Parameterization of slantwise convection
in 2D idealized and 3D real-data simulations

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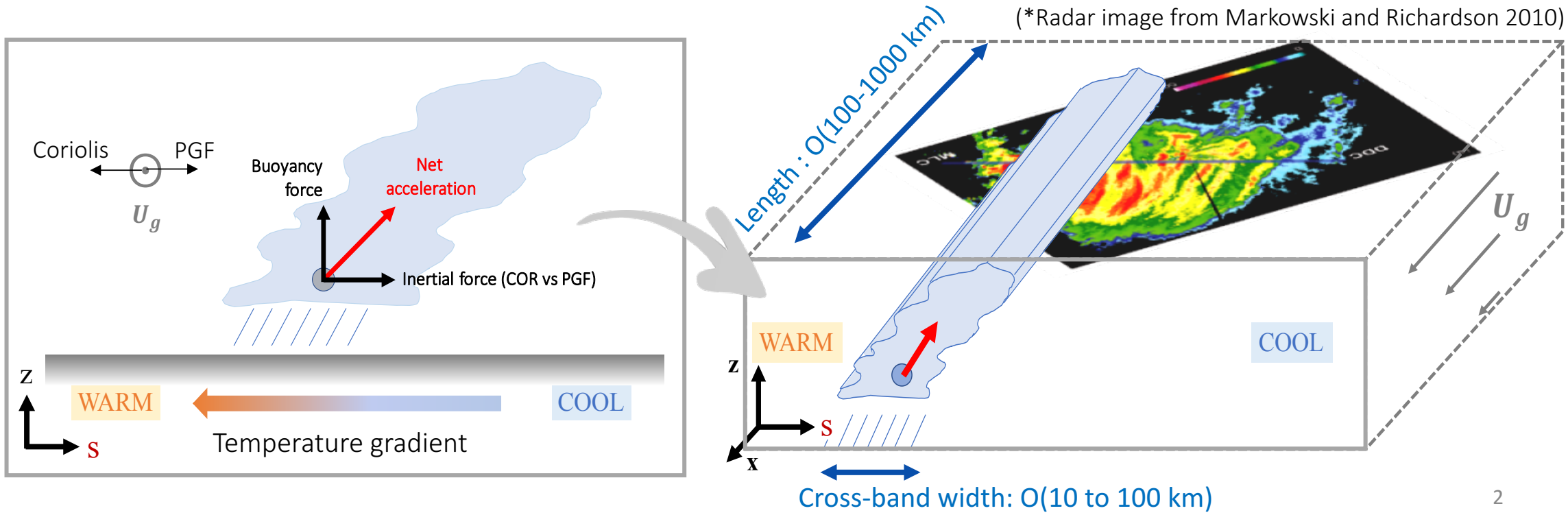
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Introduction

Slantwise convection results from the release of conditional symmetric instability (CSI)[1]:

- Involving buoyancy and inertial forces in the vertical and horizontal (along the horizontal temperature gradient, which the instability is theoretically "symmetric" about) directions, respectively.
- Often characterized by elongated bands aligned with the thermal wind.

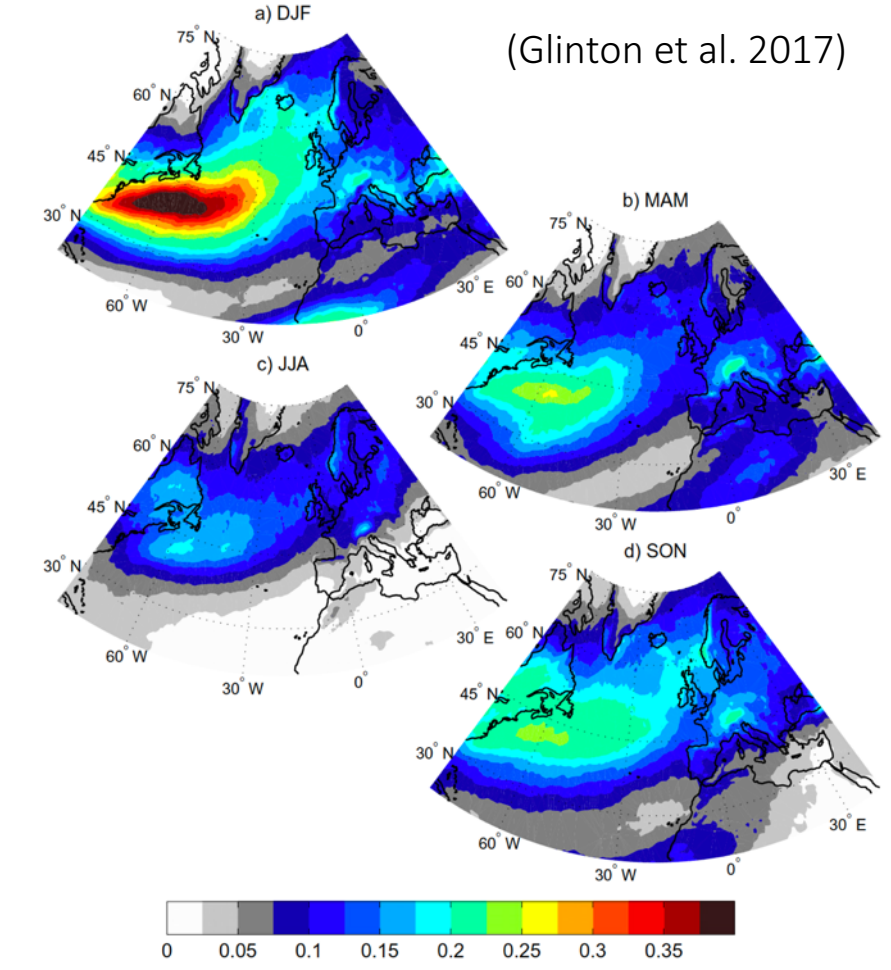


Motivation

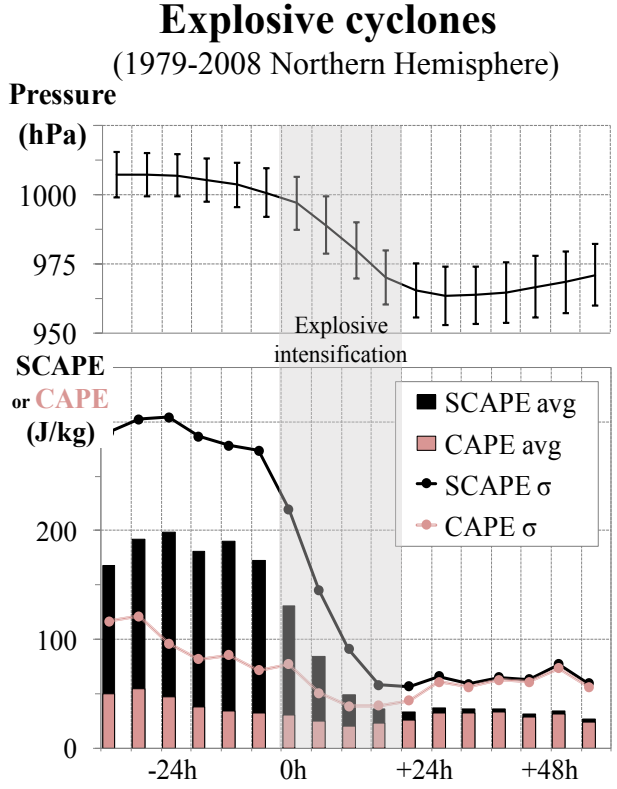
- Recent climatological studies have highlighted its importance in midlatitudes, especially its association with cyclone activity[2, 6].

- To adequately resolve slantwise convection, numerical model requires a grid spacing finer than ~10 km[7, 12], beyond which its parameterization may be needed.

1979-2010 averaged VRS (km)
(VRS: the air thickness susceptible to slantwise convection)



(Glinton et al. 2017)



(Chen et al. 2018)

Motivation

➢ Parameterizing slantwise convection?

- Most of the convective (cumulus) parameterization schemes (CPS) only consider upright convection by relating convection to moist gravitational instability, omitting the potential contribution from CSI.

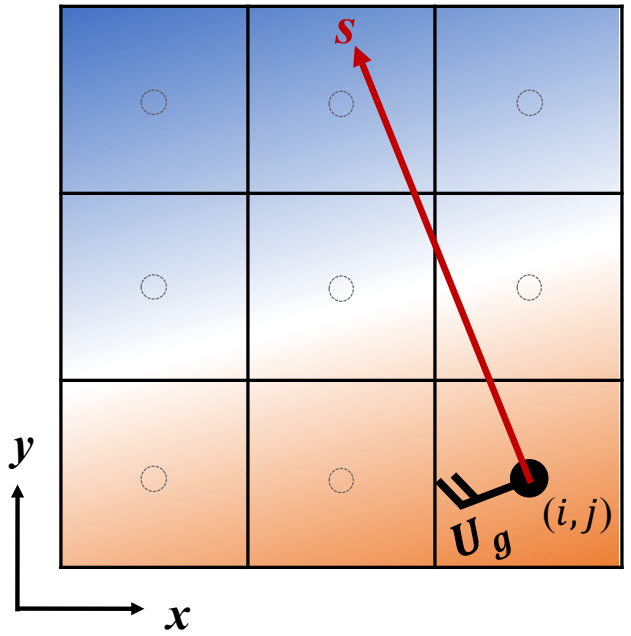
- Only a few parameterization schemes have been developed for slantwise convection (e.g., Nordeng 1987, Chou and Thorpe 1993, Ma 2000) but none of them have been tested extensively and applied operationally.

Objectives

In this study, a modified version of slantwise convective parameterization scheme (Ma 2000) is implemented in the Weather Research and Forecasting (WRF) model. Its performance is tested for an idealized case of pure CSI release and a real-data simulation of a banded precipitation event.

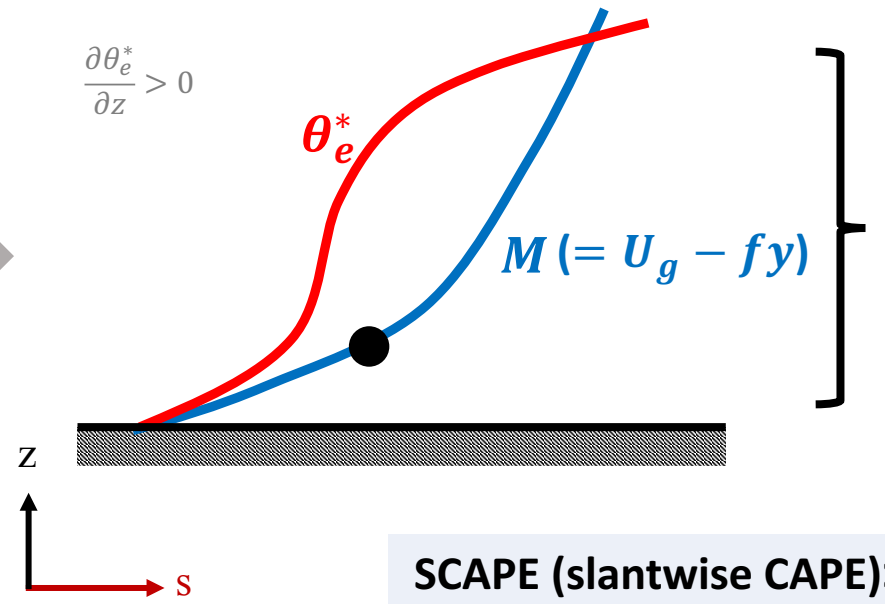
The slantwise convective (SC) parameterization scheme

- **<u>First step:</u> coordinate transformation**
  (CSI performs in the 2D cross-section along the negative horizontal temperature gradient direction, s)



Model (horizontal) grid

CSI is identified if θ_e^* surfaces slope more steeply than M_g surfaces in this cross section



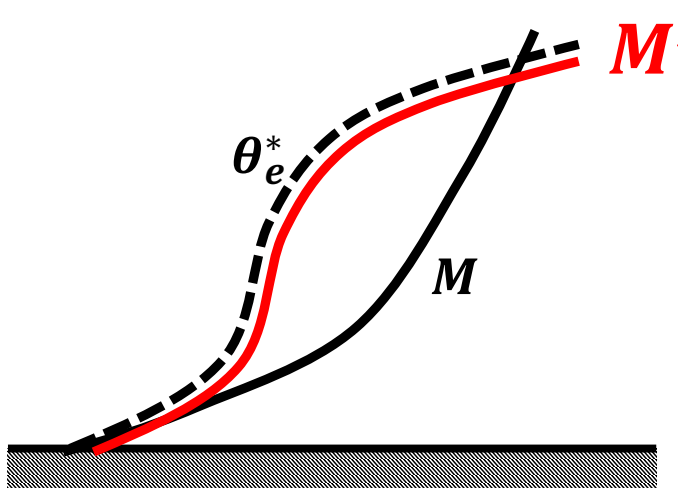
(ascending air tube obtains max positive buoyancy along the M_g surface)

SCAPE (slantwise CAPE)>0

The slantwise convective (SC) parameterization scheme

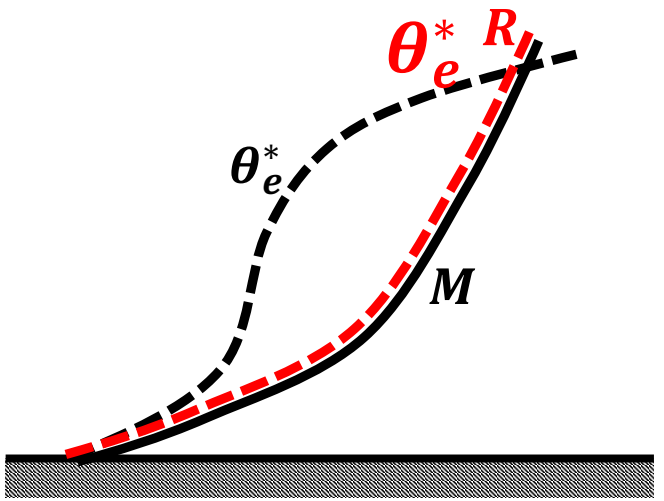
- **<u>Second step:</u> to define a reference state** (with a superscript R) that is neutral to CSI ($\theta_e^* \,//\, M$ surfaces).
  No unique solutions!

- Based on Ma (2000): adjusting the large-scale fields toward a reference state with an adjustment timescale.



e.g., Chou and Thorpe (1993), Ma (2000)

Assuming that the momentum adjustment due to slantwise convection is predominant (Emanuel 1983)



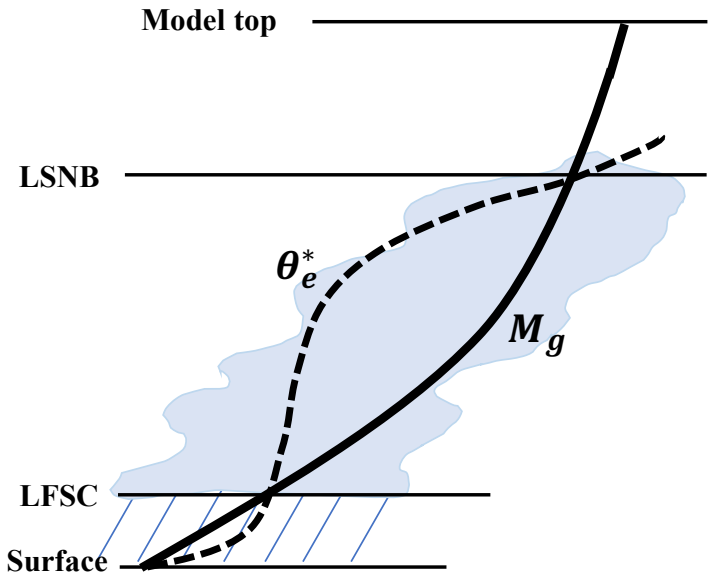
e.g., Nordeng (1987)

The slantwise convective (SC) parameterization scheme

- Note that the adjustment must ensure *momentum conservation* ($\int \Delta M_g \, dp = 0$).

Current state

SCAPE (slantwise CAPE)>0



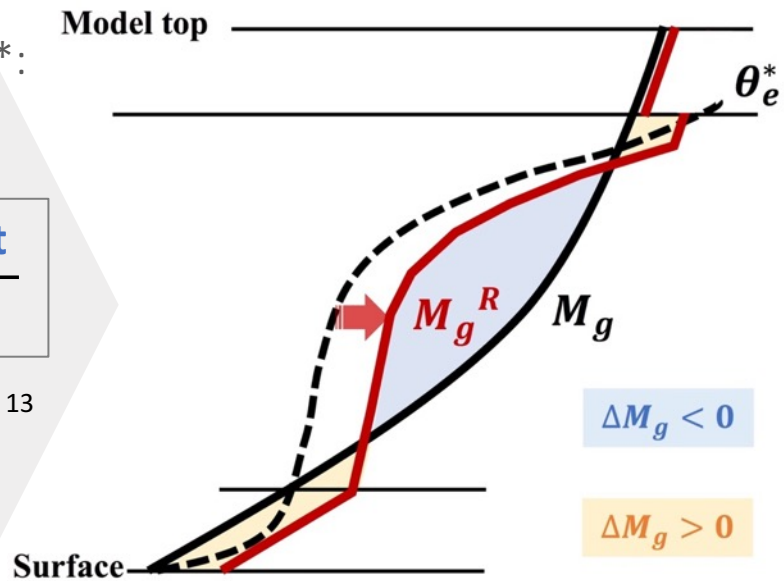
If subgrid slantwise convection is expected*:

$$\left(\frac{\partial M_g \text{ or } U_g}{\partial t}\right)_{sc} = \frac{\text{Reference} - \text{Current}}{\tau_{sc}}$$

τ_{sc}: prescribed adjustment timescale (3-5 h)[5, 13]

Reference state

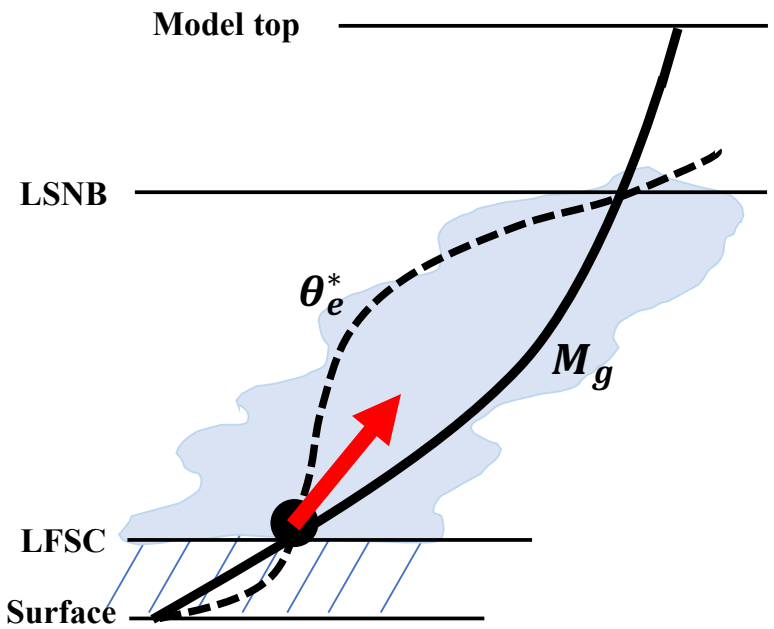
SCAPE → 0



*trigger function: w and v at LCL >0; RH at LCL > 85%;
SCAPE-CAPE > certain thresholds; Cloud thickness > 2 km*

The slantwise convective (SC) parameterization scheme

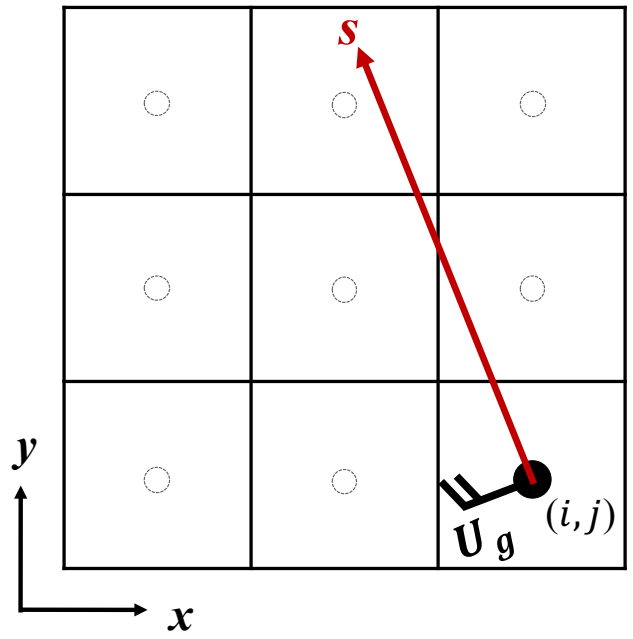
- **Condensational heating, moisture loss, and precipitation:**



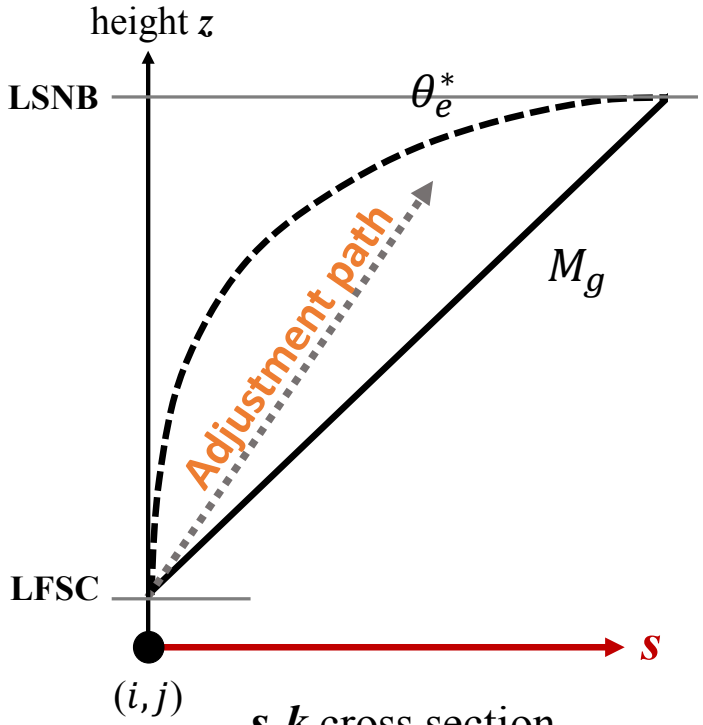
1. Assume a parabolic vertical profile of w ($\propto$ SCAPE)
2. Condensation produced by the supersaturation due to the updraft is (Rogers and Yau, 1989): $\frac{d\chi}{dt}(k) = \frac{Q_1(T)}{Q_2(T,p)} w(k)$
3. Total precipitation rate $R_{sc} = \int \rho \frac{d\chi}{dt} dz$
4. Latent heating rate $\left[\frac{\partial T}{\partial t}(k)\right]_{SC} = \frac{L_v}{C_p}\frac{d\chi}{dt}(k)$
5. Moisture lost rate $\left[\frac{\partial q_v}{\partial t}(k)\right]_{SC}$ focusing in the sub-cloud layer (also a parabolic profile).

The slantwise convective (SC) parameterization scheme

- **Last step:** to decide where to apply the parameterized U_g, T and q_v tendencies: an adjustment path.



Model (horizontal) grid

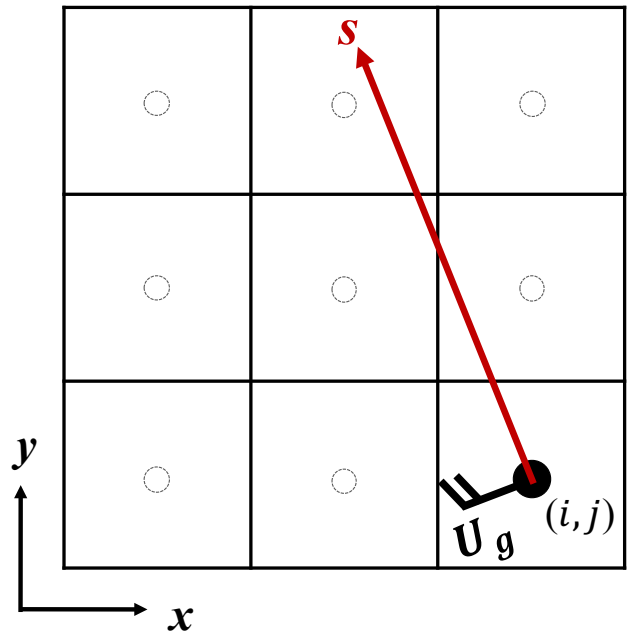


s-k cross section

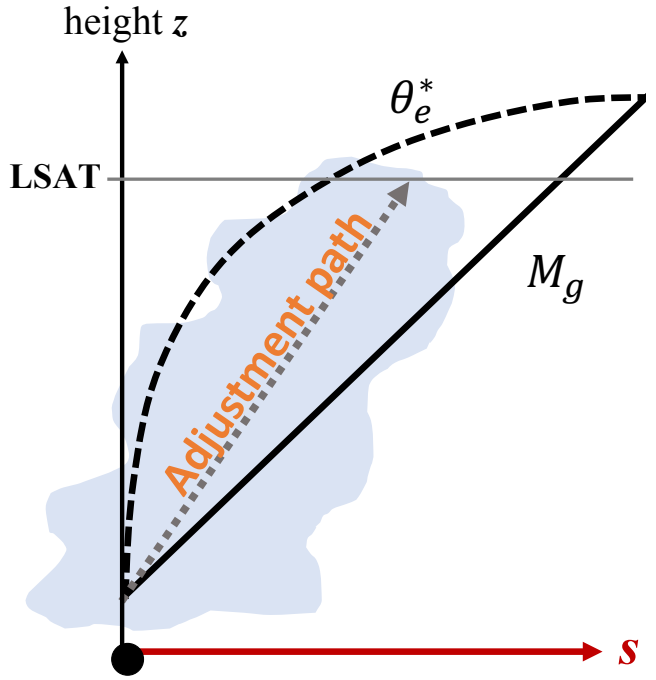
Assumption: adjustment path lies half way between θ_e^* and M_g surfaces *or* a slope between θ_e^* and M_g surfaces where the grid-resolved RH= 90% reaches the highest altitude

The slantwise convective (SC) parameterization scheme

- **Last step:** to decide where to apply the parameterized U_g, T and q_v tendencies: an adjustment path.



Model (horizontal) grid

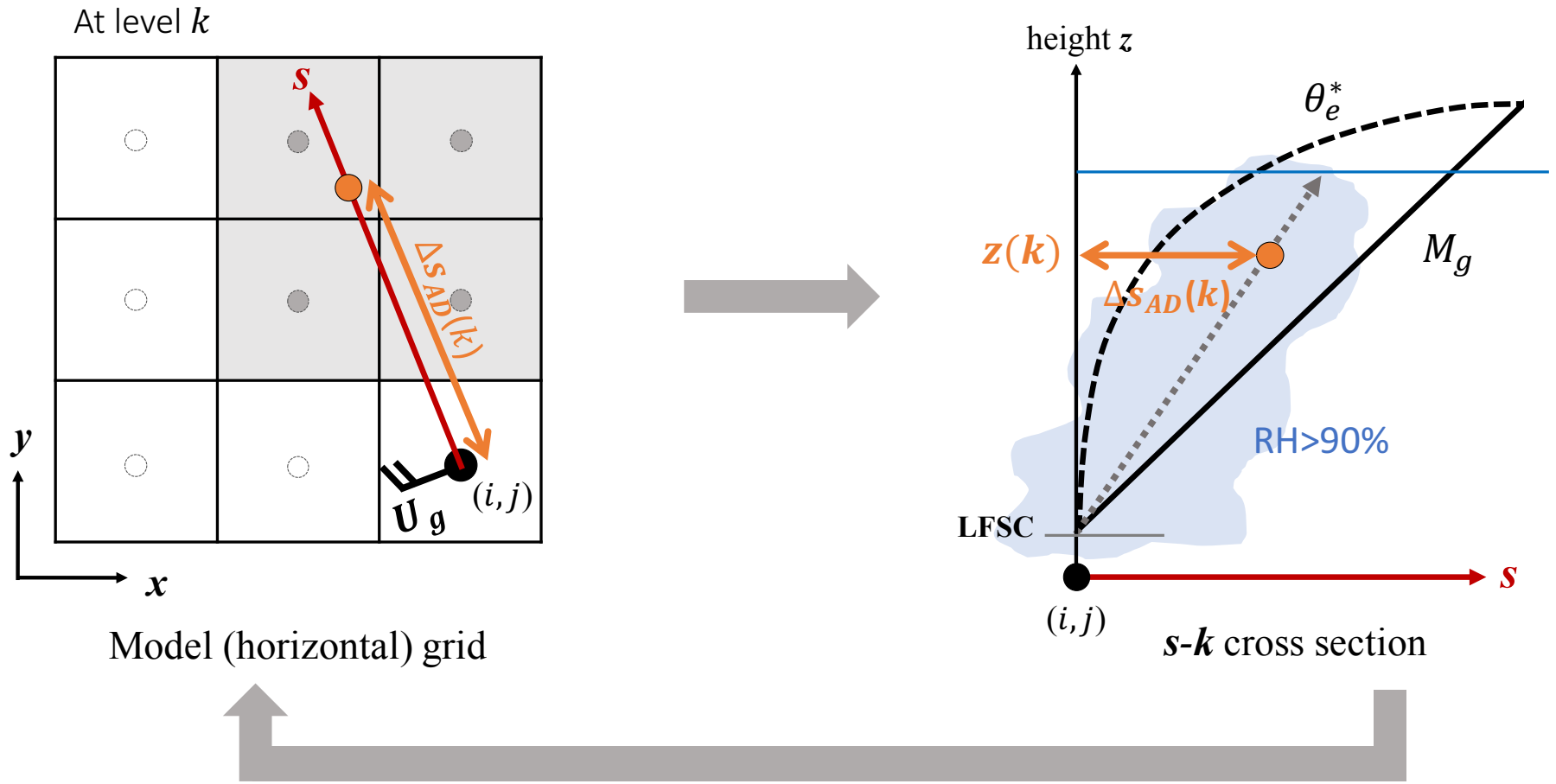


s-k cross section

Assumption: adjustment path is upper-bounded by the level where the grid-resolved RH drops below 90% for 1 km.

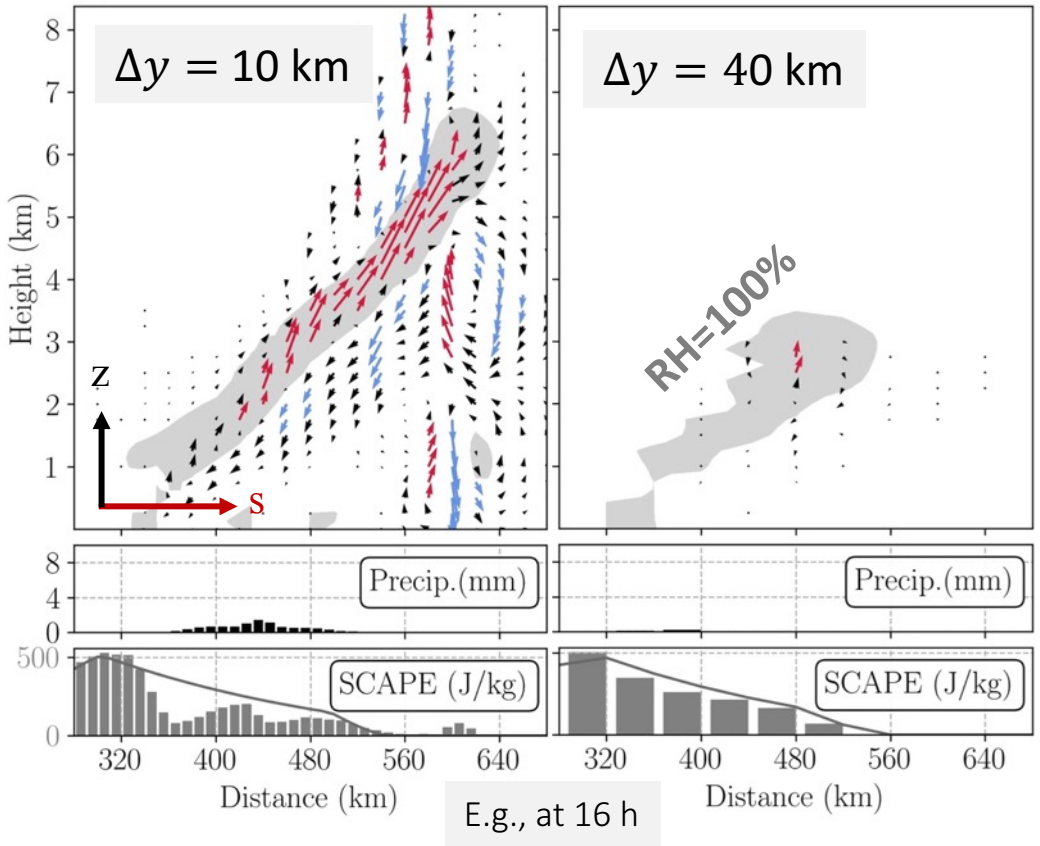
The slantwise convective (SC) parameterization scheme

- **Last step:** distribute the tendencies along the adjustment path to the model grid points at every model level.

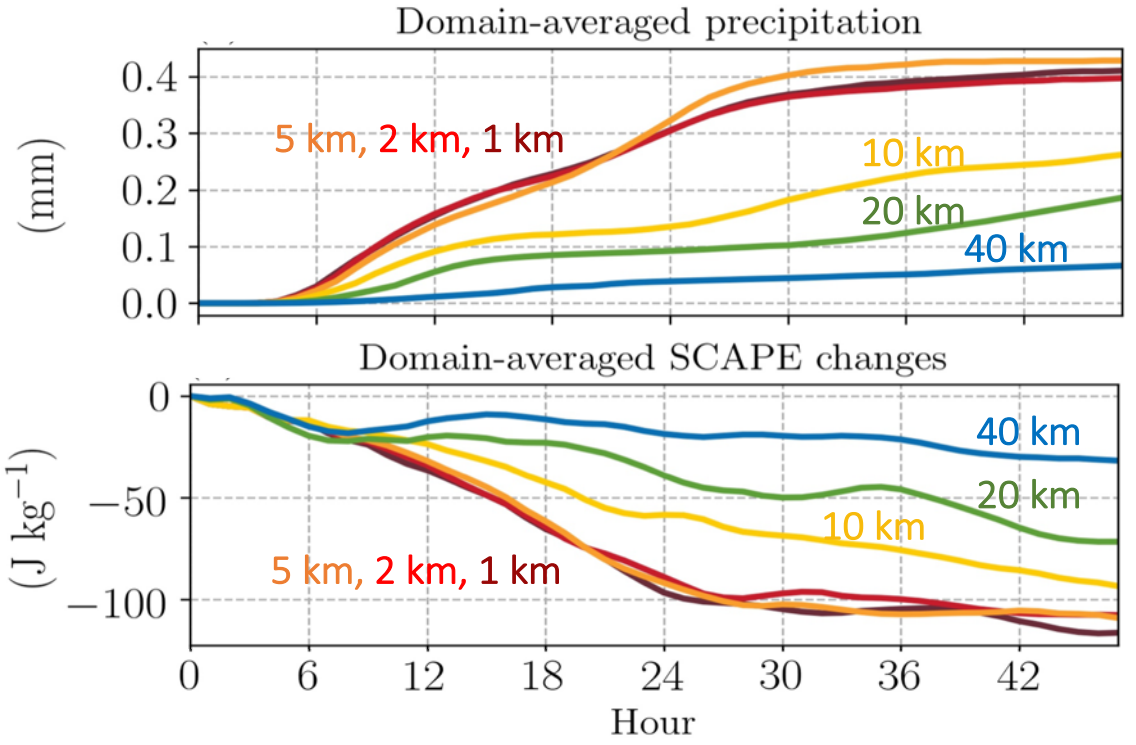


Idealized simulation: pure CSI release

- The 2D idealized, non-hydrostatic Advanced Research WRF model V3.8.1.
- Initial condition: conditionally (upright) stable but symmetrically (slantwise) unstable.
- Chen et al. (2021) conducted such simulations with different grid lengths (Δy) (no CPS for all runs), and found that **the large-scale feedbacks associated with CSI release numerically converge at $\Delta y \leq$5 km:**



E.g., at 16 h



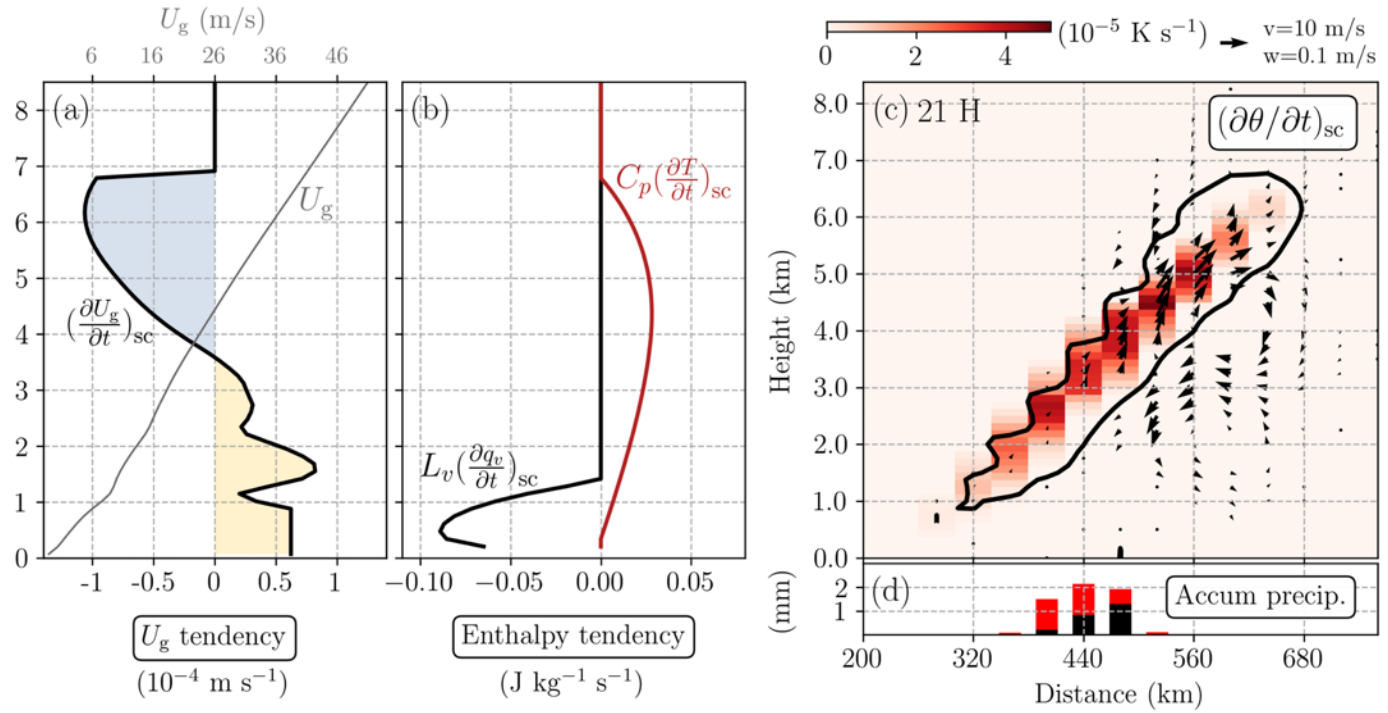
Idealized simulation: pure CSI release

- To evaluate the impact of the SC scheme on the coarse-gridded runs:

EXP	Δy	Convective Parameterization Schemes (CPS)	
		Upright	Slantwise
CTL	2 km	-	-
40KF	40 km	Kain-Fritsch (KF) scheme (no shallow cloud)	-
40KFSC	40 km	Kain-Fritsch (KF) scheme (no shallow cloud)	SC scheme

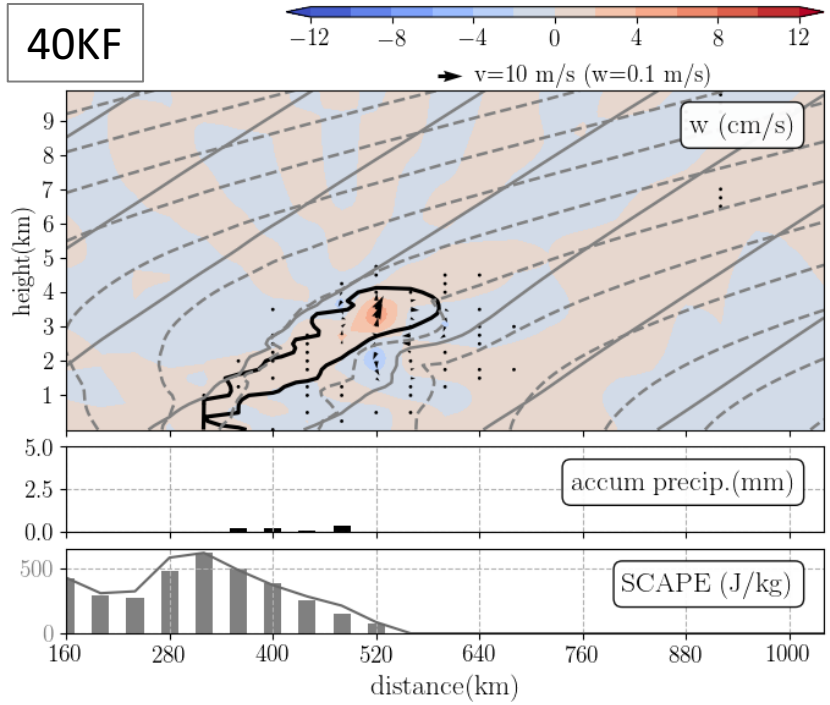
SC-parameterized tendencies in 40KFSC:

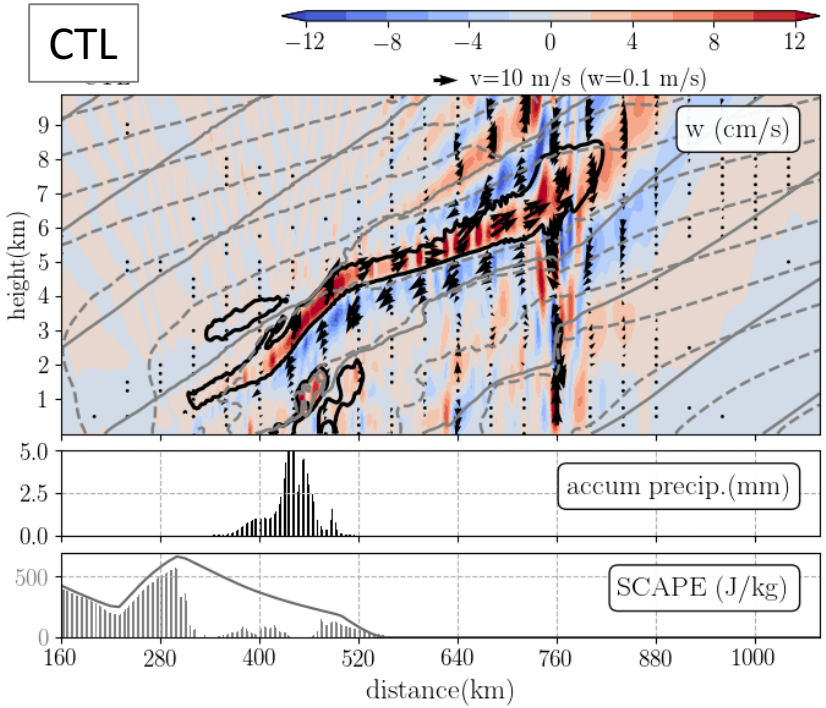
The scheme acts to reduce the vertical wind shear (less susceptible to CSI)

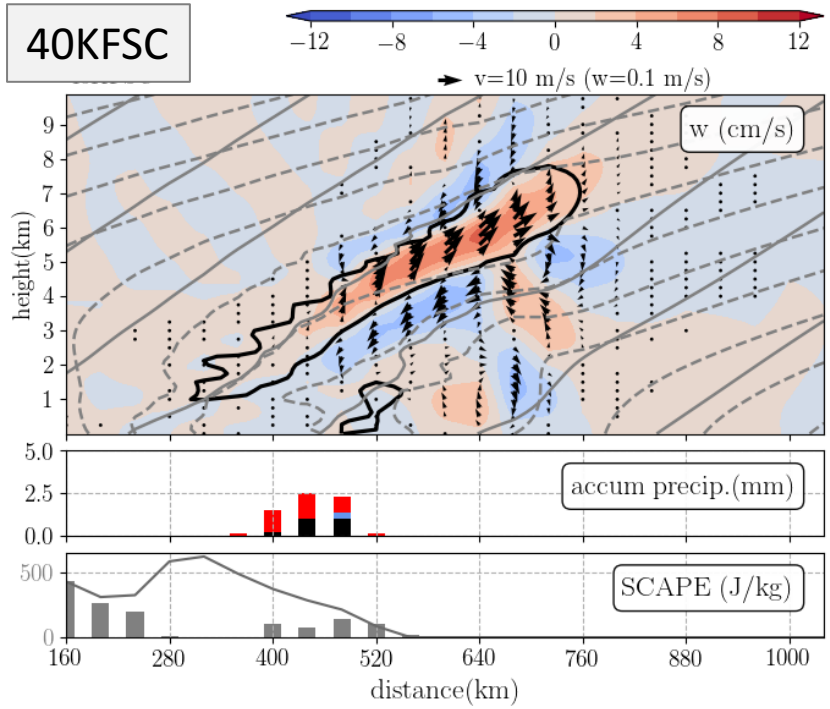


Idealized simulation (snapshots at 25h)

(**animations** can be found at http://www.meteo.mcgill.ca/~tcchen/







Idealized simulation (averaged properties)

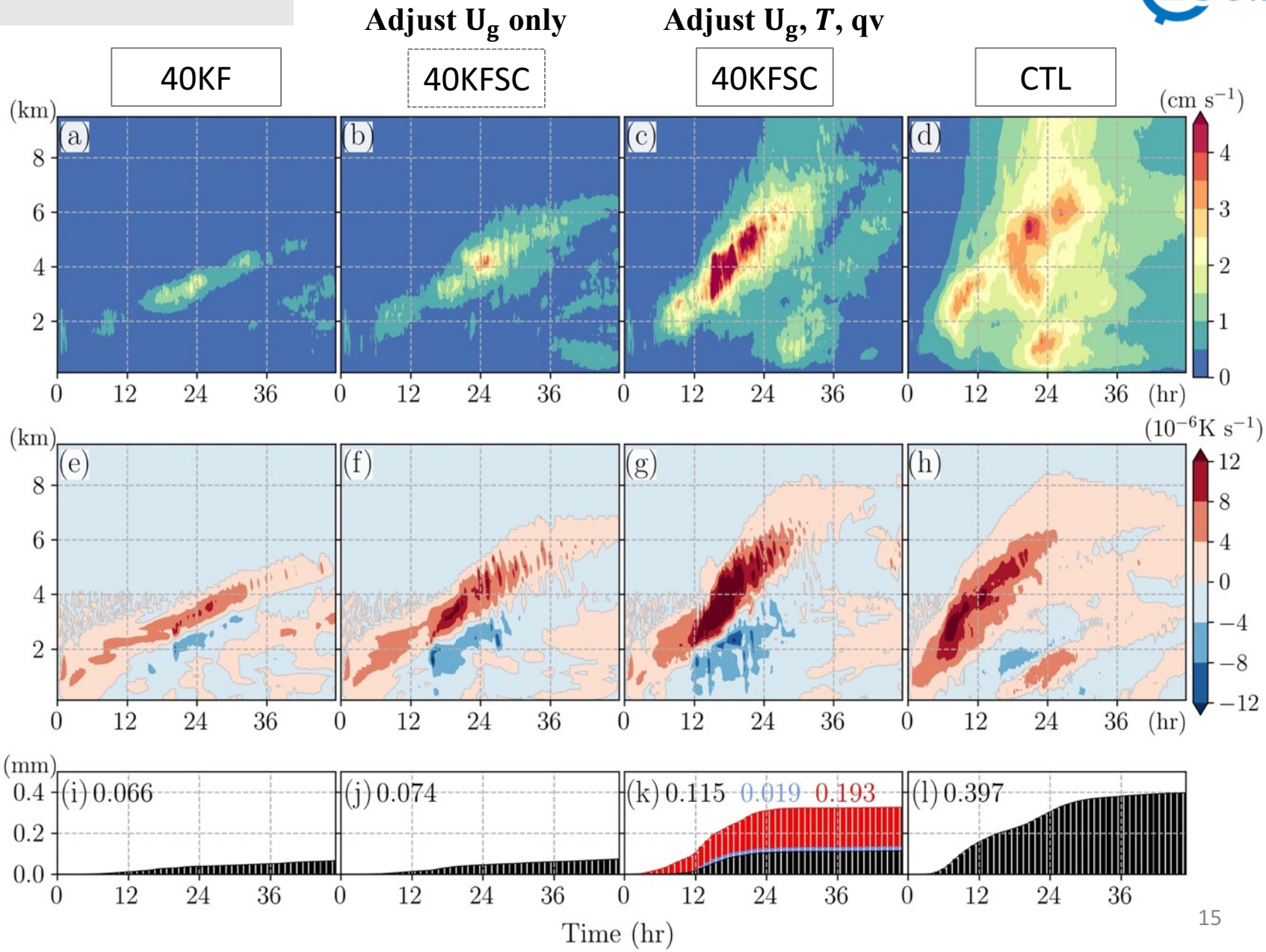
Time-height distribution of the horizontally-averaged

(a)-(d) w over ascent region

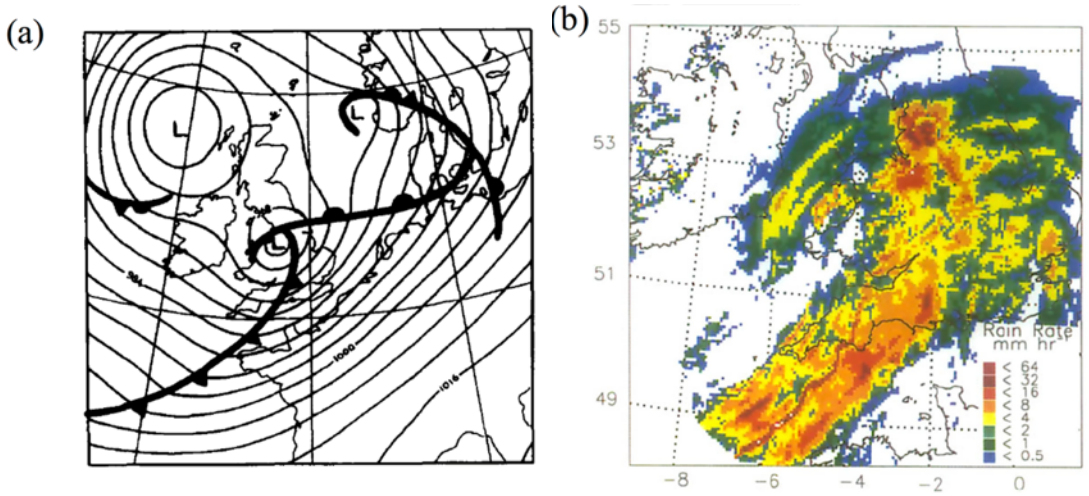
(e)-(h) diabatic heating

(i)-(l) averaged precipitation over time (numbers denote the total 48-h values)

Black, blue, and red bars indicate the precip. from the microphysics, the KF, and SC schemes, respectively.



Real-data simulation: cold frontal system of a storm in 2000

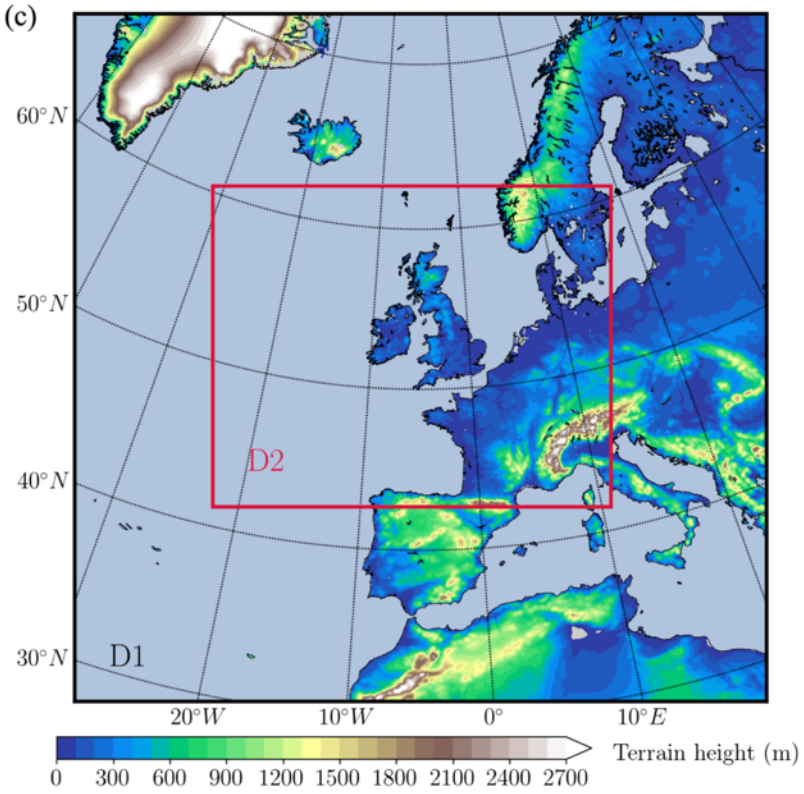


(a) Met Office surface analysis at 0600 UTC on Oct 30, 2000.
(b) Weather radar network display at 0400 UTC, showing the estimated rainfall intensities (shaded; mm h^{-1}).
Both from Browning et al. (2001).

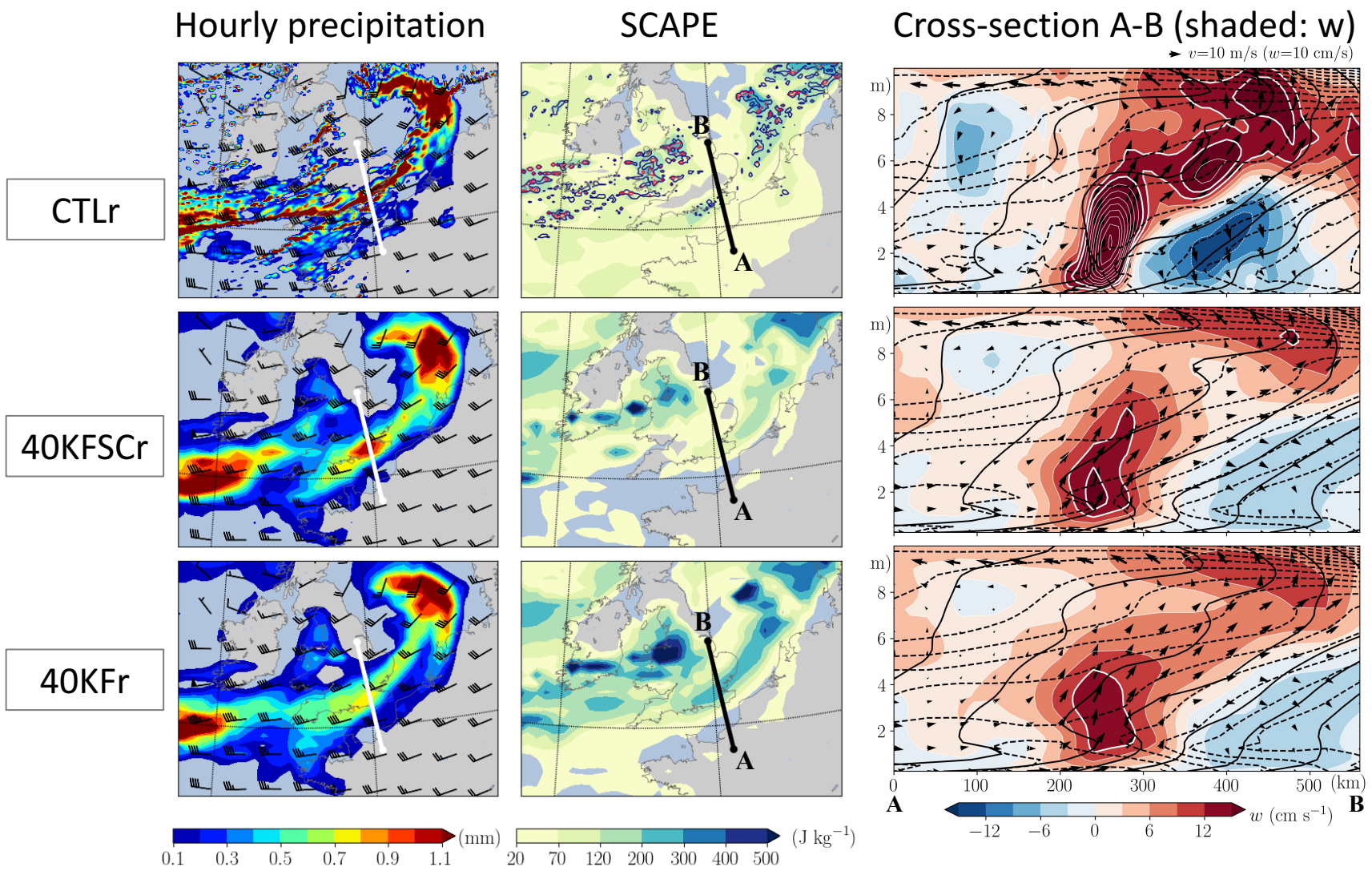
- **Experimental setup used in this study (right: domain configuration)**

EXP	Δy	CPS	
		Upright	Slantwise
CTLr	D1 (10 km), D2 (3.333 km)	D1: KF, D2: -	-
40KFr	D1 (40 km) only	KF	-
40KFSCr	D1 (40 km) only	KF	SC

Initialized at 1200 UTC on Oct 29, 2000. Using WRF V4.1.5



Real-data simulation: cold frontal system of a storm in 2000

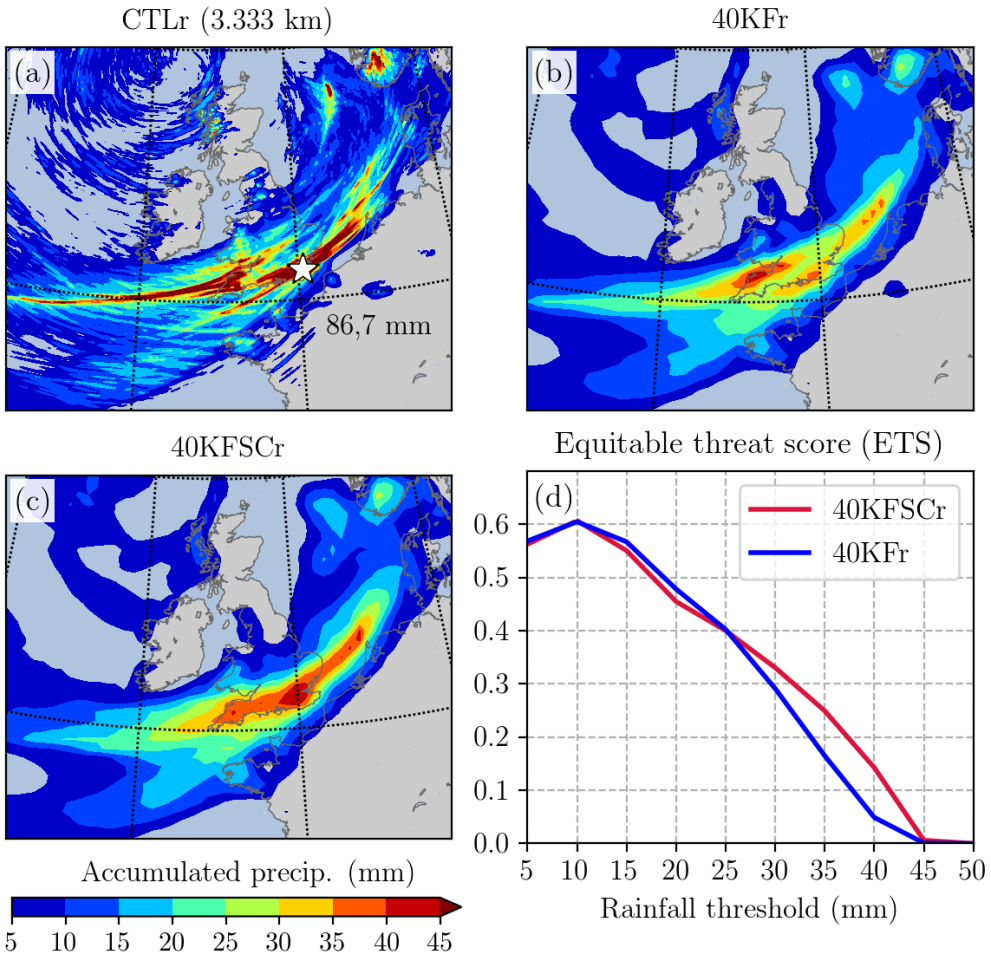


at 2215 UTC on Oct 29, 2000

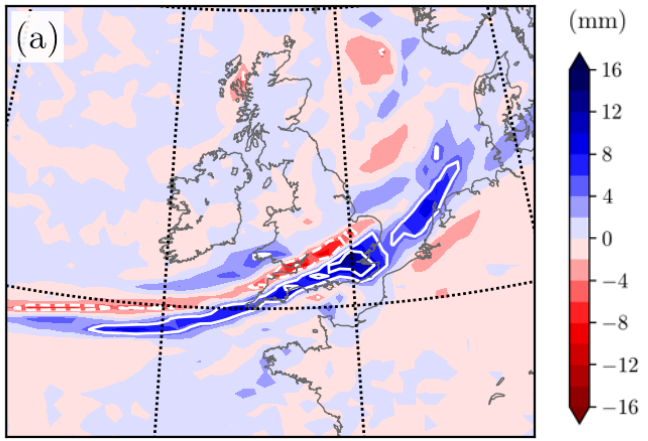
Compared to 40KF, 40KFSCr releases more SCAPE, generates a stronger grid-resolved slantwise updraft, producing greater amounts of precipitation, all in better agreement with the fine-gridded CTLr.

Real-data simulation: cold frontal system of a storm in 2000

12-h accumulated precipitation (from 1800 UTC on Oct 29)



Difference (40KFSCr-40KFr)



(white contours indicate ±5, 10, 15, 20 mm)

While 40KFr reasonably captures the curved band(s) (exhibiting two separated narrow line convection), 40KFSCr shows one major precipitation band with a peak coinciding with that in CTLr (denoted by star in (a)). The quantitative precipitation forecast skill based on the equitable threat score (ETS) shows a overall higher (closer-to-one) value in 40KFSCr than 40KFr.

Summary and ongoing work

- A 2D slantwise convective (SC) parameterization scheme is implemented in the WRF model.
- The scheme primarily eliminates SCAPE by adjusting the absolute momentum with a prescribed timescale. Condensational heating ($\propto$SCAPE) and moisture loss are also parameterized.
- Comparing “40KF” (with only Kain-Fritsch (KF) scheme for upright convection) and “40KFSC” (with KF and SC):

i. For both the 2D idealized pure slantwise convection simulation and the real-data simulation shown here, we found the additional SC scheme helps to release more SCAPE, leading to stronger grid-resolved slantwise circulations and total precipitation, in better agreement with the fine-gridded reference run.

ii. The improvement is less significant in the real-data simulation whose environment is unstable for both upright and slantwise convection. The upright and slantwise convective parameterization schemes may compete with each other (the reference CSI neutral state the SC scheme adjusts toward is statically stable) and thus their compatibility requires further investigation.

References

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