36th Conference on Hurricanes and Tropical Meteorology

Modifications to Three-Dimensional Turbulence Parameterization for Tropical Cyclone Simulation at Convection-Permitting Resolution

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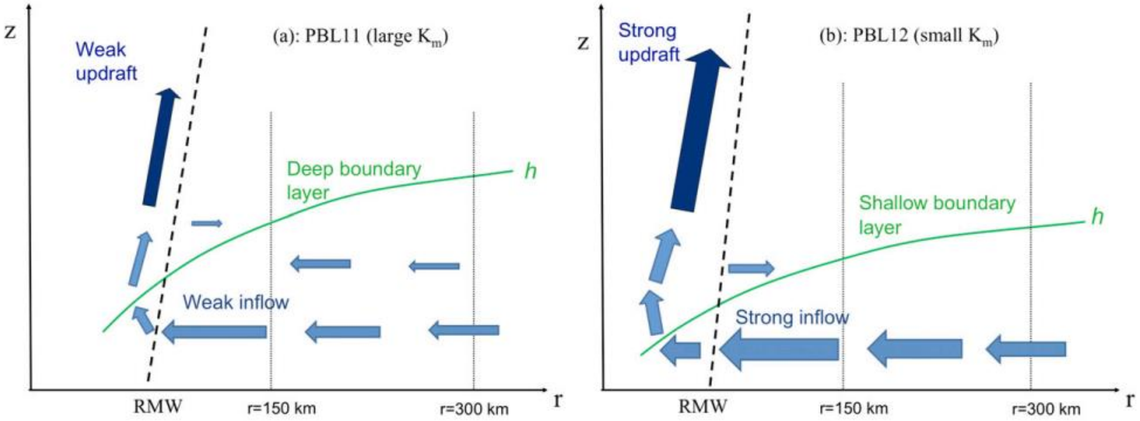
1. Background

- To accurately represent the subgrid-scale (SGS) turbulent fluxes in numerical weather prediction models (NWP) is important for simulating the dynamic and thermal structure of the TC.



(Zhang et al., 2015)

- Drawbacks for the turbulence parameterization at convection-permitting resolution (CPR:1~4 km)

1) 1D PBL schemes are still mainly used (excessive turbulent transport)

2) 1D and 3D schemes are based on the **Eddy-diffusivity closure** (downgradient)

3) All the schemes were developed within PBL (unable to accurately describe the turbulence above PBL)

1. Background

- A new SGS model, **H-gradient closure**, was proposed by Moeng et al. (2010)

$$\overline{u_i'u_j'}^{\Delta} = C_s \frac{\Delta^2}{12}\left(\frac{\partial \overline{u}_i^{\Delta}}{\partial x}\frac{\partial \overline{u}_j^{\Delta}}{\partial x} + \frac{\partial \overline{u}_i^{\Delta}}{\partial y}\frac{\partial \overline{u}_j^{\Delta}}{\partial y}\right) \qquad \overline{u_i's'}^{\Delta} = C_s \frac{\Delta^2}{12}\left(\frac{\partial \overline{u}_i^{\Delta}}{\partial x}\frac{\partial \overline{s}^{\Delta}}{\partial x} + \frac{\partial \overline{u}_i^{\Delta}}{\partial y}\frac{\partial \overline{s}^{\Delta}}{\partial y}\right)$$

1) scale aware
2) countergradient

- The H-gradient closure was already shown good performance in the simulation of near-equilibrium tropical convection and supercell convection systems (Verrelle et al., 2017; Hanley et al., 2019; Strauss et al., 2019; Sun et al., 2021).

This work aims to:

1) Evaluate the performance of H-gradient closure in TC at CPR

2) Improve the <u>scale-adaptive three-dimension turbulent parameterization</u>

SMS-3DTKE scheme (Zhang et al., 2018)

2. Performance of H-gradient closure in TC at CPR

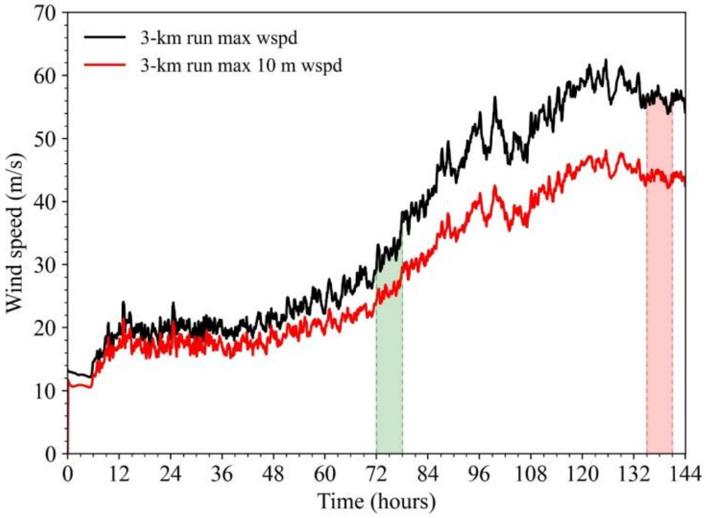
- **Benchmark：3 km results coarse-grained from idealized TC LES (200 m)**

$$\overline{u_i'\varphi'}^{\Delta} = \overline{\left(u_i - \overline{u_i}^{\Delta}\right)\left(\varphi - \overline{\varphi}^{\Delta}\right)}^{\Delta}$$

LES:

Initial and boundary conditions (3 km-run)		
Simulated period	144 hours	
Domain	1	
Horizontal grid spacing	3 km	
Horizontal grid number	201*201	
Domain area (km*km)	600*600	
Vertical layer number	81（25 km）	
Turbulence scheme	YSU	
Microphysics	Thompson	
wrfout (time interval)	5 min	
Setup of LES		
Restart（LES）	RI 72 -78 h	Mature 135-141 h
Horizontal grid spacing	**200 m**	
Horizontal grid number	3000*3000	
Turbulence scheme	**SMS-3DTKE**	

Maximum wind speed



RI mature

2. Performance of H-gradient closure in TC at CPR

- **H-gradient:**

$$\overline{u_i'u_j'}^{\Delta} = C_s \frac{\Delta^2}{12}\left(\frac{\partial \overline{u}_i^{\Delta}}{\partial x}\frac{\partial \overline{u}_j^{\Delta}}{\partial x} + \frac{\partial \overline{u}_i^{\Delta}}{\partial y}\frac{\partial \overline{u}_j^{\Delta}}{\partial y}\right)$$

$$\overline{u_i's'}^{\Delta} = C_s \frac{\Delta^2}{12}\left(\frac{\partial \overline{u}_i^{\Delta}}{\partial x}\frac{\partial \overline{s}^{\Delta}}{\partial x} + \frac{\partial \overline{u}_i^{\Delta}}{\partial y}\frac{\partial \overline{s}^{\Delta}}{\partial y}\right)$$

- **Eddy-diffusivity:**

$$\overline{u_i'u_j'}^{\Delta} = -K_M\left(\frac{\partial \overline{u}_i^{\Delta}}{\partial x_j} + \frac{\partial \overline{u}_j^{\Delta}}{\partial x_i}\right)$$

$$\overline{u_i's'}^{\Delta} = -K_H \frac{\partial \overline{s}^{\Delta}}{\partial x_i}$$

- **Transport direction of turbulent flux:**

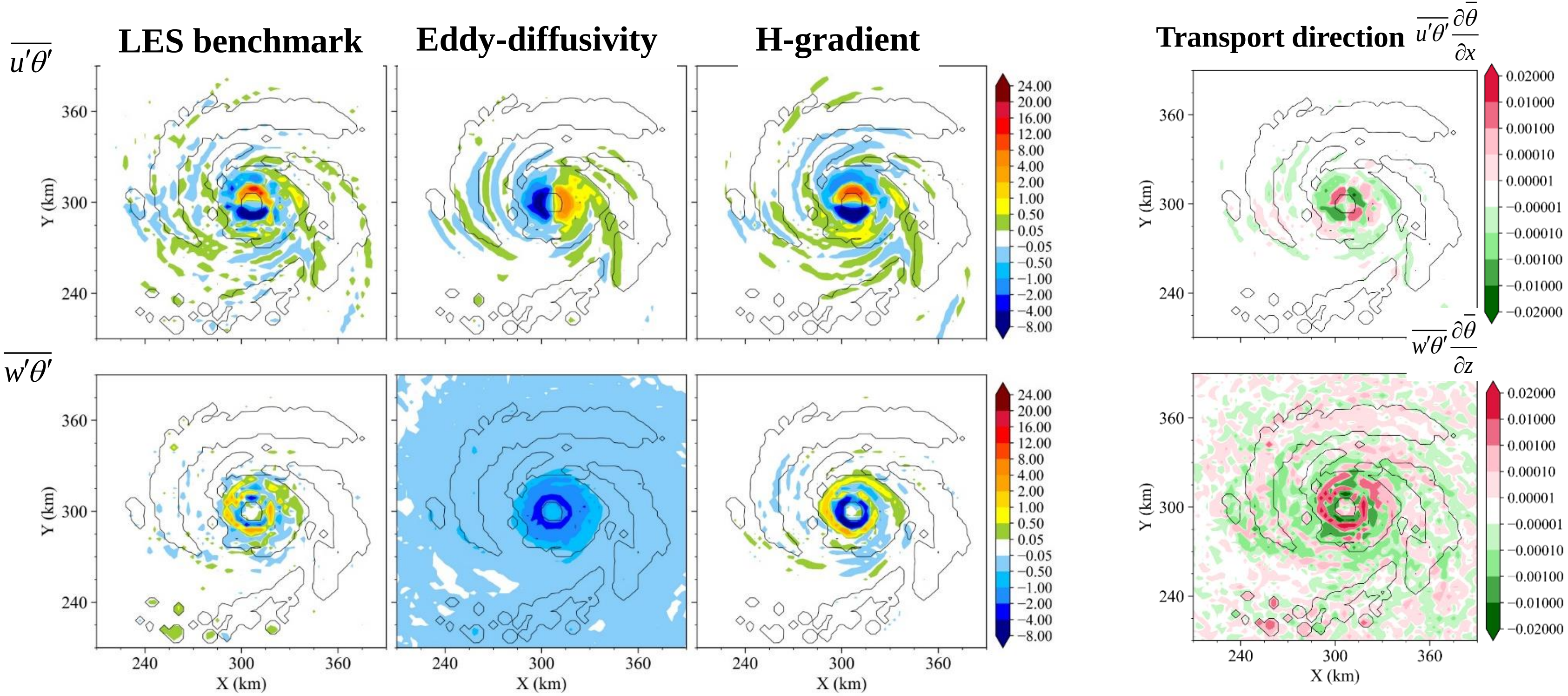
$$\overline{u_i'u_j'}^{\Delta}\frac{\partial \overline{u}^{\Delta}}{\partial x_i} \qquad \overline{u_i's'}^{\Delta}\frac{\partial \overline{s}^{\Delta}}{\partial x_i}$$

Negative: along the gradient

Positive: countergradient

2. Performance of H-gradient closure in TC at CPR

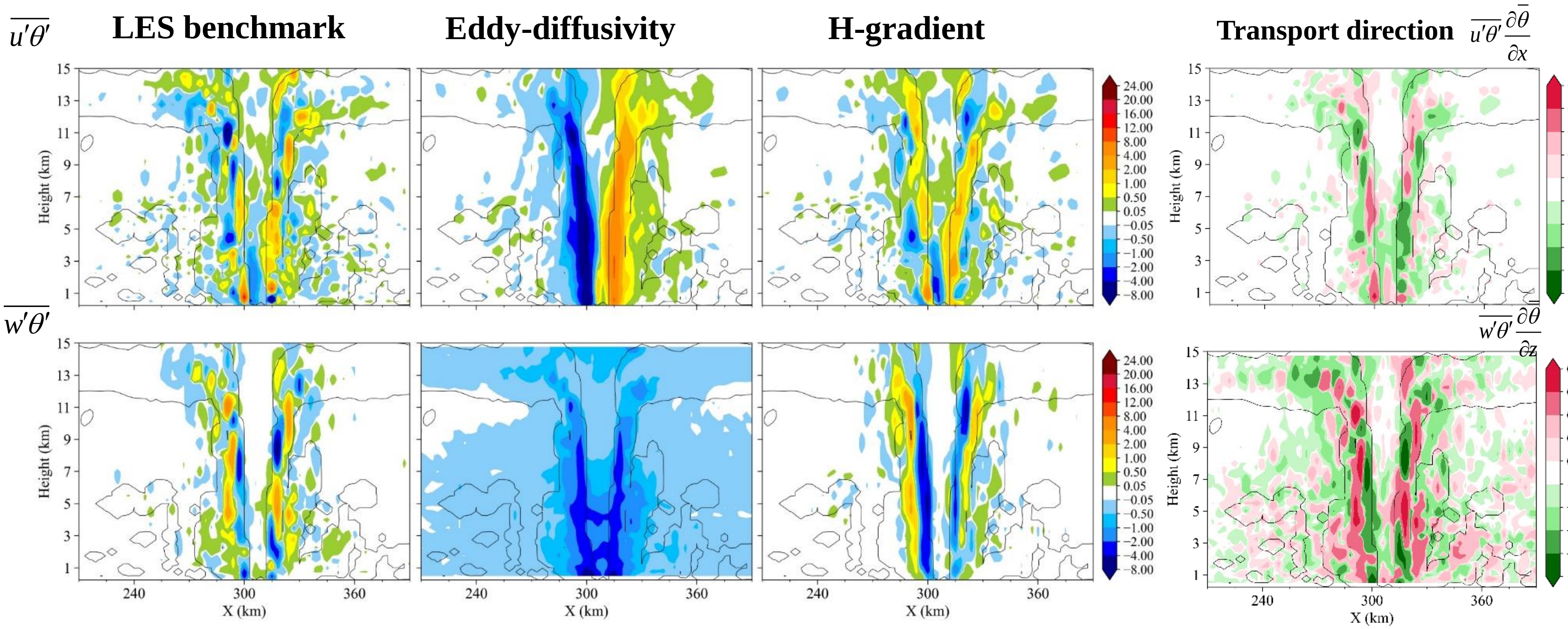
Heat fluxes at mature stage (t = 141)



- H-gradient closure is capable of accurately representing the countergradient fluxes in TC

2. Performance of H-gradient closure in TC at CPR

Heat fluxes at mature stage (t = 141)

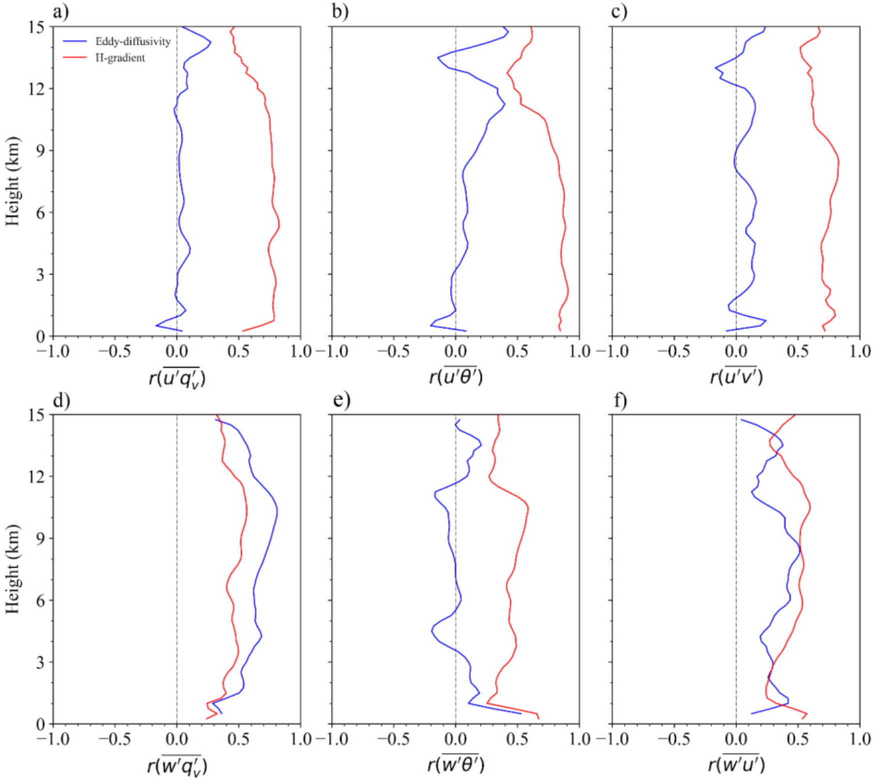


- The H-gradient closure can capture the significant upward heat transports in the eyewall throughout the troposphere.

2. Performance of H-gradient closure in TC at CPR

Spatial correlation coefficients with height

Blue: Eddy-diffusivity **Red : H-gradient**



Mean spatial correlation coefficient

Turbulent flux	Eddy-diffusivity	H-gradient
$\overline{u'q_v'}$	0.047	0.713 ⇧
$\overline{u'\theta'}$	0.112	0.753 ⇧
$\overline{u'v'}$	0.078	0.701 ⇧
$\overline{w'q_v'}$	0.618	0.442 ⇩
$\overline{w'\theta'}$	0.027	0.427 ⇧
$\overline{w'q_v'}$	0.316	0.445 ⇧

2. Performance of H-gradient closure in TC at CPR

Turbulent kinetic energy (TKE/*e*): Subgrid scale

$$\frac{\partial e}{\partial t}+\bar{u}_j\frac{\partial e}{\partial x_j}=-\overline{u_i'u_j'}\frac{\partial \bar{u}_i}{\partial x_j}+\delta_{i3}\frac{g}{\bar{\theta}_v}\overline{u_i'\theta_v'}-\frac{\partial\overline{u_i'(e+p'/\bar{\rho})}}{\partial x_i}-\nu\overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}}$$

Mean kinetic energy (MKE/E): Resolved scale

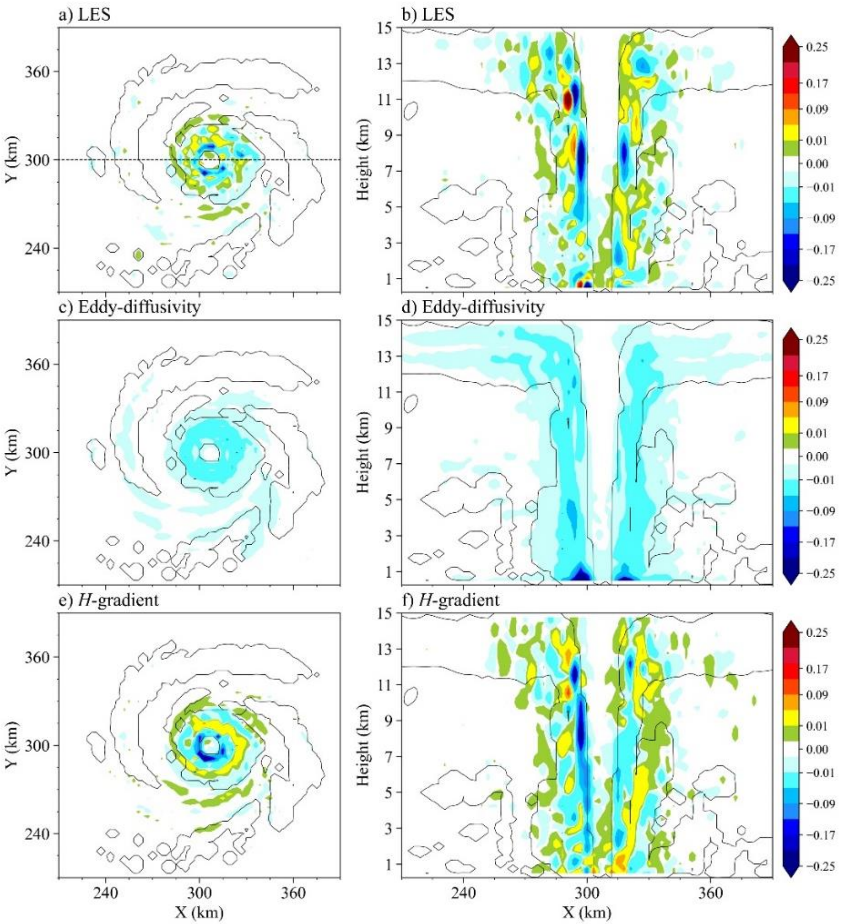
$$\frac{\partial E}{\partial t}+\bar{u}_j\frac{\partial E}{\partial x_j}=\overline{u_i'u_j'}\frac{\partial \bar{u}_i}{\partial x_j}-\frac{\partial \bar{u}_i\overline{u_i'u_j'}}{\partial x_j}+\delta_{i3}\bar{u}_i g-\frac{\bar{u}_i}{\bar{\rho}}\frac{\partial \bar{p}}{\partial x_i}-\nu\frac{\partial \bar{u}_i}{\partial x_j}\frac{\partial \bar{u}_i}{\partial x_j}$$

Energy transfer: $\overline{u_i'u_j'}\frac{\partial \bar{u}_i}{\partial x_j}$

Negative: Resolved scale (e) → Subgrid scale (E) **Scatter**

Positive: Subgrid scale (E) → Resolved scale (e) **Backscatter**

- H-gradient closure is capable of capturing both the scatter and backscatter of energy



3. Modification to SMS-3DTKE scheme

H-gradient

SMS-3DTKE → **SMS-3DTKE-H**

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial \overline{u'u'}}{\partial x} - \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'w'}}{\partial z}$$

$$\frac{\partial \overline{v}}{\partial t} = -\frac{\partial \overline{u'v'}}{\partial x} - \frac{\partial \overline{v'v'}}{\partial y} - \frac{\partial \overline{v'w'}}{\partial z}$$

$$\frac{\partial \overline{w}}{\partial t} = -\frac{\partial \overline{w'u'}}{\partial x} - \frac{\partial \overline{w'v'}}{\partial y} - \frac{\partial \overline{w'w'}}{\partial z}$$

$$\frac{\partial \overline{\theta}}{\partial t} = -\frac{\partial \overline{\theta'u'}}{\partial x} - \frac{\partial \overline{\theta'v'}}{\partial y} - \frac{\partial \overline{\theta'w'}}{\partial z}$$

$$\frac{\partial \overline{q_{vci}}}{\partial t} = -\frac{\partial \overline{q'_{vci}u'}}{\partial x} - \frac{\partial \overline{q'_{vci}v'}}{\partial y} - \frac{\partial \overline{q'_{vci}w'}}{\partial z}$$

Horizontal fluxes: replaced by H-gradient

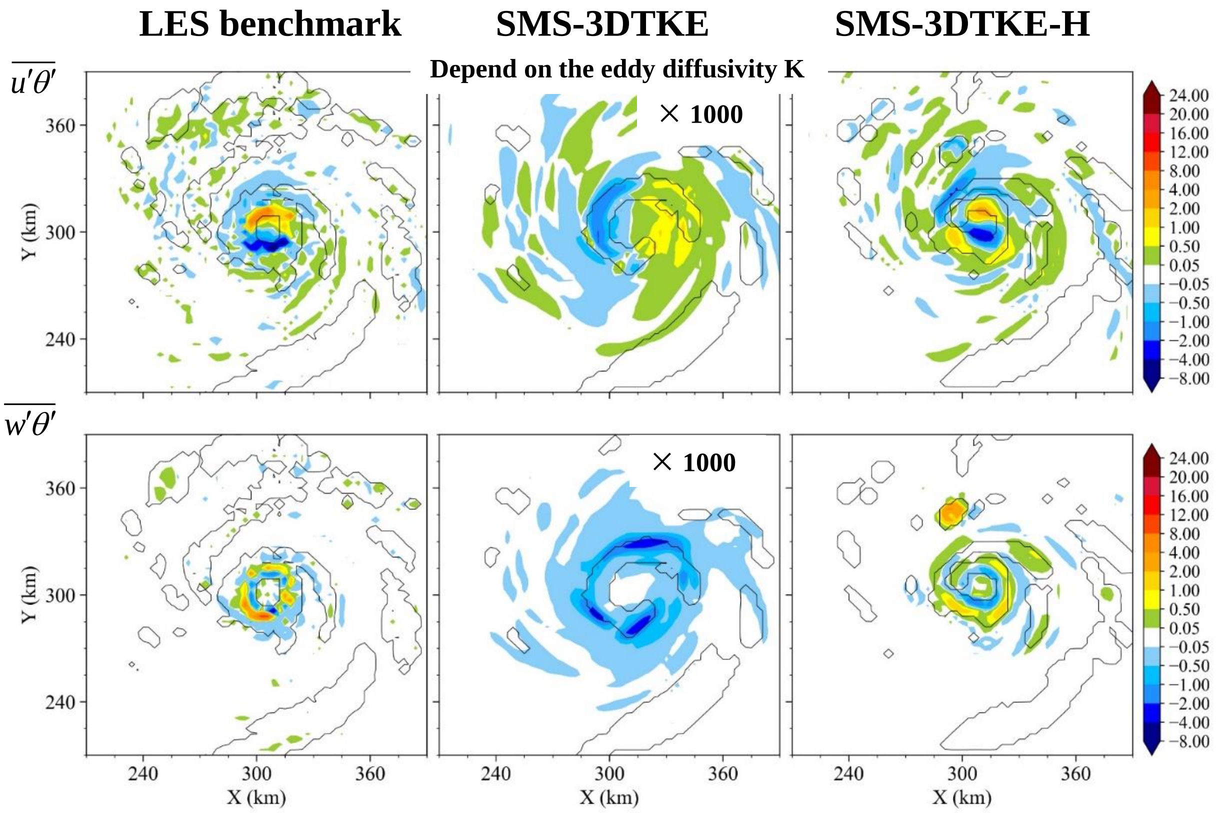
Vertical fluxes: within PBL, original SMS-3DTKE

above PBL, SMS-3DTKE +H-gradient

$$\overline{w'\theta'} = -K_H \frac{\partial \overline{\theta}}{\partial z} + \overline{w'\theta'}^{NL}_{PBL} + C_s \frac{\Delta^2}{12}\left(\frac{\partial \overline{w}}{\partial x}\frac{\partial \overline{\theta}}{\partial x} + \frac{\partial \overline{w}}{\partial y}\frac{\partial \overline{\theta}}{\partial y}\right)_{above\ \ PBL}$$

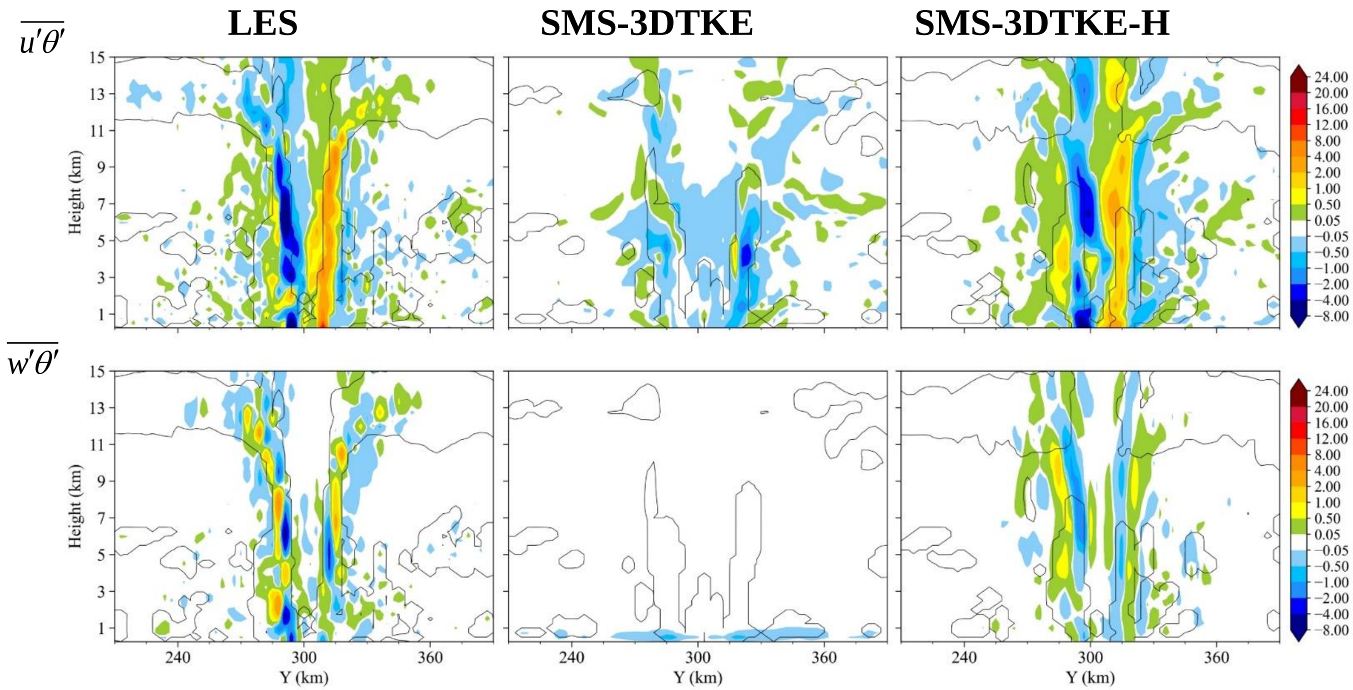
4. Evaluation of SMS-3DTKE-H scheme

Idealized TC: Heat fluxes at mature stage (t = 138)



4. Evaluation of SMS-3DTKE-H scheme

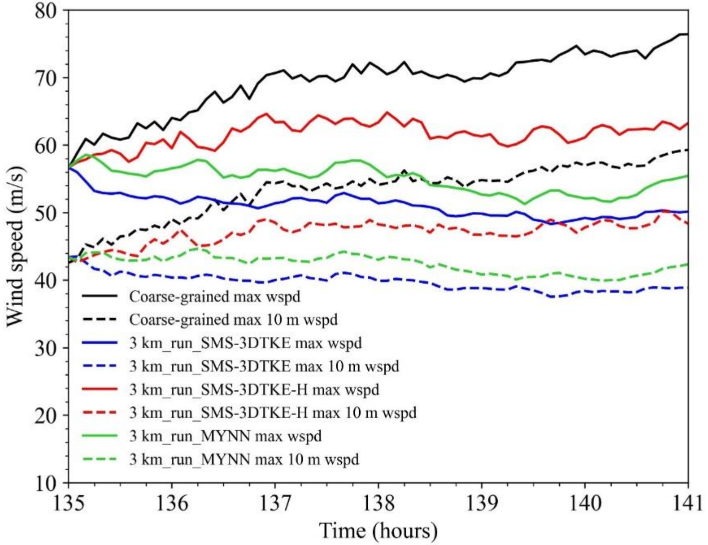
Idealized TC: Heat fluxes at mature stage (t = 138)

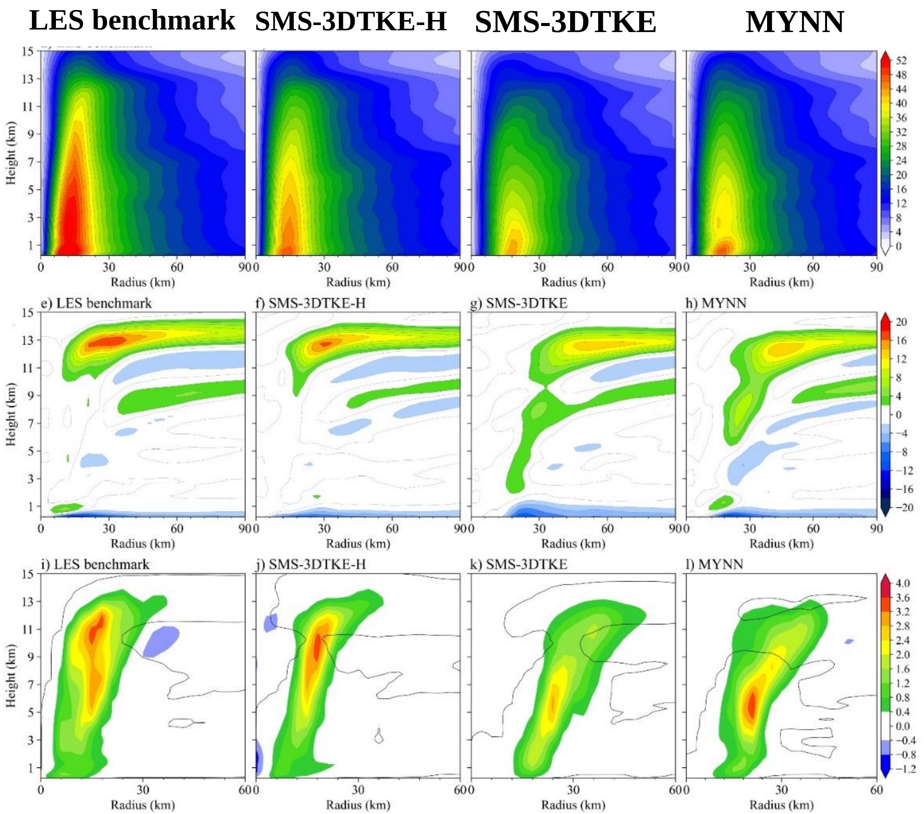


4. Evaluation of SMS-3DTKE-H scheme

Idealized TC:

Black: LES **Red: SMS-3DTKE-H**
Green: MYNN **Blue: SMS-3DTKE**



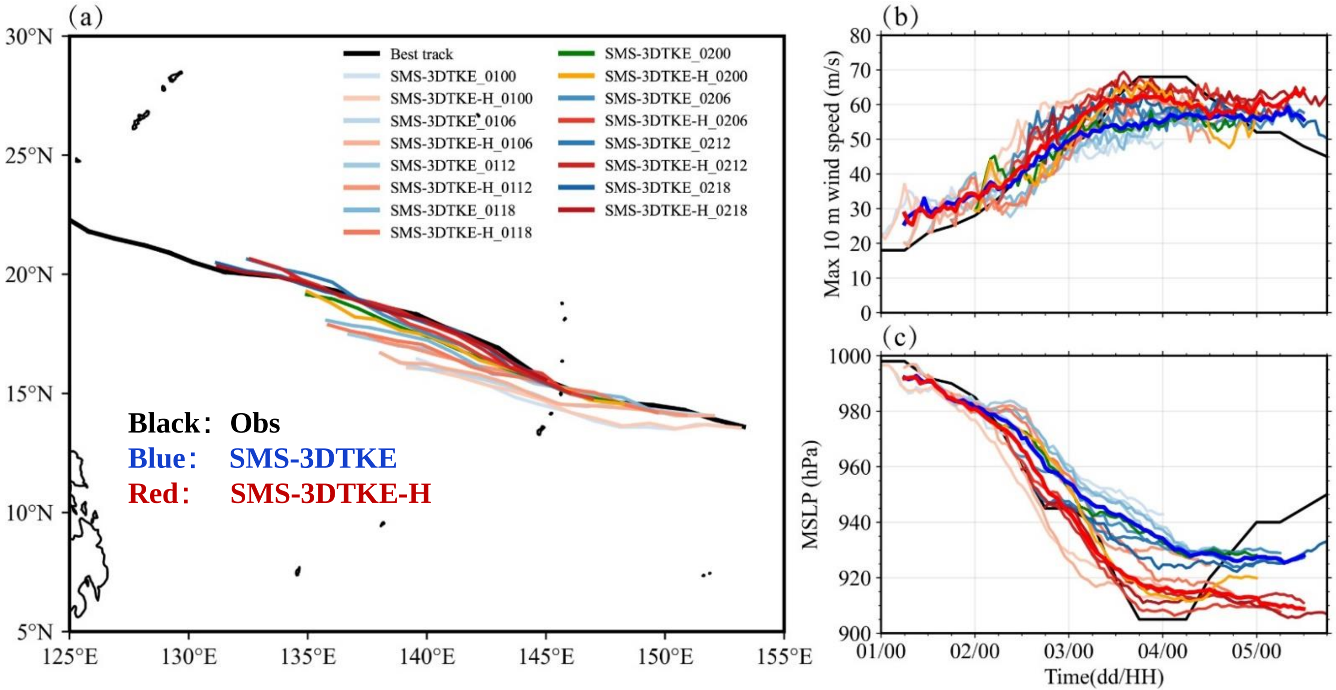


- SMS-3DTKE-H scheme significantly improves the simulation of intensity and structure of idealized TC.

4. Evaluation of SMS-3DTKE-H scheme

Real-time TC: Soudelor (2015)

- SMS-3DTKE-H scheme improves the TC intensity more significantly.



RMSE:

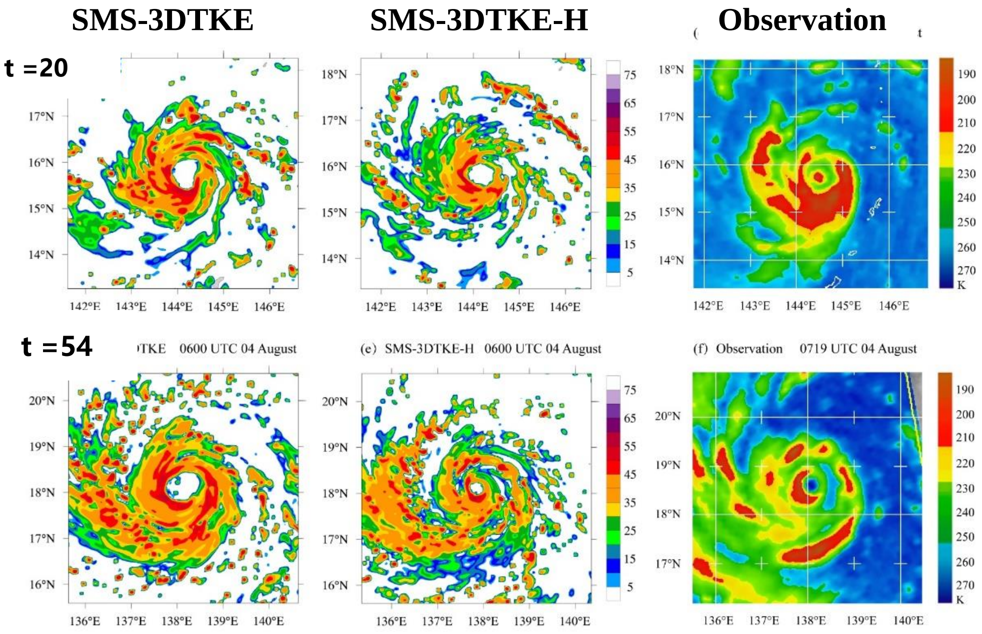
V_{max10} ⇩ 6%

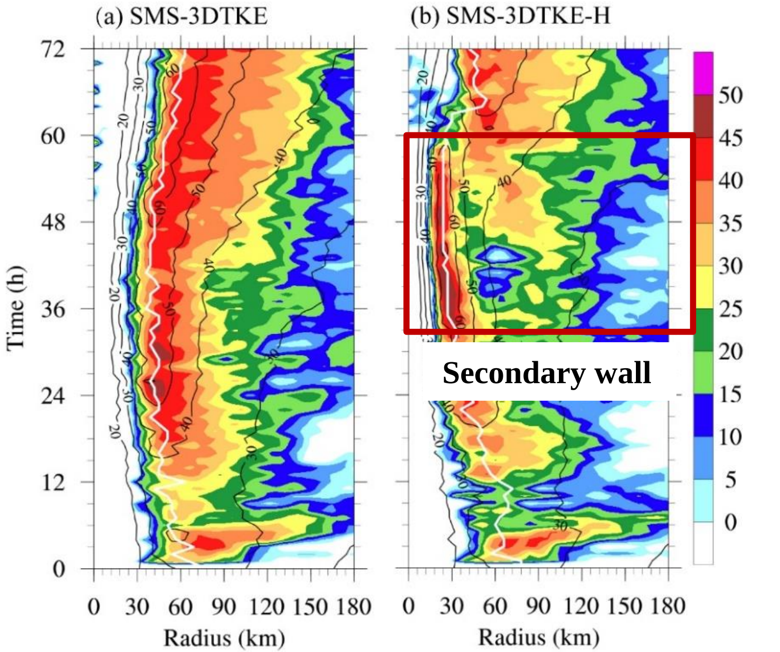
MSLP ⇩ 22%

4. Evaluation of SMS-3DTKE-H scheme

Real-time TC: Soudelor (2015)

- SMS-3DTKE-H scheme improves the simulation of TC size, shape and location of eyewall, especially the secondary wall structure.

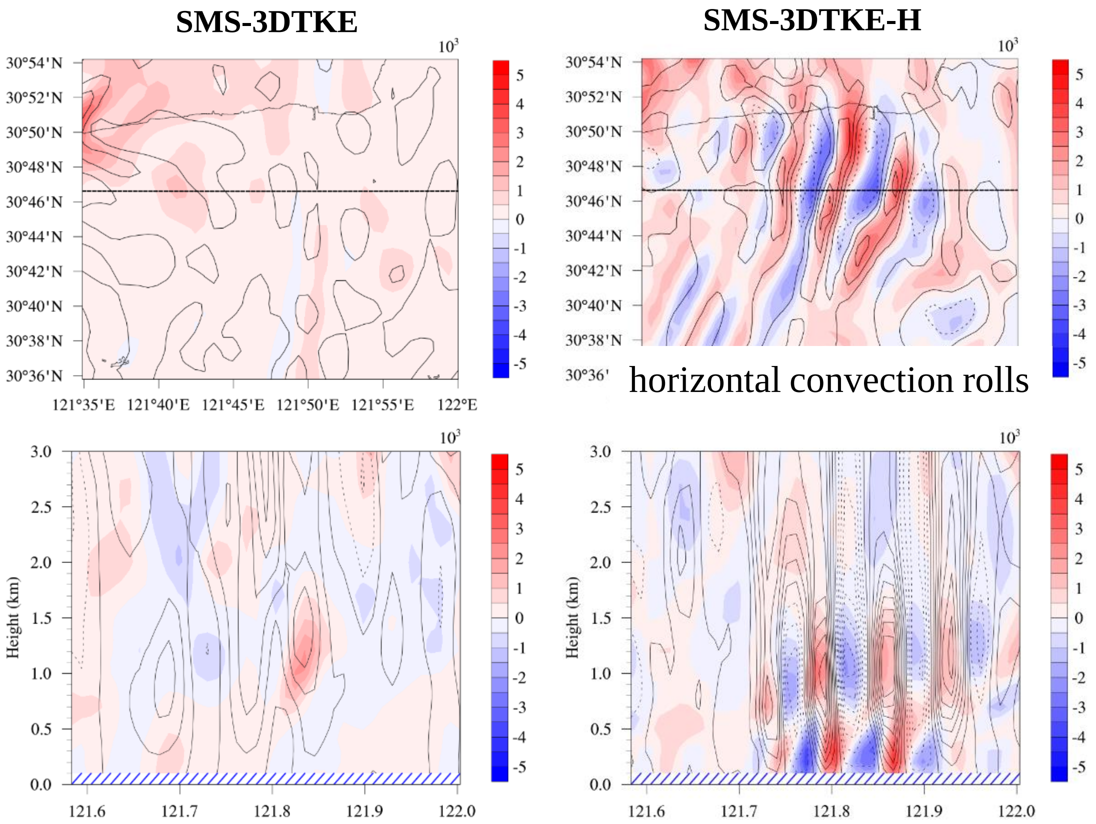




4. Evaluation of SMS-3DTKE-H scheme

Real-time TC:

- SMS-3DTKE-H is able to simulate more refined coherent structures, such as horizontal convection rolls.



Relative vorticity (Shaded) & Vertical velocity (contours)

5. Summary

(1) Compared to the Eddy-diffusivity closure, the H-gradient closure is more appropriate for representing SGS fluxes in the TC at CPR.

(2) H-gradient closure is capable of capturing both the scatter and backscatter of energy.

(3) By implementing the H-gradient closure, the modified SMS-3DTKE (SMS-3DTKE-H) scheme improves the simulation of TC intensity and structure.

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Thank you for your attention!

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