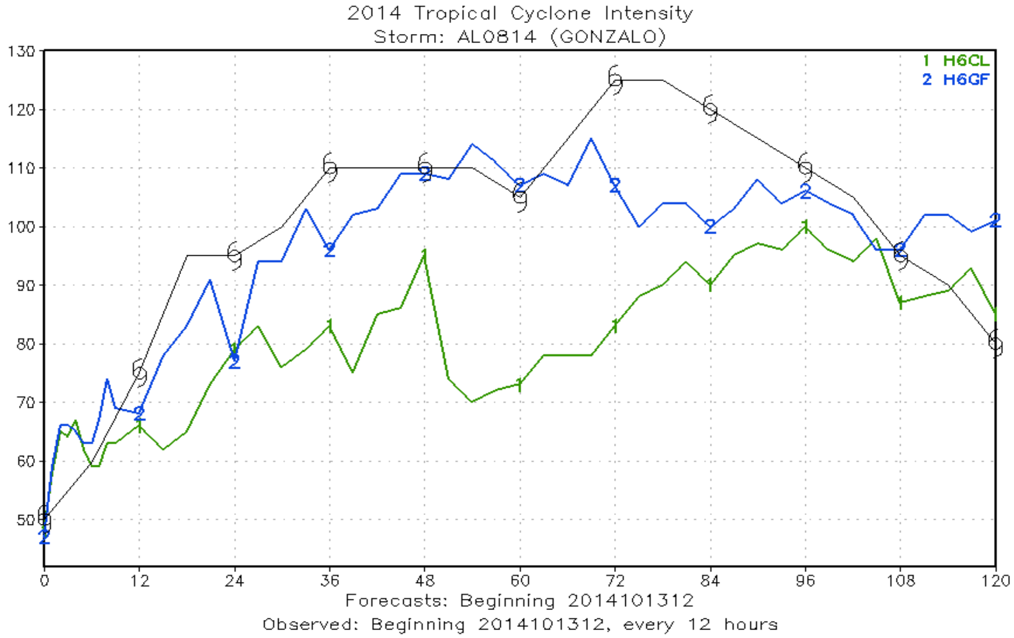
POD=47.5%
FAR=40.6%
TS=0.36

- The scale-aware cumulus parameter scheme (GF) gives slightly better RI forecast in HWRF than the SAS scheme (control).

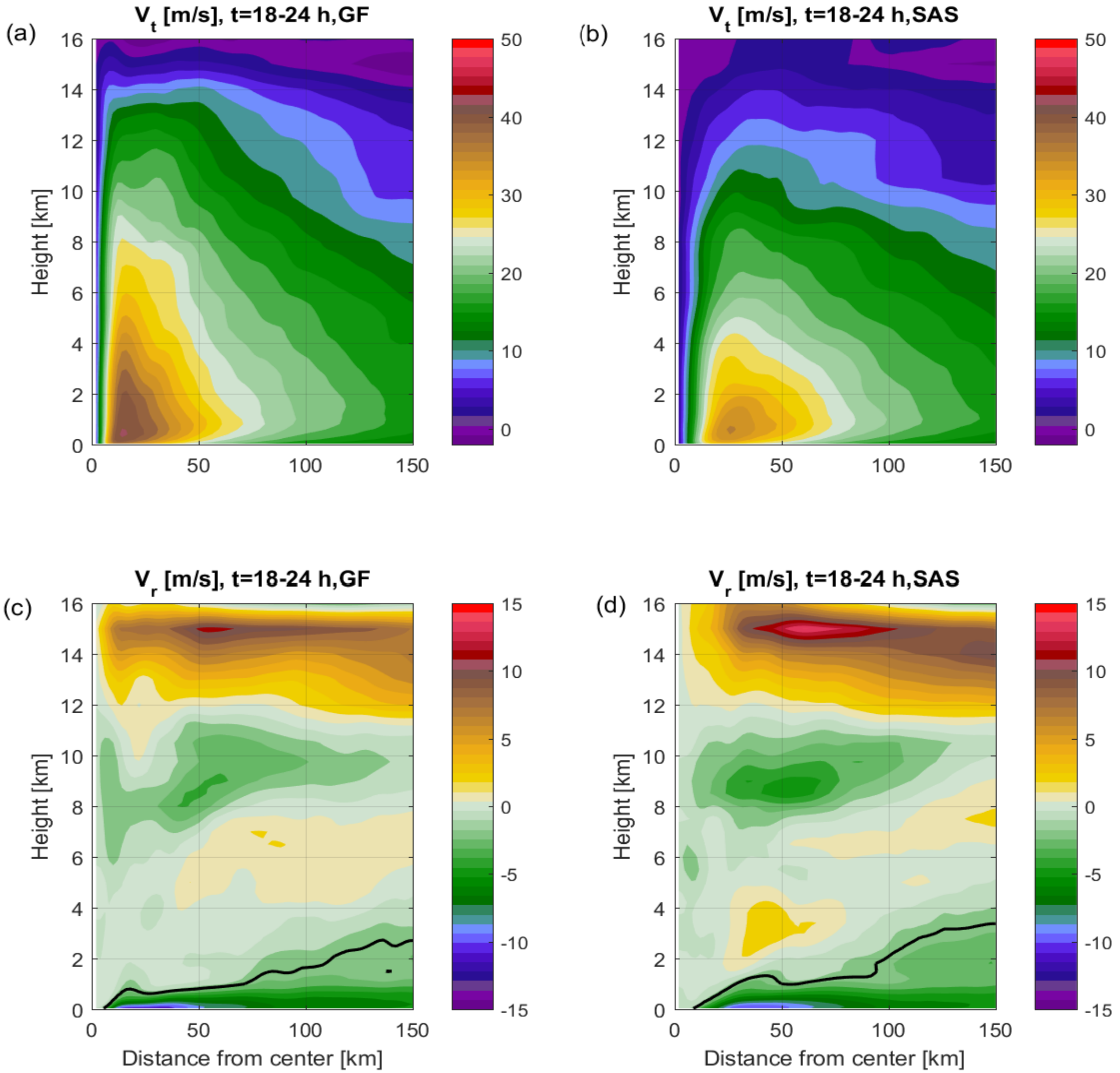
Case study



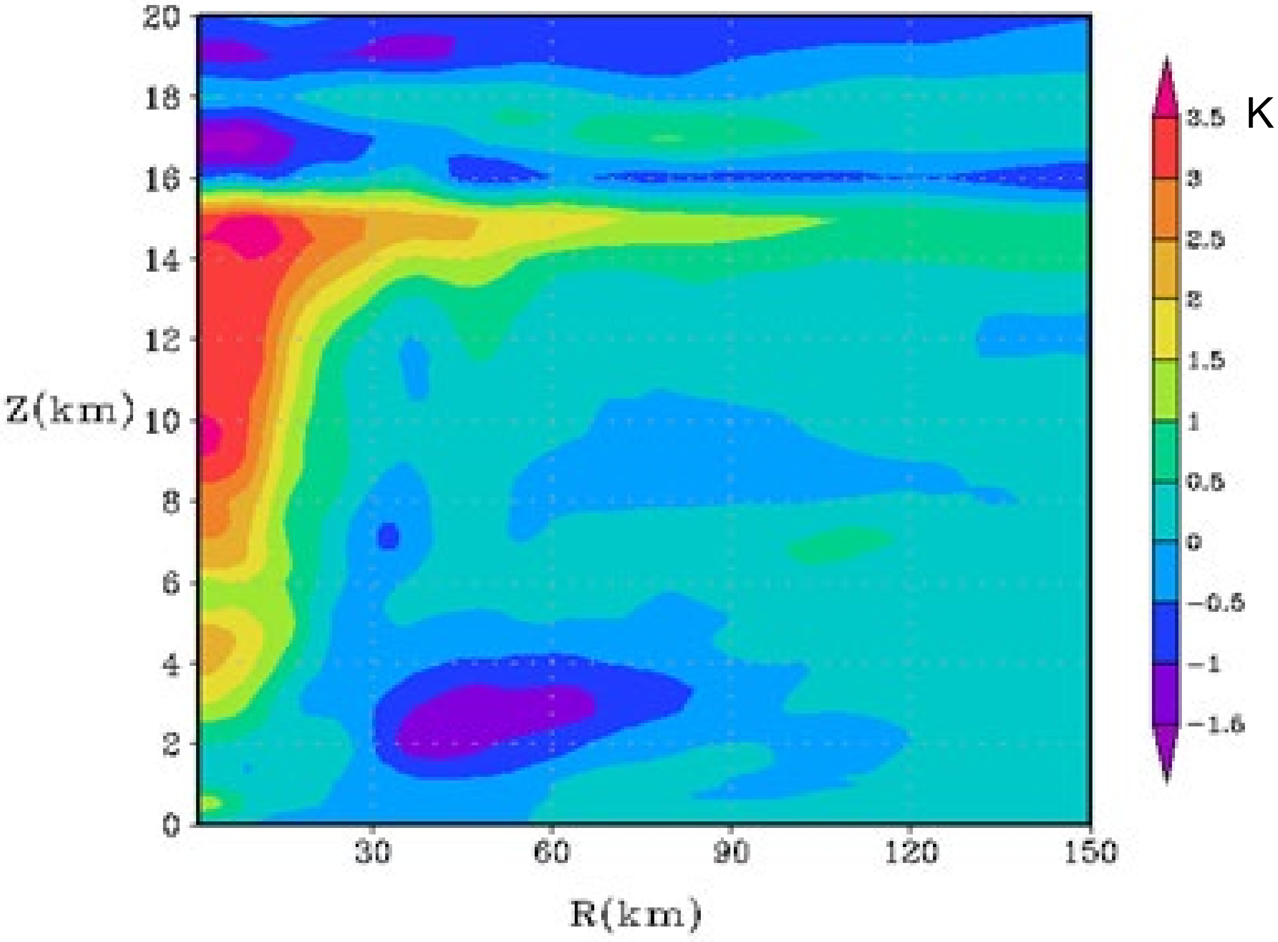
2014 Tropical Cyclone Tracks
Storm: AL0814 (GONZALO)
1 H6CL
2 H6GF
45N
40N
35N
30N
25N
20N
15N
10N
78W
75W
72W
69W
66W
63W
60W
57W
54W
Forecasts: Beginning 2014101312
Observed: Beginning 2014101312, every 12 hours

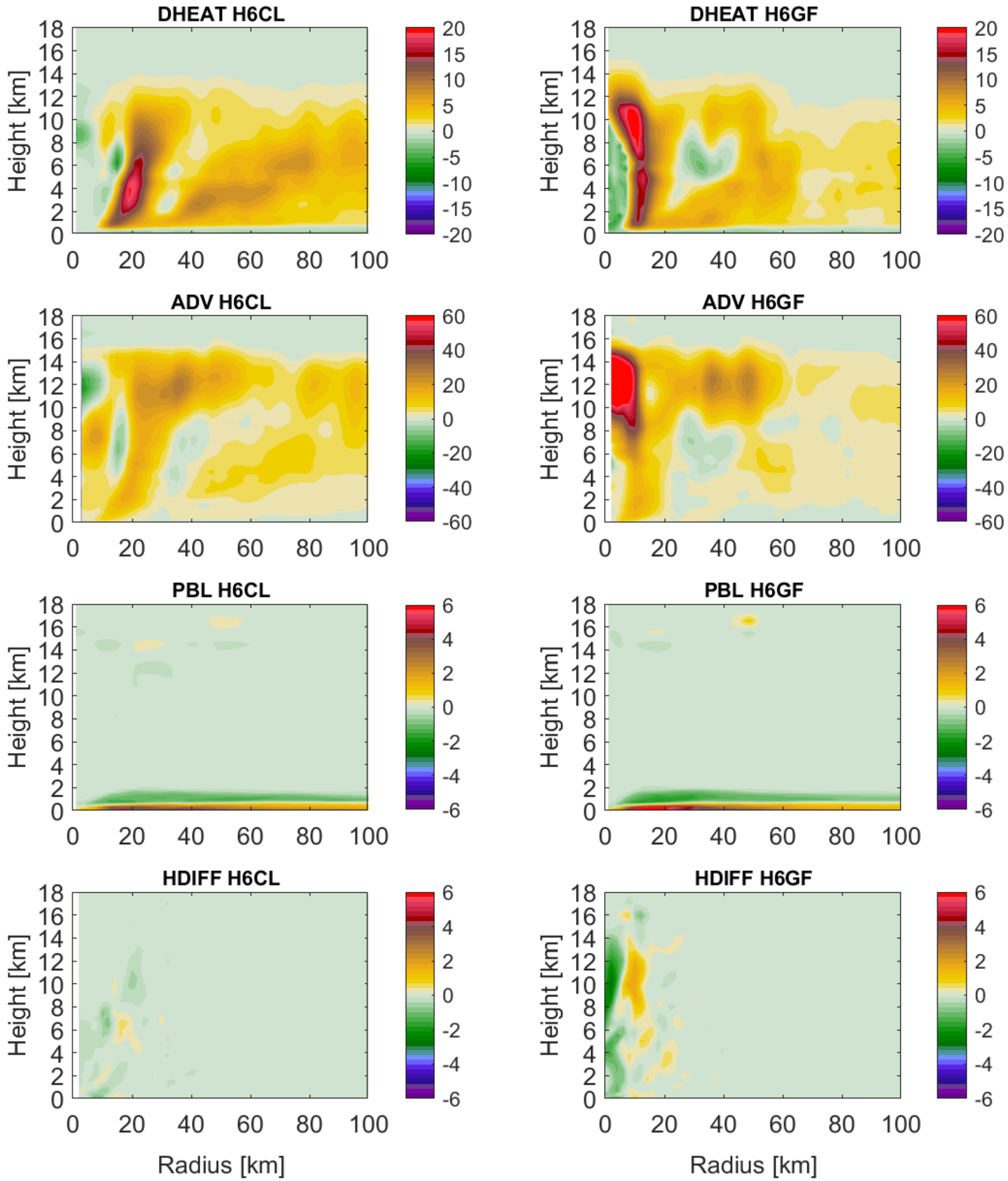


2014 Tropical Cyclone Intensity
Storm: AL0814 (GONZALO)
1 H6CL
2 H6GF
130
120
110
100
90
80
70
60
50
0
12
24
36
48
60
72
84
96
108
120
Forecasts: Beginning 2014101312
Observed: Beginning 2014101312, every 12 hours


(a)
V$_t$ [m/s], t=18-24 h,GF
(b)
V$_t$ [m/s], t=18-24 h,SAS
(c)
V$_r$ [m/s], t=18-24 h,GF
(d)
V$_r$ [m/s], t=18-24 h,SAS
Height [km]
0
2
4
6
8
10
12
14
16
0
50
100
150
Distance from center [km]
0
10
20
30
40
50
-15
-10
-5
0
5
10
15

Difference in azimuthally-averaged temperature between H6GF and H6CL between 18-24 h





Potential temperature budget between 18-24 h

$$\theta_{ten} = DHEAT + ADV$$
$$+PBL + HDIFF$$

Impact of PBL physics on RI forecasts in HWRF

Observed

		Yes	**No**
lowKm	**Yes**	Hit 16	False Alarm 8
$\alpha= 0.5$	**No**	Miss 2	194---

Observed

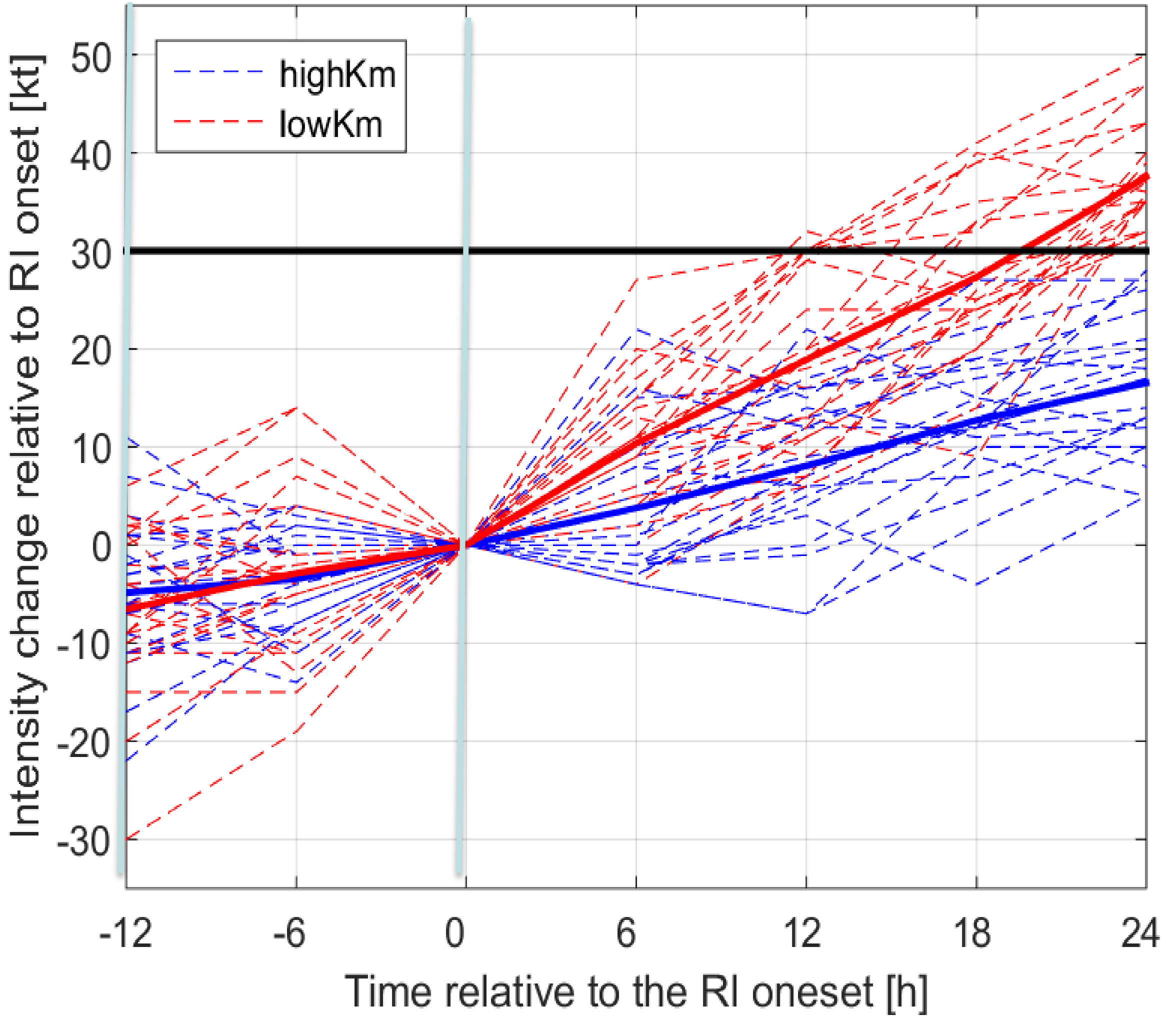
		Yes	**No**
highKm	**Yes**	Hit 4	False Alarm 0
$\alpha= 1$	**No**	Miss 14	202---

lowKm
POD=88.9%
FAR=33.3%
TS=0.62

highKm
POD=22.2%
FAR=0%
TS= 0.22

$$K_m = k\,(U_*/\Phi_m)\,Z\,\{\alpha(1 - Z/h)^2\}$$

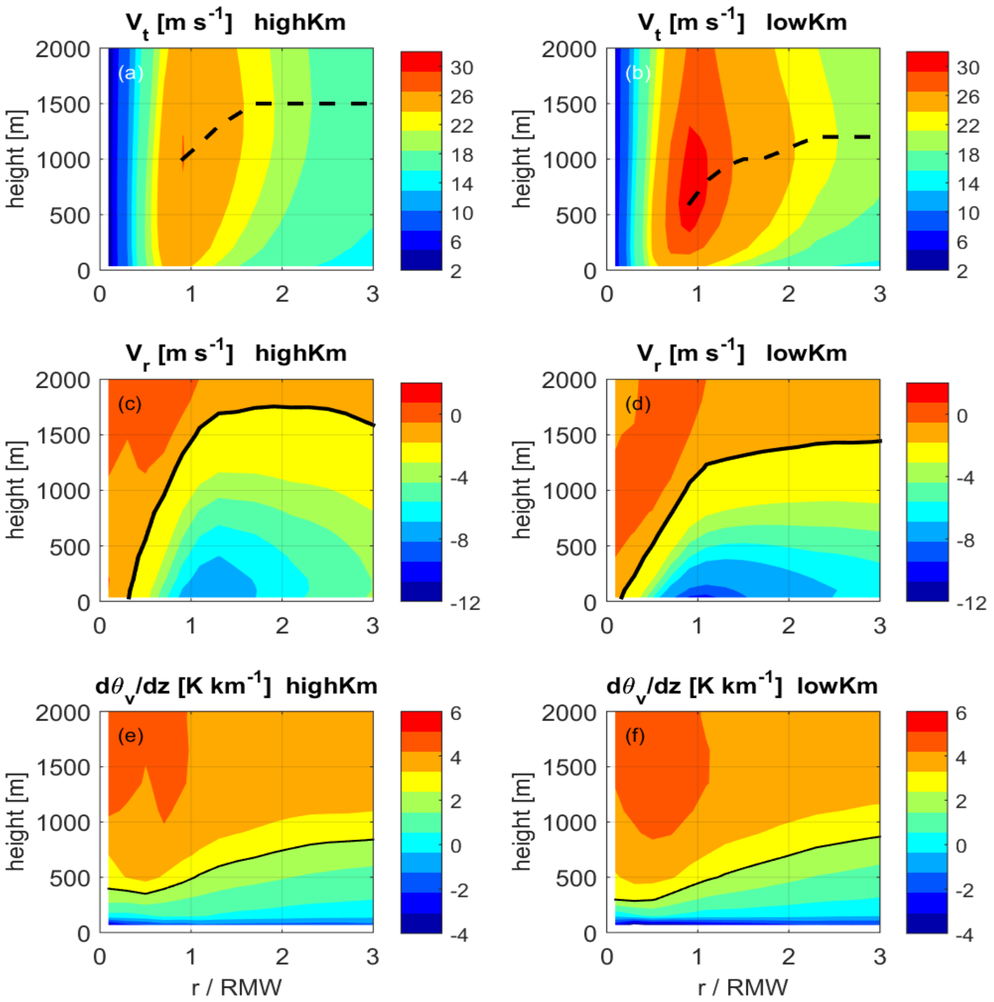
What are the structural differences between the *highKm* and *lowKm* forecasts at onset of RI?



RI threshold

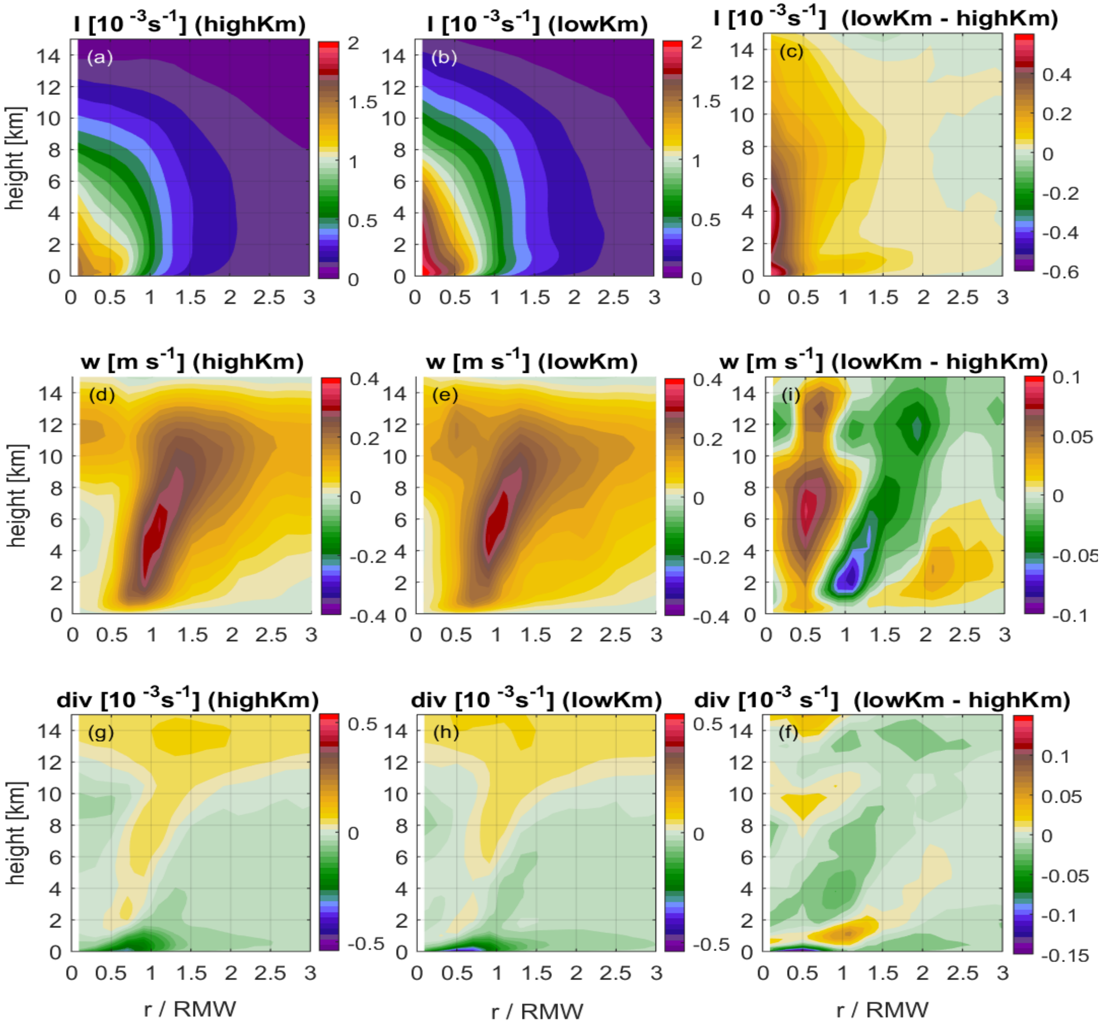
(Zhang et al. 2017 MWR)

Boundary-layer composites at RI onset



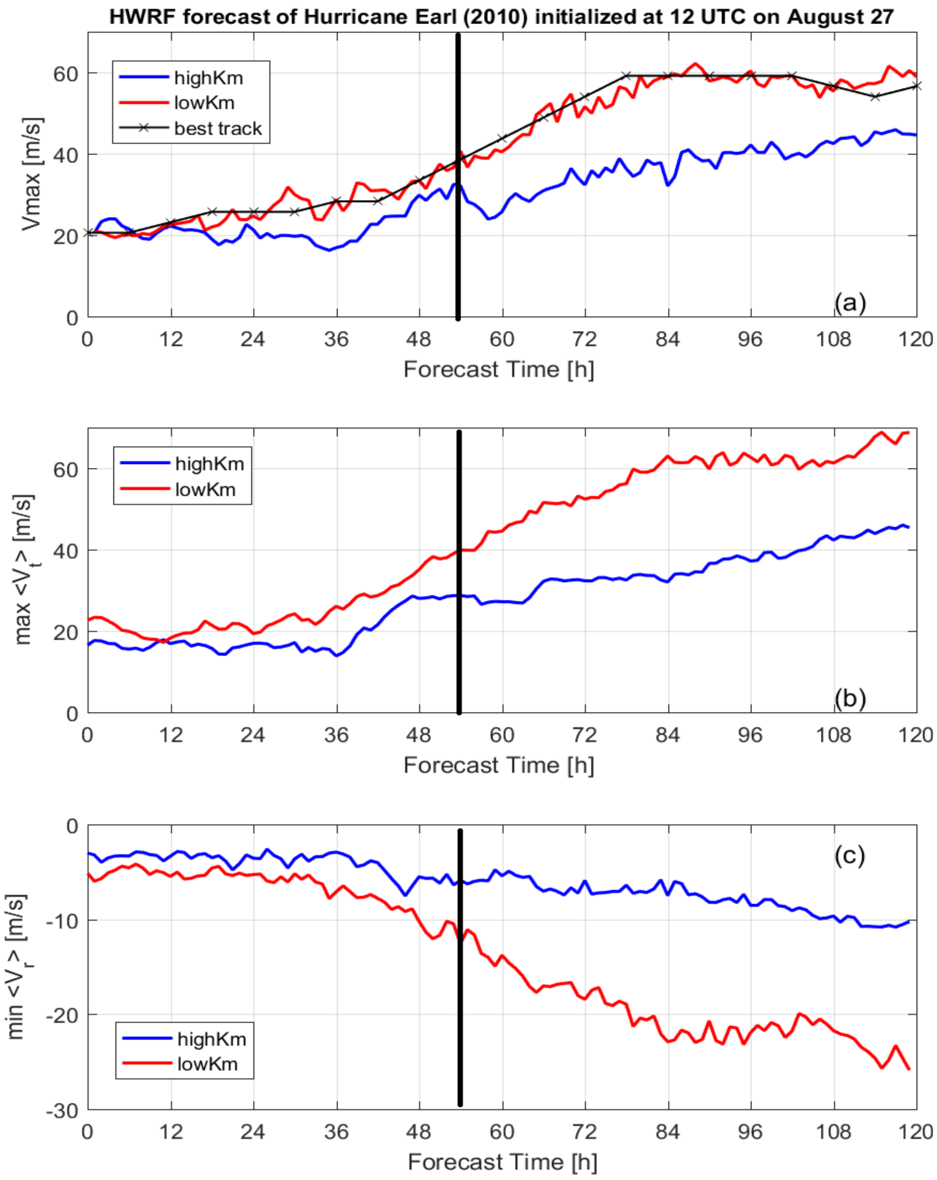
- At RI onset, forecasts with reduced vertical diffusion have a shallower boundary layer with stronger inflow, more unstable near-surface air outside the eyewall.

Composites of inertial stability, vertical velocity and divergence at RI onset

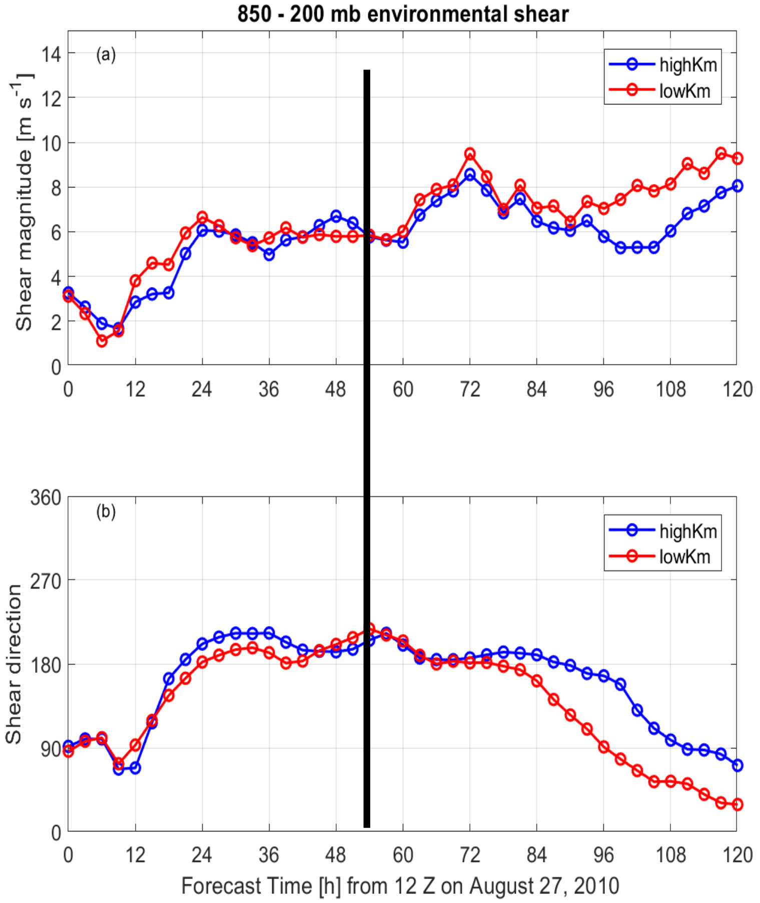


- At RI onset, HWRF forecasts with reduced vertical diffusion have stronger and deeper updrafts in regions inward from the radius of maximum wind (RMW) where the inertial stability is larger, and stronger boundary layer convergence closer to the storm center.

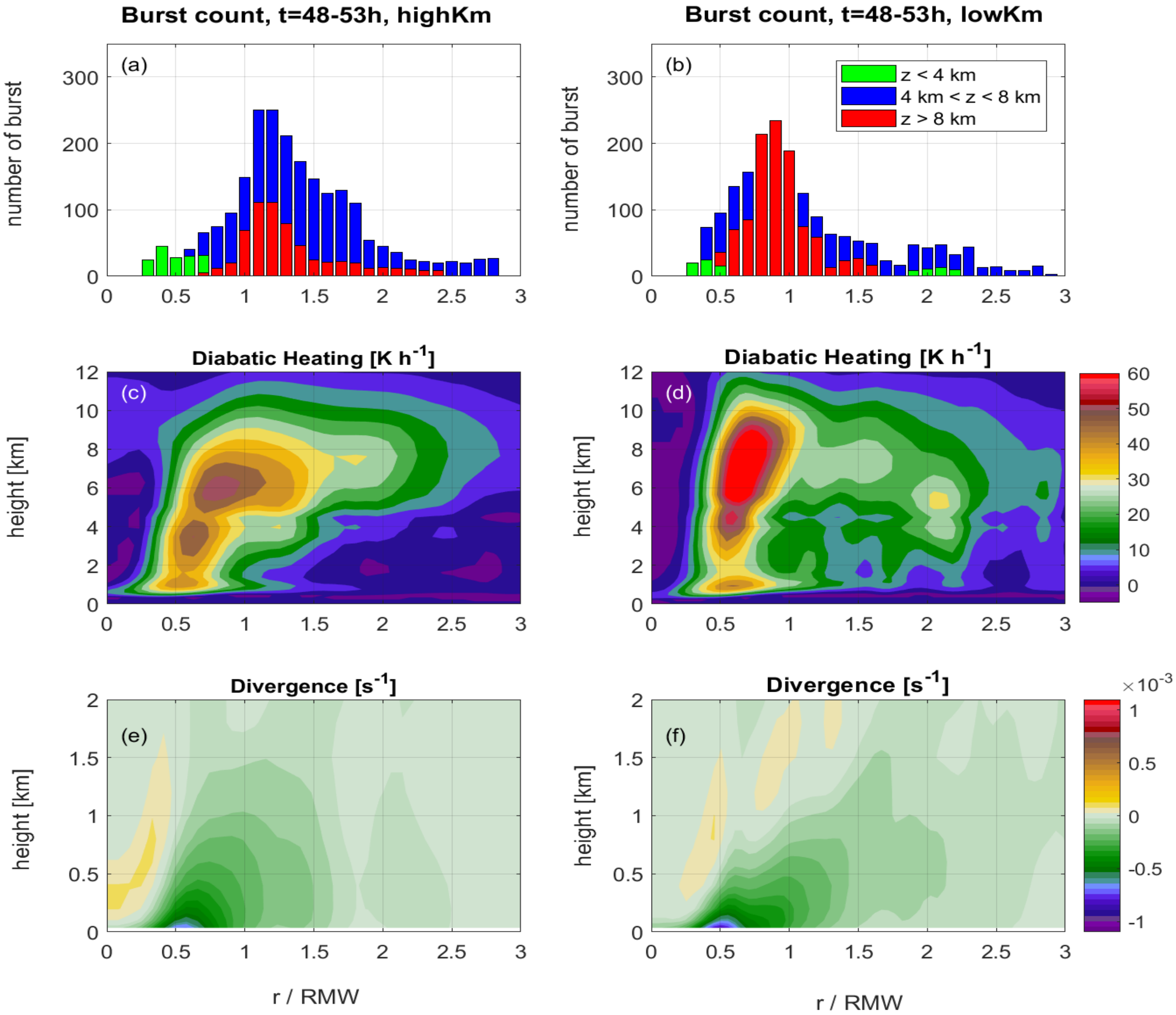
Case study



Hurricane Earl intensified in a moderate shear environment.



(Zhang and Rogers 2019)

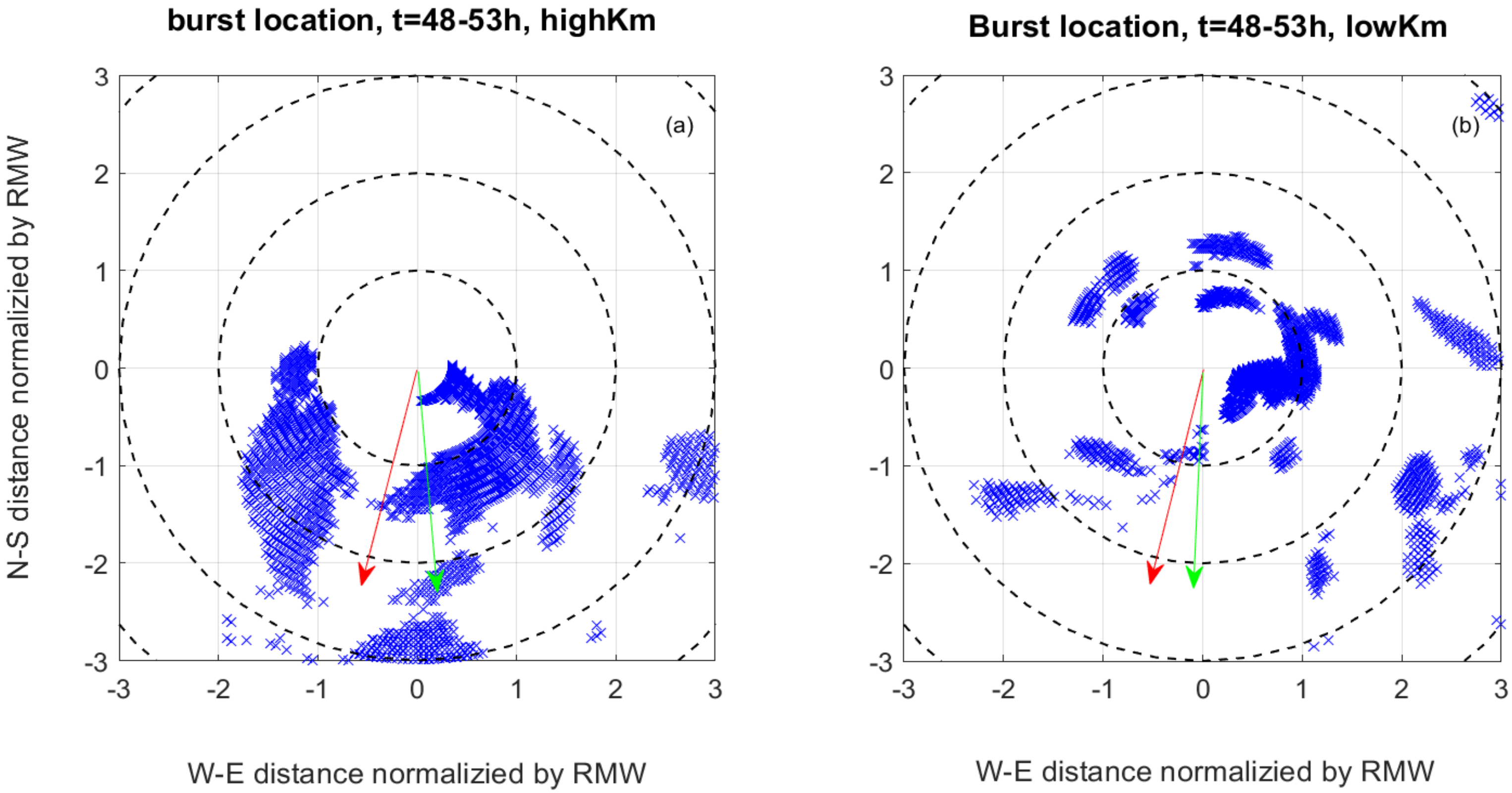


- Before the intensity bifurcation point, low-Km forecast produces more bursts inside the RMW than the high-Km forecast at RI onset.
- The larger number of convective bursts inside the RMW are collocated with larger inertial stability and diabatic heating in the low-Km forecast than in the high-Km forecast.

Azimuthal distribution of convective bursts

Red arrow – shear direction

Green arrow – tilt direction

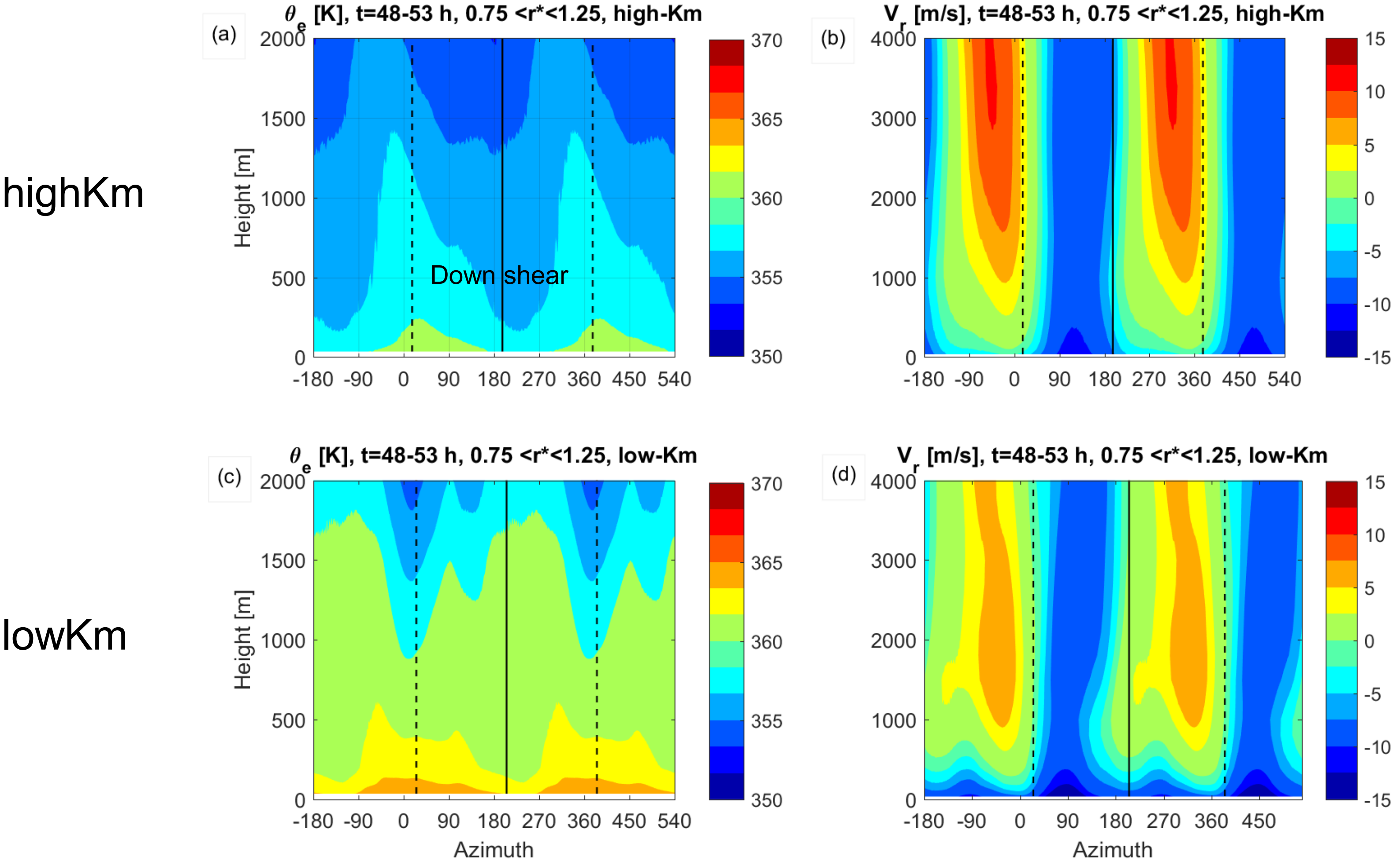


burst location, t=48-53h, highKm

Burst location, t=48-53h, lowKm

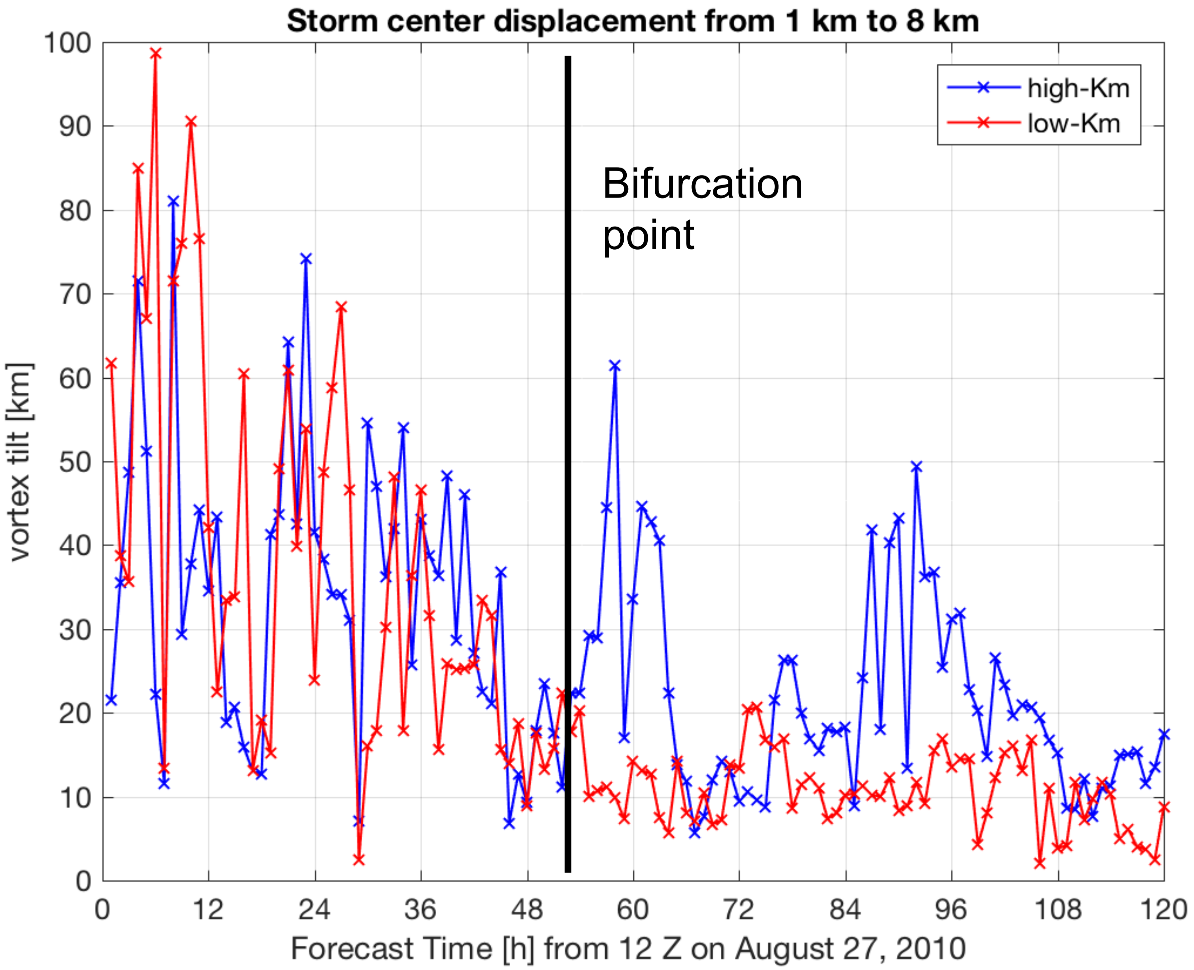
- ➢ The bursts are more symmetrically distributed near RMW in the low-Km forecast than in the high-Km forecast, with more bursts located in the upshear-left quadrant in low-Km forecast.

Asymmetric distribution of θ_e and V_r

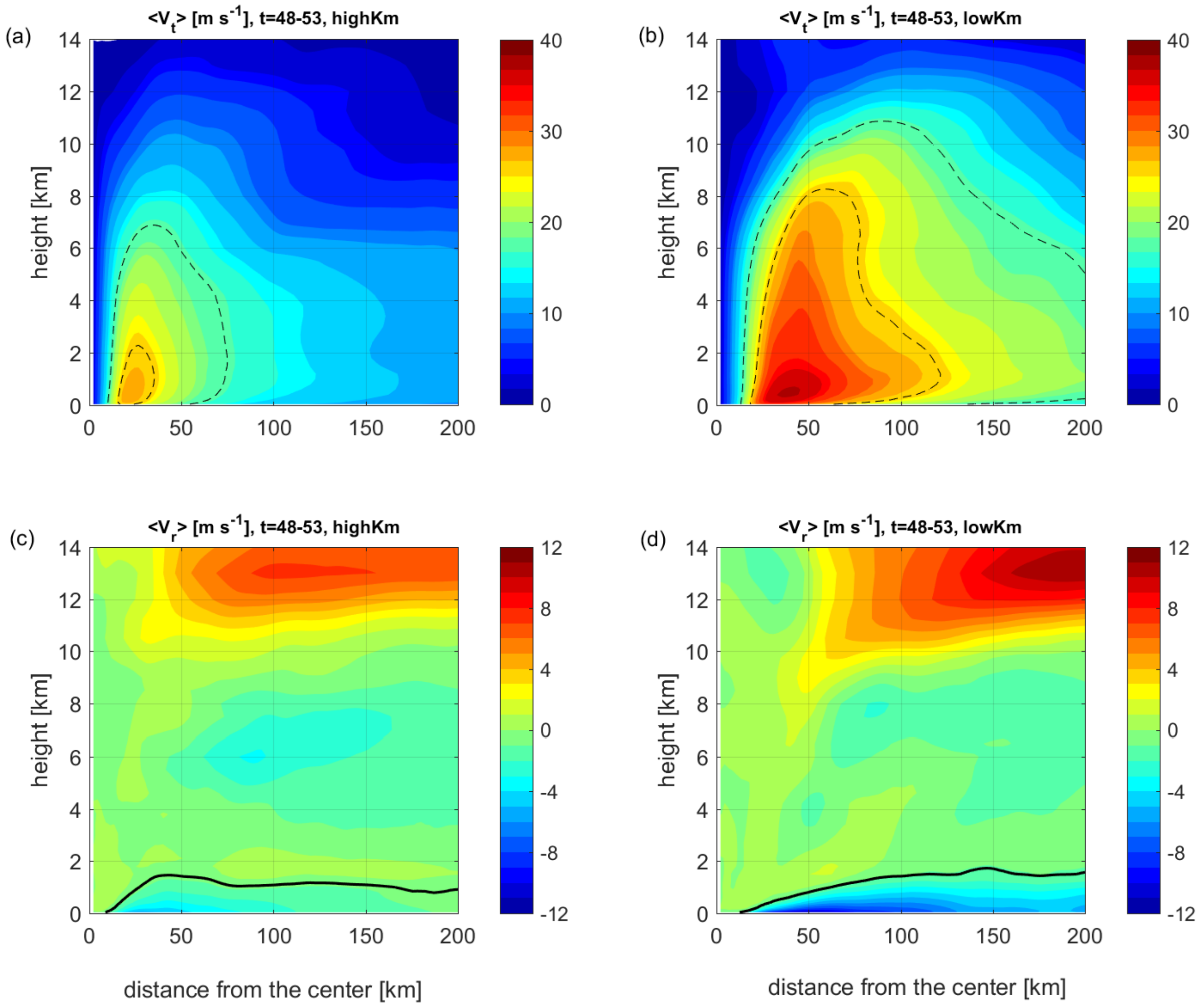


- At the eyewall region, both the low-level inflow and moist entropy (θ_e) are more symmetrically distributed in the low-Km forecast than in the high-Km forecast, especially within in the inflow layer.

Vortex tilt

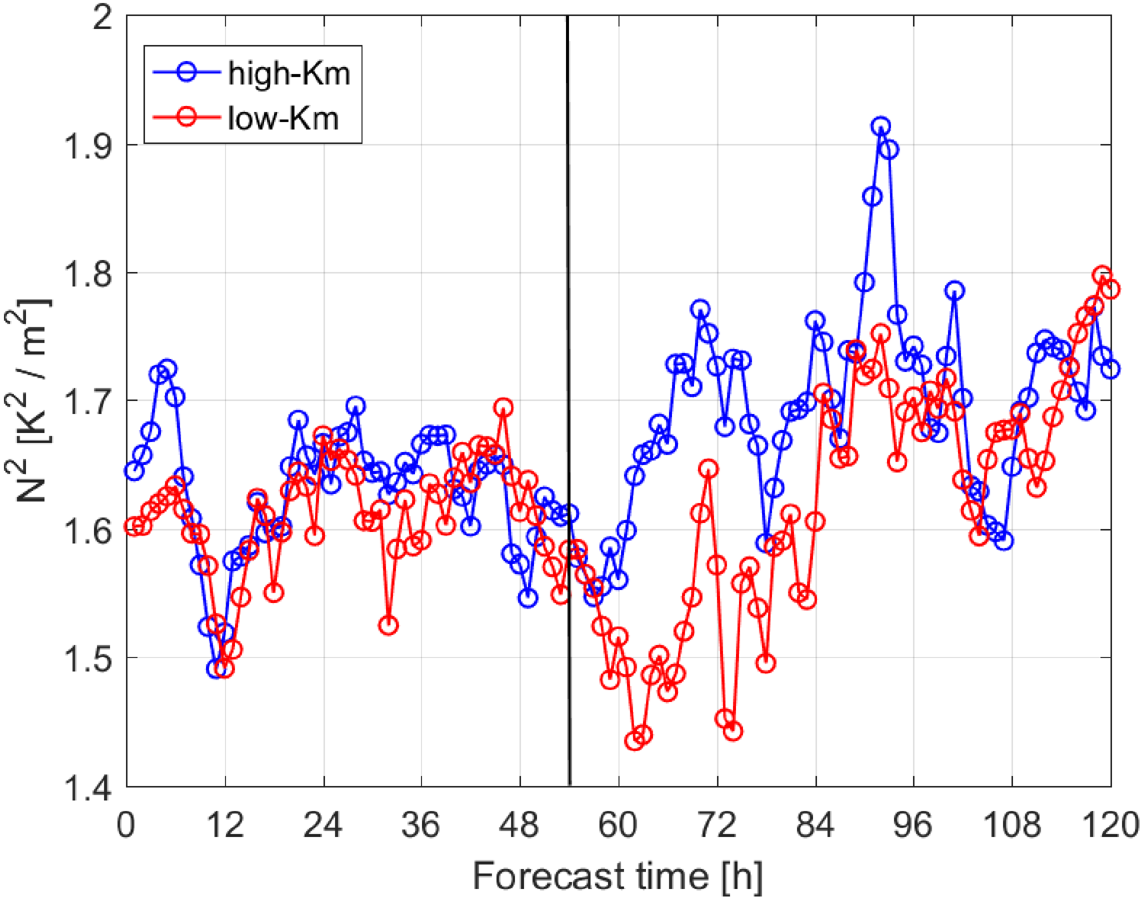


- ➢ Both forecasts show significant 1-8 km tilt up to intensity bifurcation point at ~54 h.
- ➢ After that point, tilt in the low-Km forecast settles down to ~10 km; that in the high-Km oscillates between 10 and 60 km.



- The vortex in the low-Km forecast is deeper, stronger and broader than that in the high-Km forecast, so that it is more resilient to shear in the low-Km forecast, according to tilt dynamics (Jones 1995; Reasor et al. 2001).

Static stability above the boundary layer

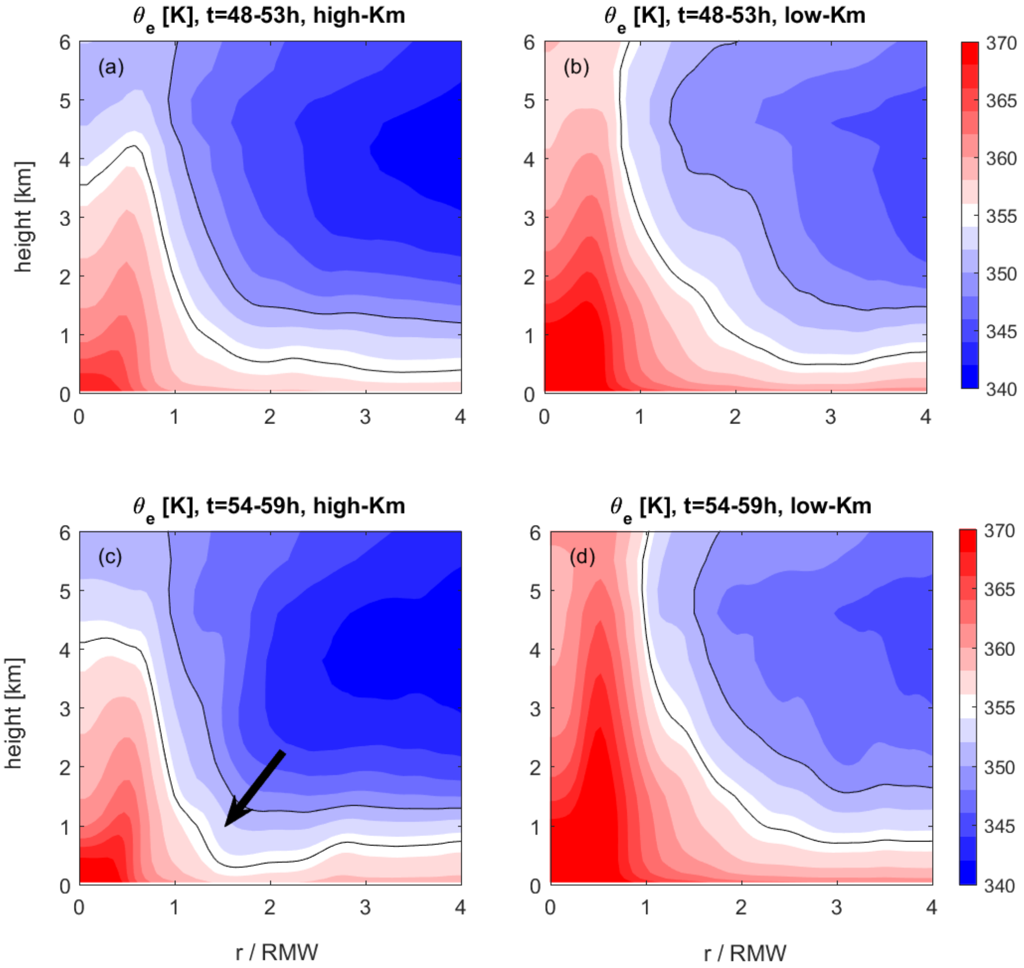


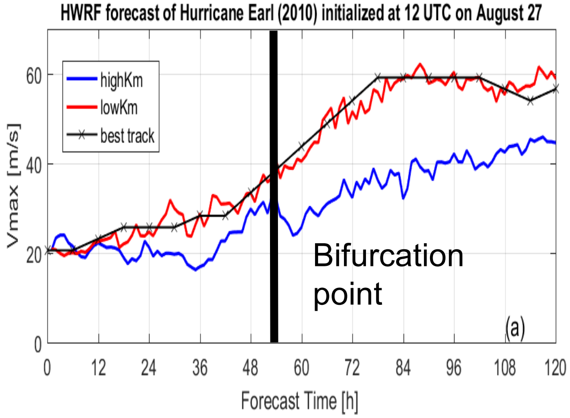
- The mid to upper level static stability is much smaller in the low-Km forecast than in the high-Km forecast, which makes the vortex more resilient to shear from being tilted, according to theoretical and numerical studies on tilt dynamics (Jones 1995; 2004; Reasor et al. 2004; Schecter 2015).

Axisymmetric Boundary-layer θ_e Distribution

Before Bifurcation point

After bifurcation point





- ➢ The boundary-layer θ_e becomes smaller in the high-Km forecast than in the low-Km forecast after the intensity bifurcation point .

Can surface enthalpy fluxes recover the θ_e deficit for air parcels traveling from upshear-left to downshear-right quadrant?

$$\frac{d\theta_e}{dt} = \frac{\theta_e}{\theta}\frac{d\theta}{dt} + \frac{\theta_e L_v}{c_p T_{LCL}}\frac{dq}{dt}$$

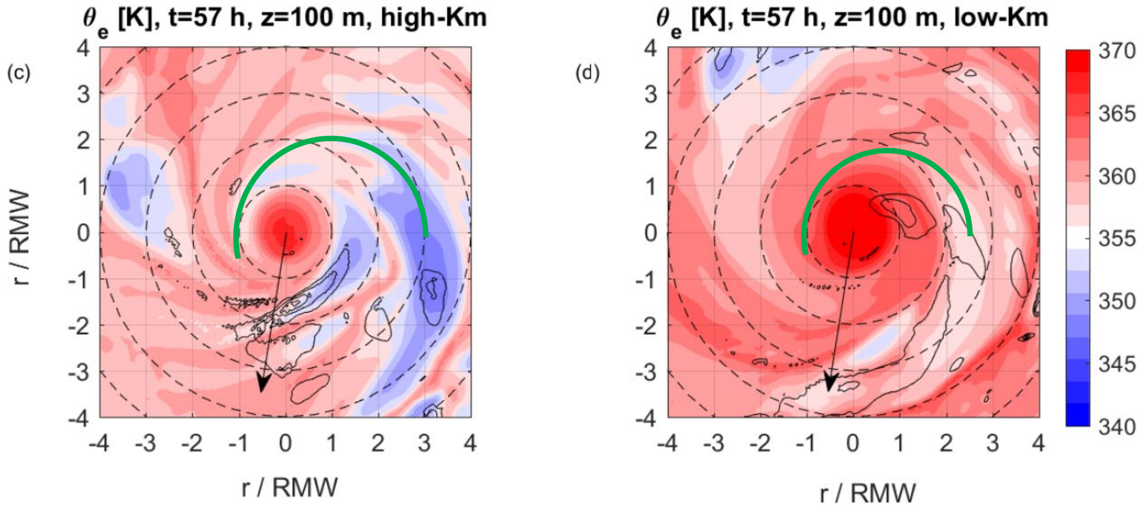
$$\theta_e = \theta \exp(\frac{L_v q}{c_p T_{LCL}})$$

$$\frac{d\theta}{dt} = \frac{\theta}{c_p T}(-\frac{1}{\rho}\frac{\partial F_{Hz}}{\partial z}) = \frac{\theta}{c_p T}(\frac{F_{H0}}{\rho \Delta z})$$

$$\frac{dq}{dt} = -\frac{1}{\rho L_v}\frac{\partial F_{qz}}{\partial z}) = \frac{F_{q0}}{\rho L_v \Delta z}$$

Fq is the latent heat flux (Wm^{-2}), F_H is the sensible heat flux ((Wm^{-2}),
T_{LCL} is the temperature at the level of lifting condensation (K),
θ_e is the equivalent potential temperature (K), θ is the potential temperature (K),
$d\theta/dt$ is the calculated rate of change of θ (K hr^{-1}), dq/dt is the calculated rate of change of q (g kg^{-1} hr^{-1}) , $d\theta_e/dt$ is the rate of change of θ_e (K hr^{-1}),
$\Delta\theta_e$ (ES) is the estimated change in θ_e due to surface fluxes,
and $\Delta\theta_e$ (OB) is the observed change in θ_e in the model.

Can surface enthalpy fluxes recover the θ_e deficit?



Green curve shows inflow trajectory

HWRF	θ	θ_e	T_{LCL}	F_H	F_q	$d\theta/dt$	dq/dt	$d\theta_e/dt$	$\Delta\theta_e$ (ES)	$\Delta\theta_e$ (OB)
HighKm	301.5	354.5	294.8	19.9	236.1	0.06	0.30	0.95	4.9	8.5
lowKm	301.9	371.0	299.8	38.2	360.6	0.12	0.46	1.53	8.2	6.3

- no
- yes

(Zhang and Rogers 2019 MWR)

Summary

- The cumulus and boundary-layer parameterization schemes have substantial impacts on HWRF’s RI prediction, while the impact of the horizontal diffusion parameterization is small.
- A temperature budget showed that both the temperature advection and diabatic heating are larger near the storm center in the HWRF forecast with the scale-aware cumulus scheme (GF) than that with the SAS scheme.
- The boundary-layer eddy diffusivity regulates not only the boundary-layer structure but also the vortex-scale and convective-scale structures, and their interaction with the environmental wind shear.