Uncertainties in Representations of Model Processes

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提纲

- Resolution dependency (Bryan’s work, Hue Morrison’s work, Funning tornado simulation, May 20, 2013 tornado simulations, hail prediction), CAM, CRM, LES
- Corey’s FV3 comparisons?
- Microphysics
- PBL parameterizations (Hu, Sobash comparison papers, Chunxi’s FV comparisons, Hu recent results, Zhou’s paper,)
- SGS turbulence parameterization (Sun Shiwei’s results, related papers)
- Radiation-cloud interactions, cumulus scheme
- Land surface model/hydrology model/urban processes
- Gravity wave drag
- IC versions physics perturbations (Mandy’s work)

Components in Atmospheric Models

- Model equations, dynamic core
- Parameterization of SGS processes, a.k.a. model physics
  - Cloud/precipitation physics/microphysics
  - PBL turbulence and SGS turbulence
  - Land/Ocean/Ice surface fluxes/surface layer physics
  - Land surface/Urban canopy/Vegetation/Ocean/Sea ice models
  - Radiation physics, cloud/aerosol interactions
  - Chemical processes and effects on cloud and radiation physics

Most important components for short-range weather forecasting

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  - PBL and SGS turbulence parameterizations
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  - Land surface model
  - Radiation and cloud interactions

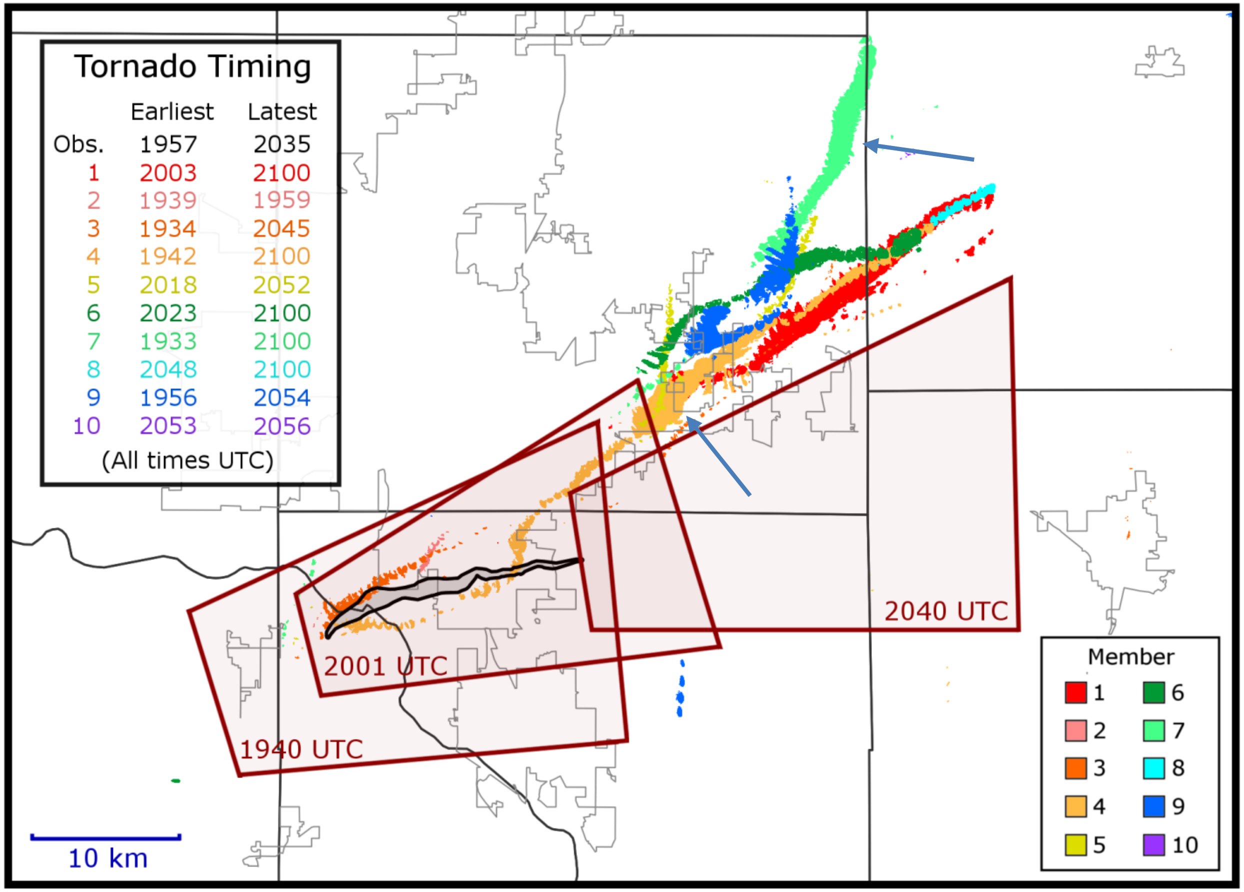
Dynamic core

- Nonhydrostatic/fully compressible, no approximation to governing equations
- Numerical grid for discretization
  - Trend – grid based, quasi-uniform resolution over the sphere (MAPS, FV3, etc.); need to parallelize well for O(1000) grid.
- Accuracy, stability, conservation
  - Accuracy (truncation error) → effective resolution
  - Stability → damping of weak instability can lead to inaccuracy; stability also affects integration efficiency
  - Conservation → damping also affects conservation, but material/mass conservation must be preserved
- All reasonably constructed dynamic cores are accurate up to certain scale, the main question is at what scale?
- What resolution is needed to accurately predict local high-impact weather (heavy precipitation, severe winds, hail, tornado, etc)?

Resolution Needs

- Enough resolution to allow explicit representation of convective cells (CA and CR models 1 to 4 km grid spacings), avoid Cu parameterization;
- How good are CA models in predicting heavy precipitation, tornadoes and hail? Is there major benefit in further increasing resolution, to, e.g., LES resolution?
- Bryan et al. (2003) suggested that O(100m) is needed to simulate deep moist convection and associated turbulence (for SGS turbulence closure to work) although O(1km) grid can be used for practical purposes (can still provide valuable information to forecasters)

Ensemble Prediction of May 20, 2013 Newcastle-Moore tornado at 50 m grid spacing with EnKF DA on 500 m grid


Tornado Timing

	Earliest	Latest
Obs.	1957	2035
1	2003	2100
2	1939	1959
3	1934	2045
4	1942	2100
5	2018	2052
6	2023	2100
7	1933	2100
8	2048	2100
9	1956	2054
10	2053	2056

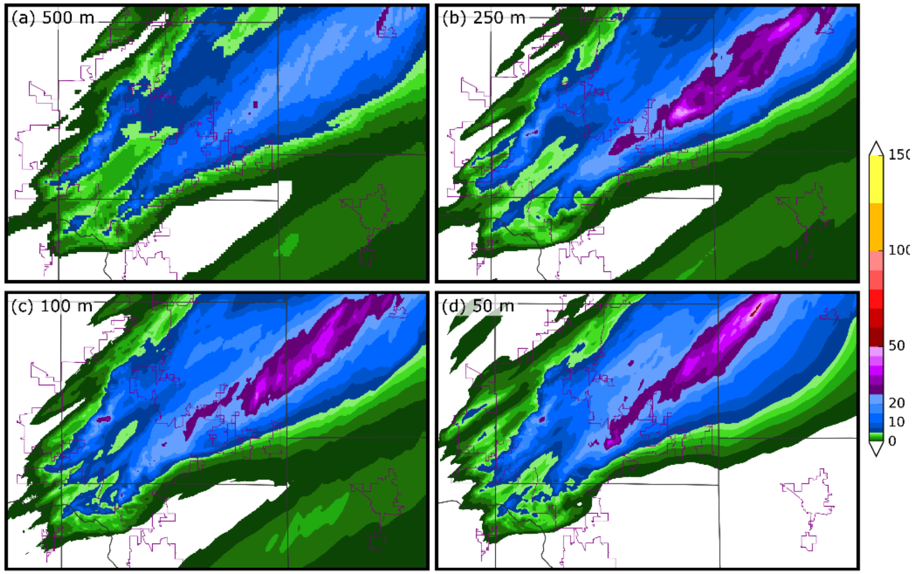
(All times UTC)

Swaths of surface wind speed exceeding the EF0 threshold (29 m s^{-1}) for each of the ten members of the 50 m ensemble. Tornado warnings issued between 1930 and 2100 UTC by the NWS Norman WFO, labelled by time of issuance, are plotted (dark red boxes) for comparison.

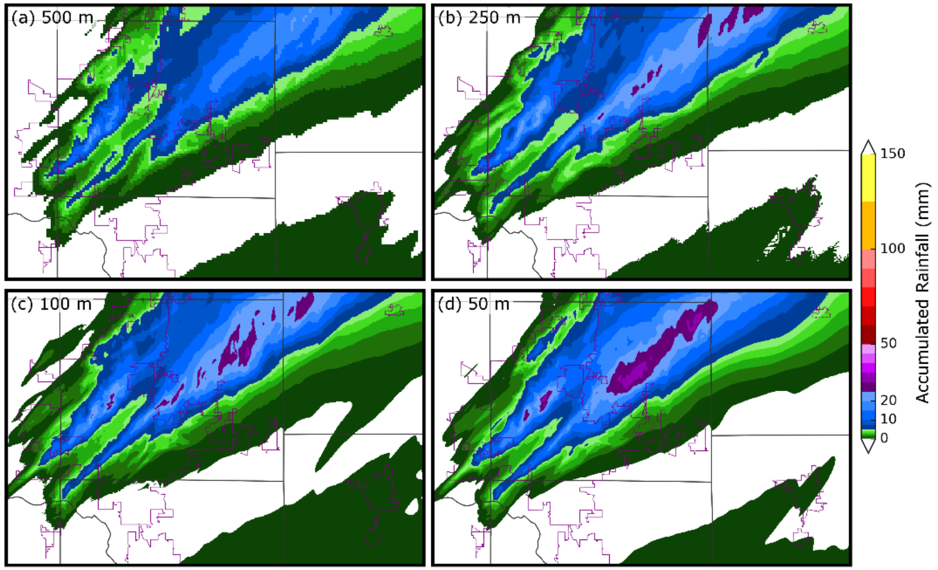
Snook et al. (2018)

90 min Rainfall Accumulation at 500-50m Grid Spacings for May 20, 2013 Tornado Case (two ensemble members from EnKF IC)

Ensemble No. 4



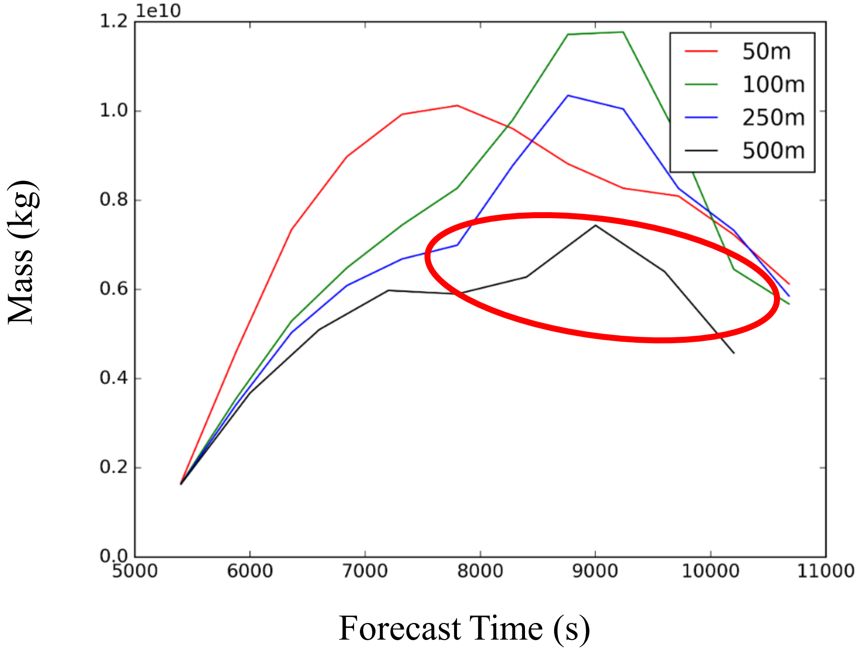
Ensemble No. 7



- Jump appears to be largest between 500 and 250 m.
- Precip generally increases with increasing resolution,
- Max difference can be > a factor 2.
- Milbrandt and Yau 2-moment scheme was used.

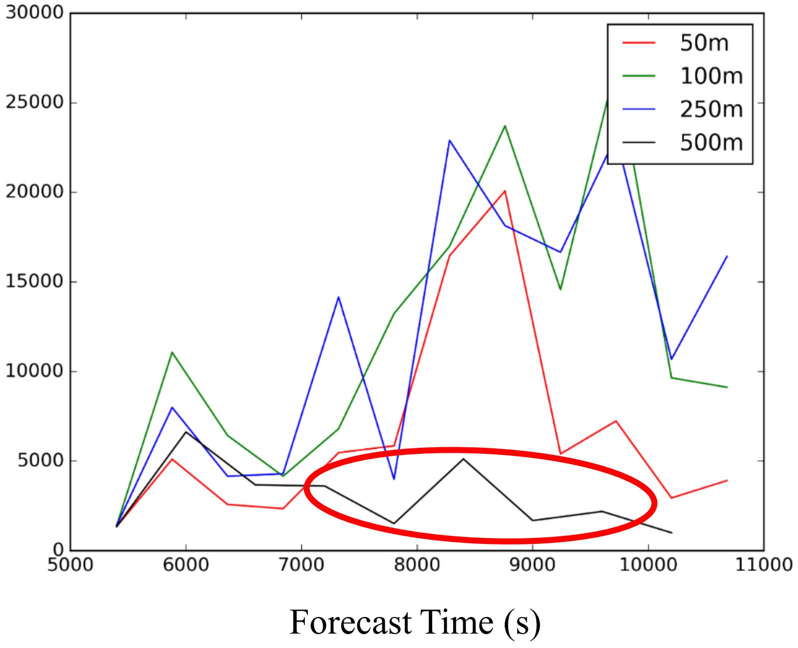
Hail Mass in Ensemble No. 4
for May 20, 2013 Moore Tornadic Storm Case

Domain-Wide (3D) Hail Mass (kg)



Fastest increase in 3D volume hail mass in
50 m grid, lowest volume in 500 m grid.

Surface Hail Mass (kg)



Large jump in surface hail mass
from 500 m to 250 m

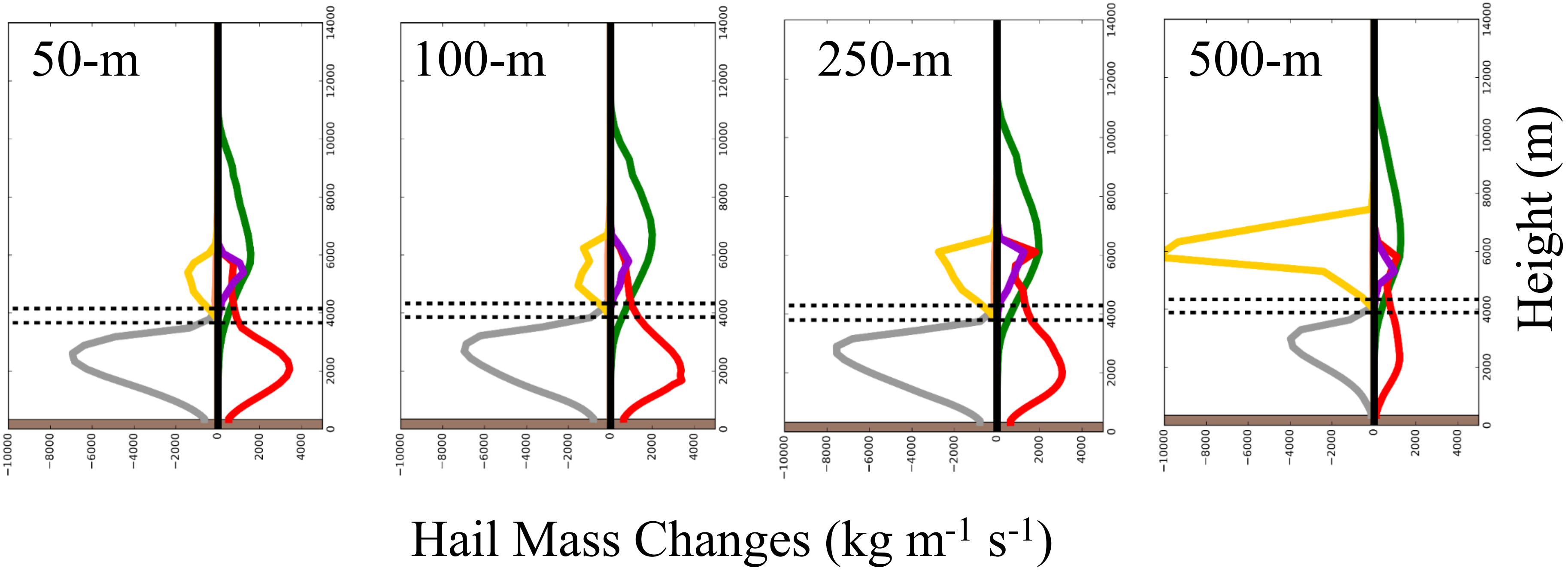
Large differences in hail production terms between 500m and other grid spacings

Growth terms:

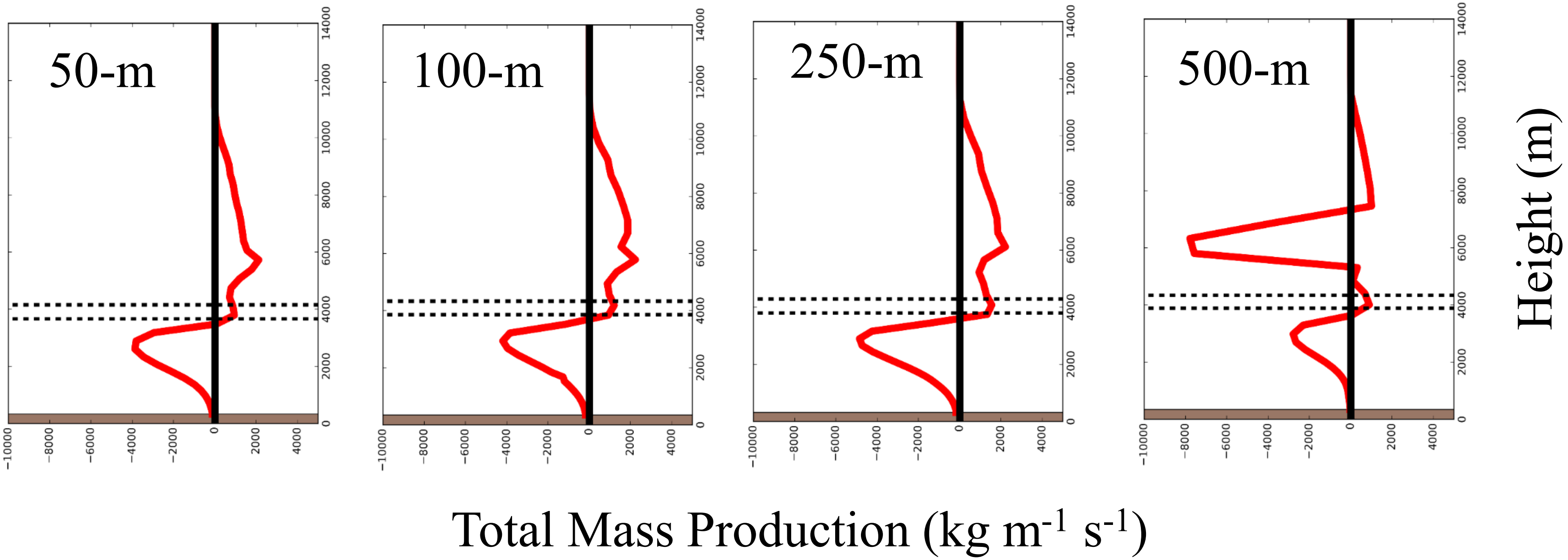
- 🟩 Hail accreting cloud water
- 🟥 Hail accreting rain
- 🟦 Graupel conversion
- 🟪 Three-component accretion

Decay terms:

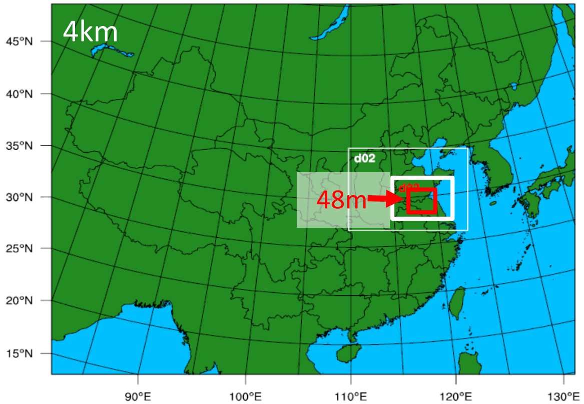
- ⬜ Melting
- 🟨 Hail shedding water
- 🟧 Hail sublimation

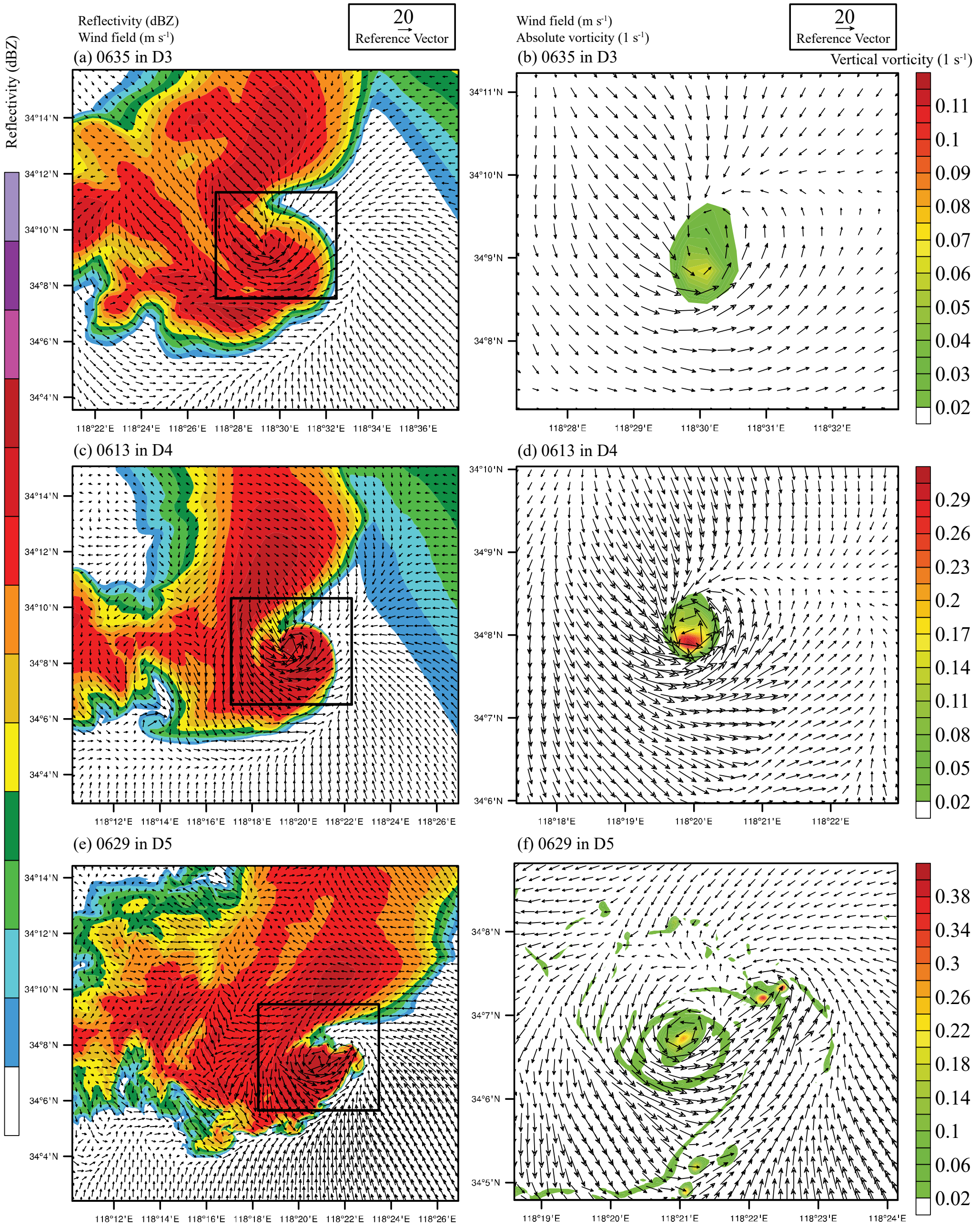


Large differences in total hail production are between 500m and other grid spacings



Prediction of 6/23/2016 Funing, China Supercell Tornado, using different number of nesting levels reaching different resolutions

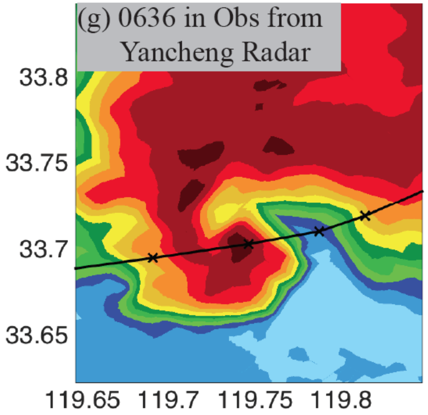




444 m Grid

148 m Grid

49 m Grid

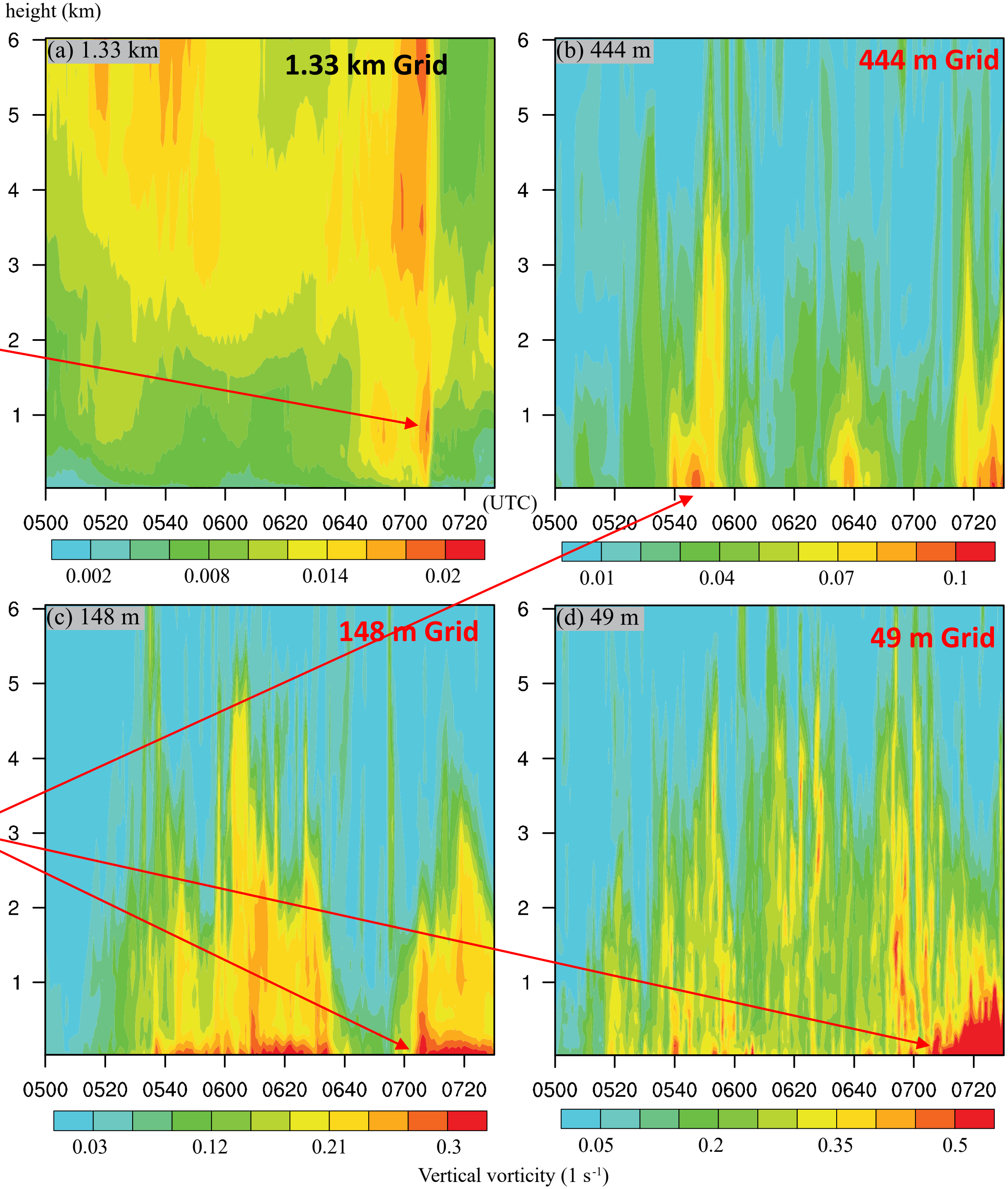


Observation

Sun, Xue et al. (2018)

Maximum vertical vorticity occurs at about 1km AGL, not at surface – no tornado vortex

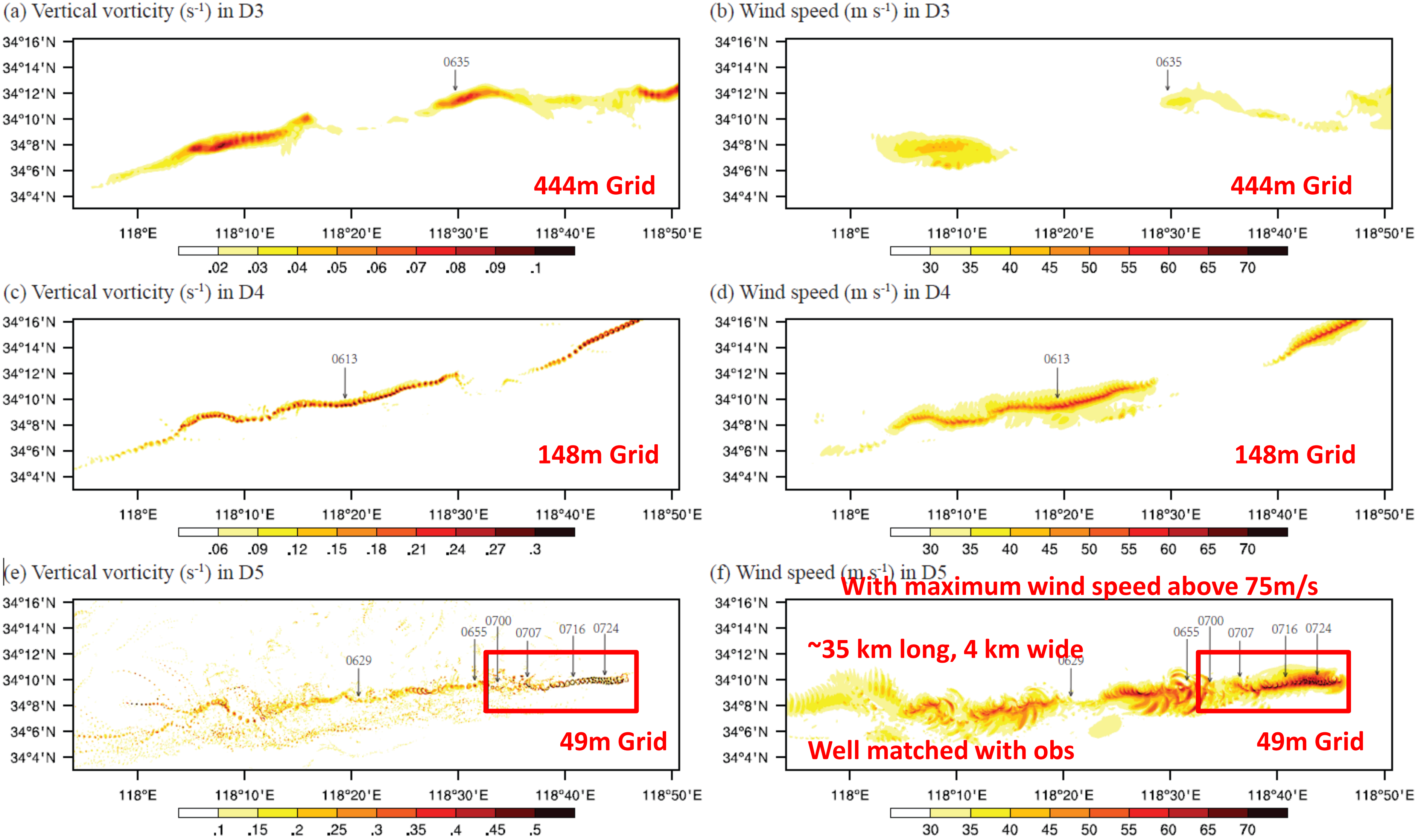
Maximum vertical vorticity occurs at Surface – tornado or tornado-like vortex!



1300-1500 LST Vorticity and Strong Wind Speed Tracks

Sfc Vorticity

Sfc Wind Speed



(a) Vertical vorticity (s^{-1}) in D3

(b) Wind speed ($m\ s^{-1}$) in D3

444m Grid

444m Grid

(c) Vertical vorticity (s^{-1}) in D4

(d) Wind speed ($m\ s^{-1}$) in D4

148m Grid

148m Grid

(e) Vertical vorticity (s^{-1}) in D5

(f) Wind speed ($m\ s^{-1}$) in D5

With maximum wind speed above 75m/s

~35 km long, 4 km wide

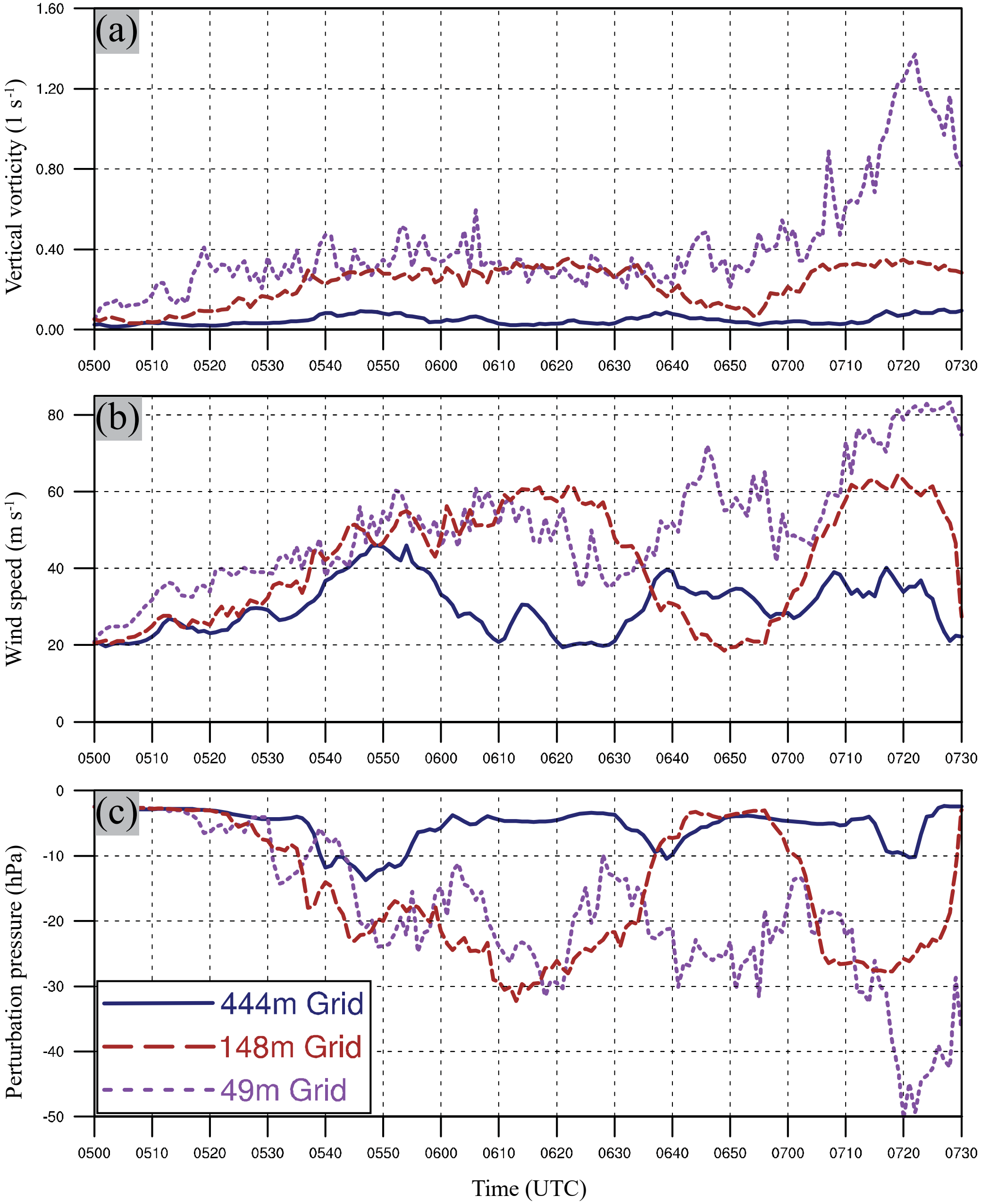
Well matched with obs

49m Grid

49m Grid

Time Series of max/min values near surface

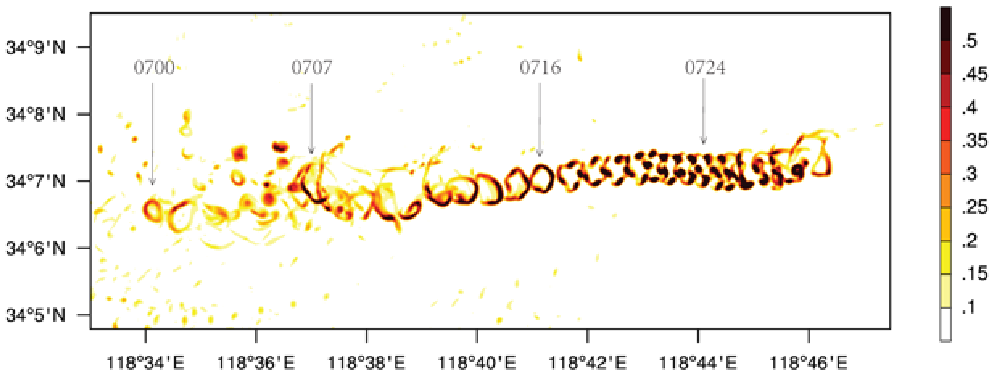
Resolution
Dependency
Of Simulated
Tornado
Intensity



444m – EF1
148m – EF2
48m – EF4

Sub-vortex scale structures requiring LES (~50 m) resolutions to resolve

(a) Vertical vorticity (s^{-1}) in D5



(b) Wind speed (m s^{-1}) in D5

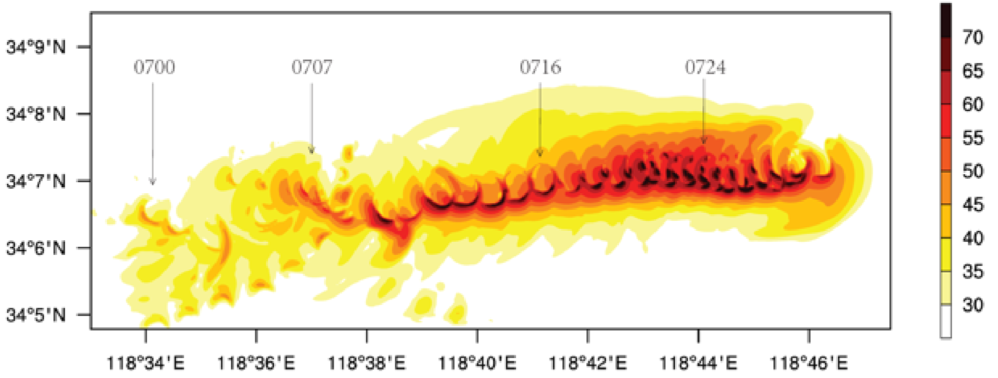


Figure S4. Composite contour maps of (upper) vertical vorticity and (lower) wind speed at the first model level, in zoomed-in rectangles in Fig. 3(e) and (f), respectively. Fields every minute from 0700 through 0730 UTC 23 June 2016 are overlaid.

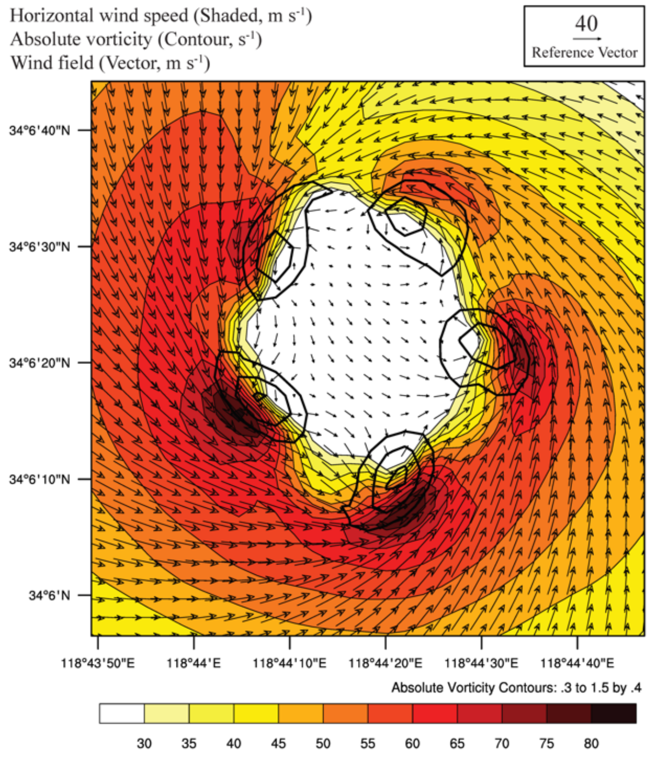


Figure S3. Horizontal cross section of horizontal wind speed (shaded, m s^{-1}), vertical vorticity (thick contours, s^{-1}) and horizontal wind vectors (plotted every grid interval or every 49 m) at 29 m AGL at 0724 from grid D5 of experiment D15.

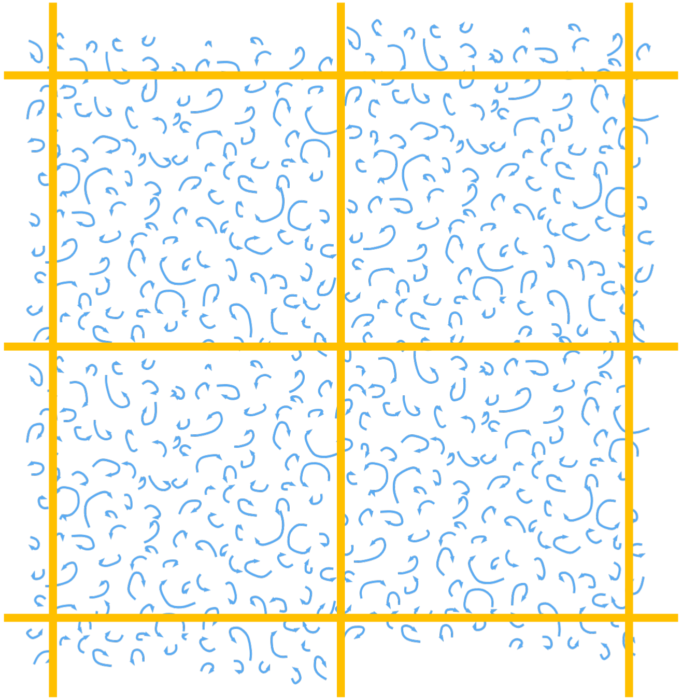
Surface wind speed within a multi-vortex tornado

- Tornado-like vortex is simulated on 444 m grid;
- Subvortices that affect maximum wind speed do not form until 48 m is used (not on 148 m);
- However, CAM forecasts have been shown to have useful skill in predicting tornado potentials – mainly by using surrogate products such as those based on updraft helicity and near-surface vertical vorticity (e.g., Clark et al. 2013; Sobash et al. 2016)

SGS Turbulence Closure

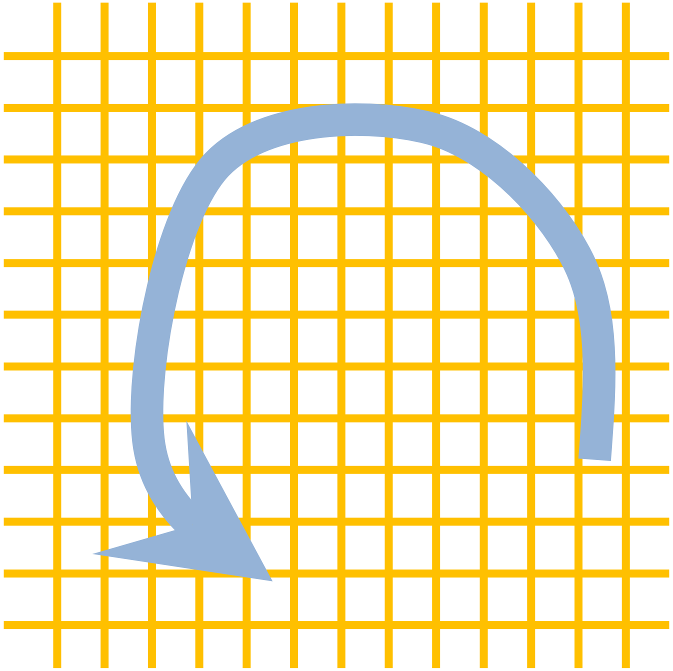
- Traditional SGS turbulence closures are really only suitable for when grid spacing is much smaller than the main features simulated; this is true for large eddy simulations.
- When grid spacing is much larger than turbulence eddies, such as in coarse-resolution models, BL turbulence fluxes (usually vertical only) are completely parameterized.

- Mesoscale (PBL)



dx (~10km) >> L

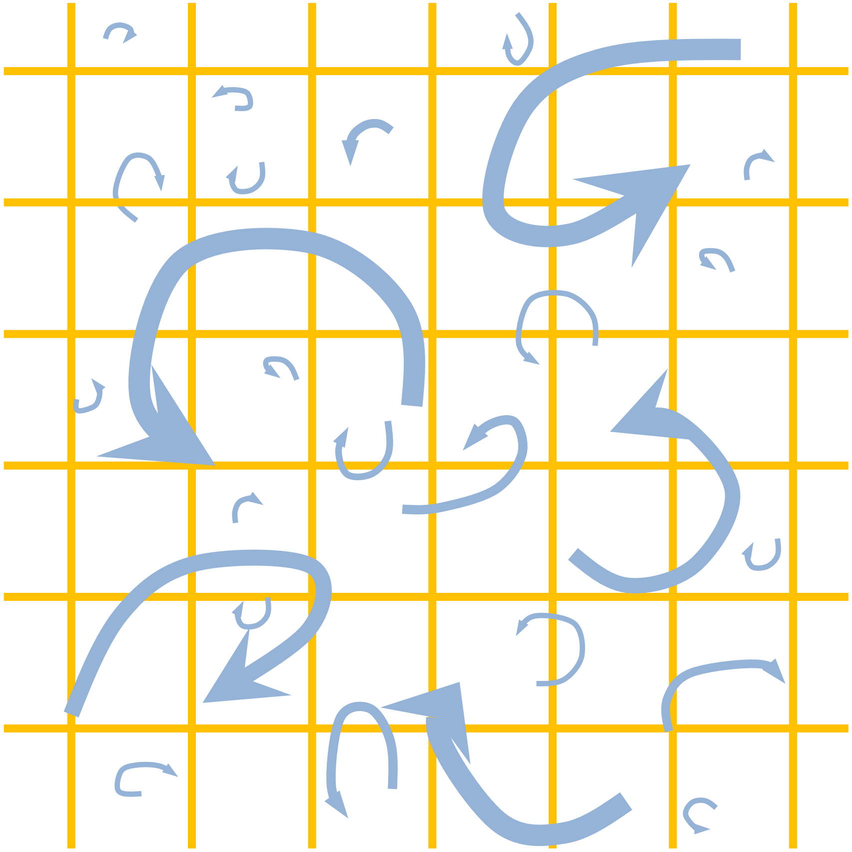
- LES



dx (~100m) << L

SGS Turbulence Closure

- CA and CR models:
  - Should consider horizontal turbulence fluxes also
  - Should consider ‘gray-zone’ effects, be scale aware
  - Should be able to model non-local counter-gradient fluxes
- Traditional SGS closures, such as Smagorinsky, TKE schemes are often used.



dx ~ L

New SGS turbulence closure scheme based on series expansion and mixed scheme

- Moeng et al. (2010) proposed a mixed scheme consisting of the traditional K local gradient term and a term based on Taylor series expansion following Leonard (1997):

$$\tau_{wc} = -K_h \frac{\partial \tilde{c}}{\partial z} + 2\left(\frac{\Delta_f^2}{12}\right)\left(\frac{\partial \tilde{w}}{\partial x}\frac{\partial \tilde{c}}{\partial x} + \frac{\partial \tilde{w}}{\partial y}\frac{\partial \tilde{c}}{\partial y}\right),$$

where K_h is provided by a conventional closure scheme such as TKE scheme

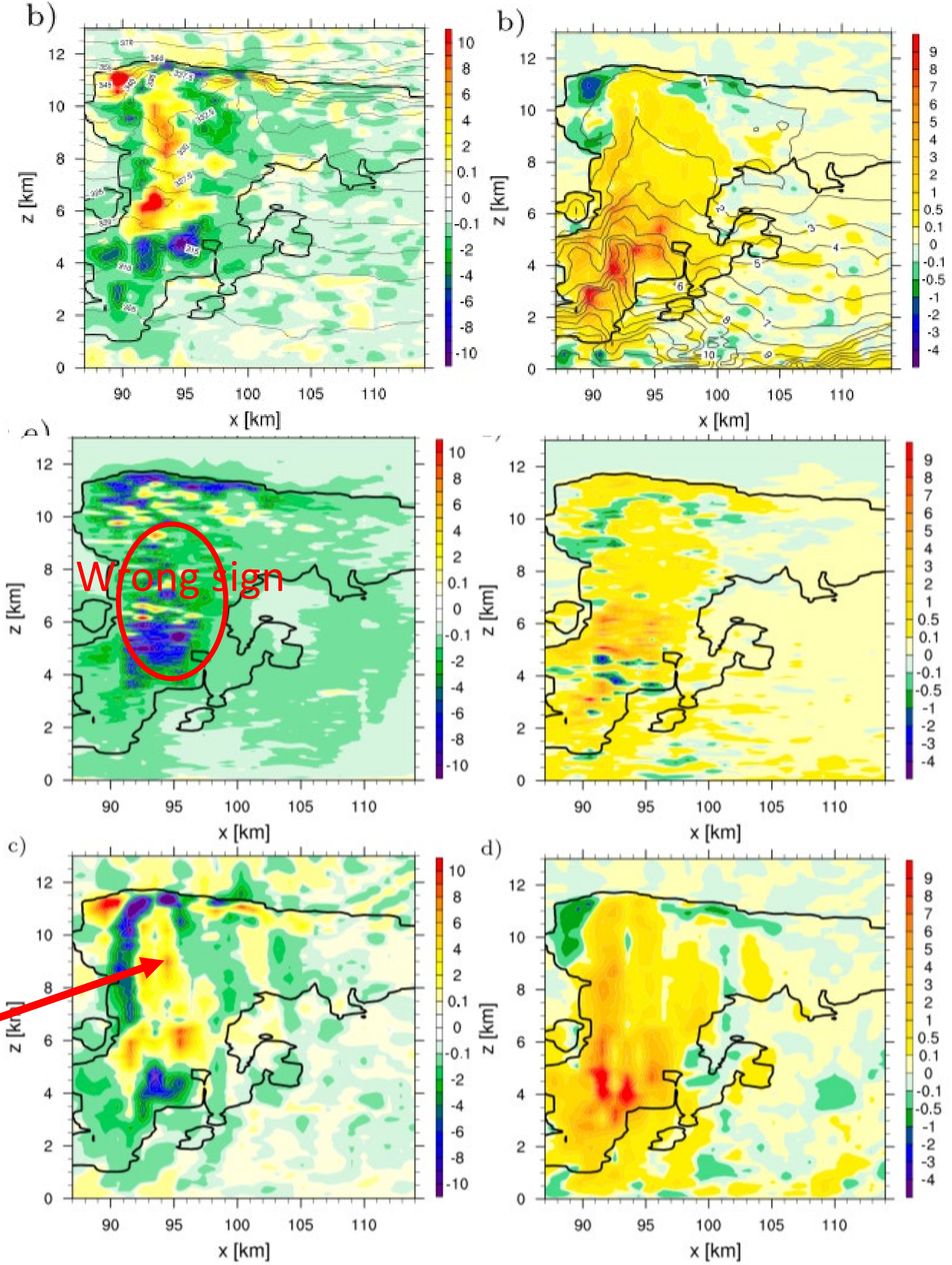
Verrelle et al. (2017) compared sub-filter-scale fluxes using K-local gradient scheme

$$\tau_{wc} = -K_h \frac{\partial \tilde{c}}{\partial z}$$

and

$$\tau_{wc} = 7\left(\frac{\Delta_f^2}{12}\right)\left(\frac{\partial \tilde{w}}{\partial x}\frac{\partial \tilde{c}}{\partial x} + \frac{\partial \tilde{w}}{\partial y}\frac{\partial \tilde{c}}{\partial y}\right),$$

for deep convection based on filtered LES simulation data.



Upgradient heat fluxes in updraft region

Turbulent heat flux

Turbulent q_{ci} flux

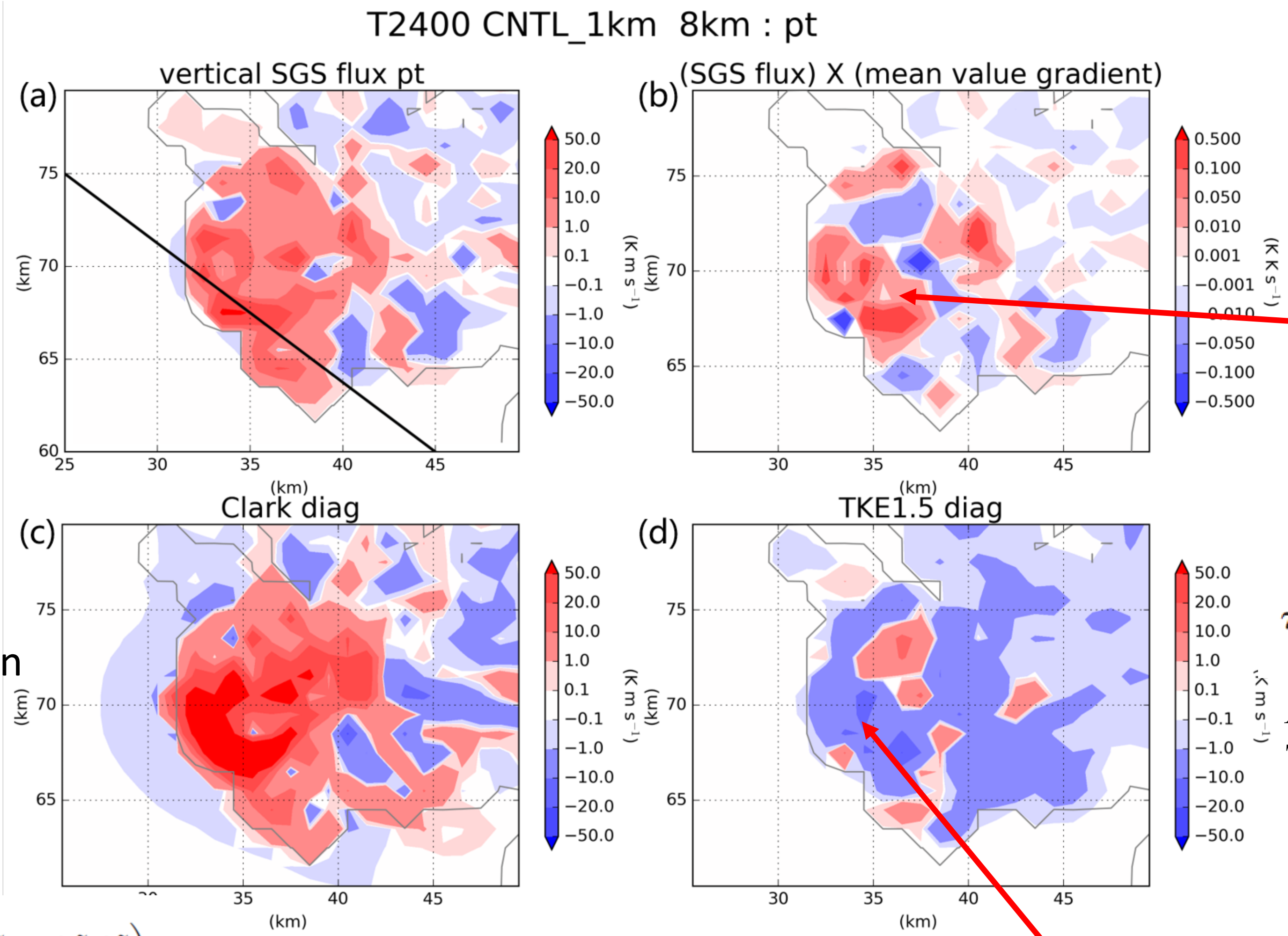
LES calculations (truth)

$$\tau_{wc} = -K_h \frac{\partial \tilde{c}}{\partial z}$$

$$\tau_{wc} = 7\left(\frac{\Delta_f^2}{12}\right)\left(\frac{\partial \tilde{w}}{\partial x}\frac{\partial \tilde{c}}{\partial x} +\right.$$

$\overline{w'\theta'}$ offline comparisons for a supercell storm using 50 m LES data

Filtered LES Estimation (truth)



$$\overline{w'\theta'}\cdot\frac{\partial\theta}{\partial z}$$

Positive means upgradient flux

Series Expansion Formulation

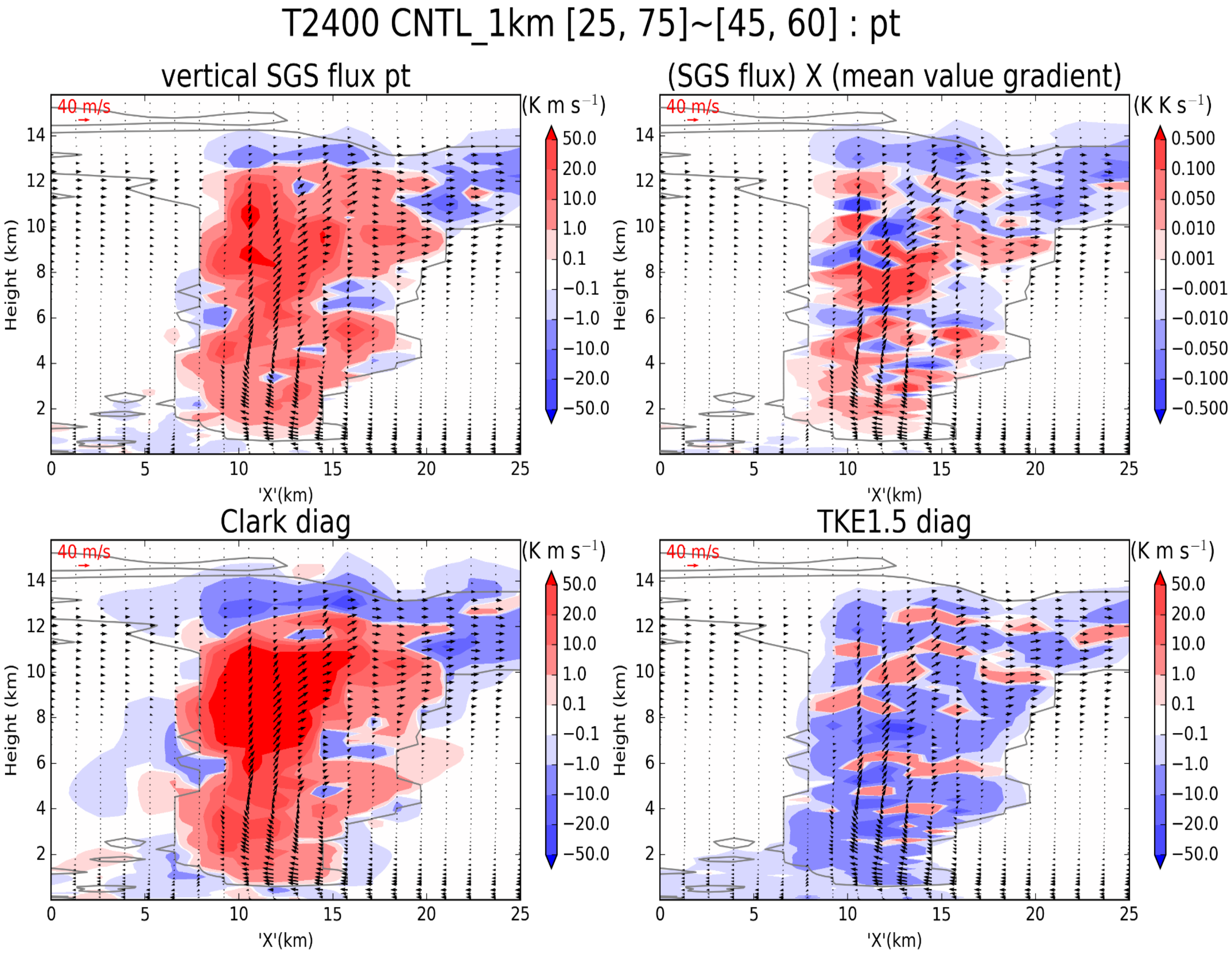
$$\tau_{wc} = 12\left(\frac{\Delta_f^2}{12}\right)\left(\frac{\partial\tilde{w}}{\partial x}\frac{\partial\tilde{c}}{\partial x}+\frac{\partial\tilde{w}}{\partial y}\frac{\partial\tilde{c}}{\partial y}\right),$$

$$\tau_{wc} = -K_h\frac{\partial\tilde{c}}{\partial z}$$

K_h from TKE scheme

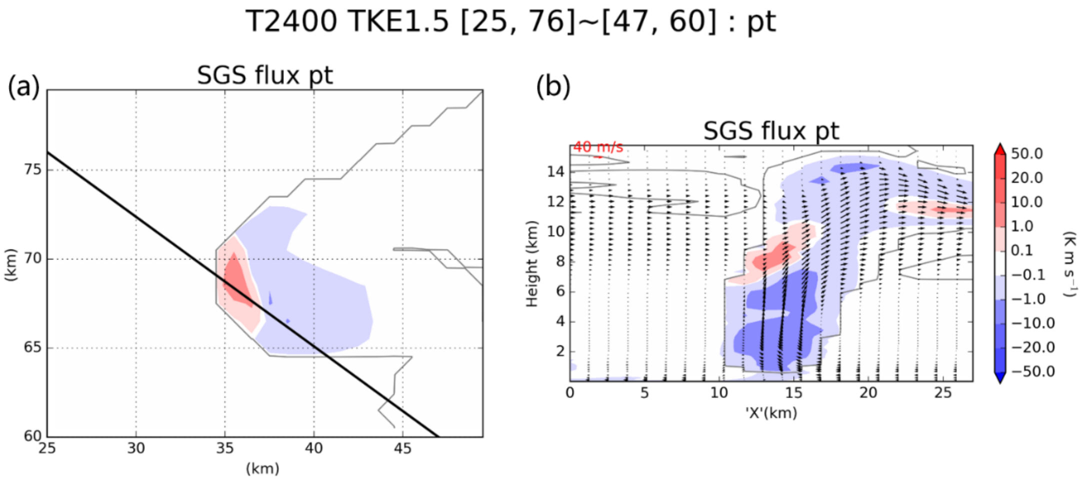
Incorrect sign – fails to represent Upgradient fluxes

Offline comparisons of $\overline{w'\theta'}$ for a supercell storm using 50 m LES data

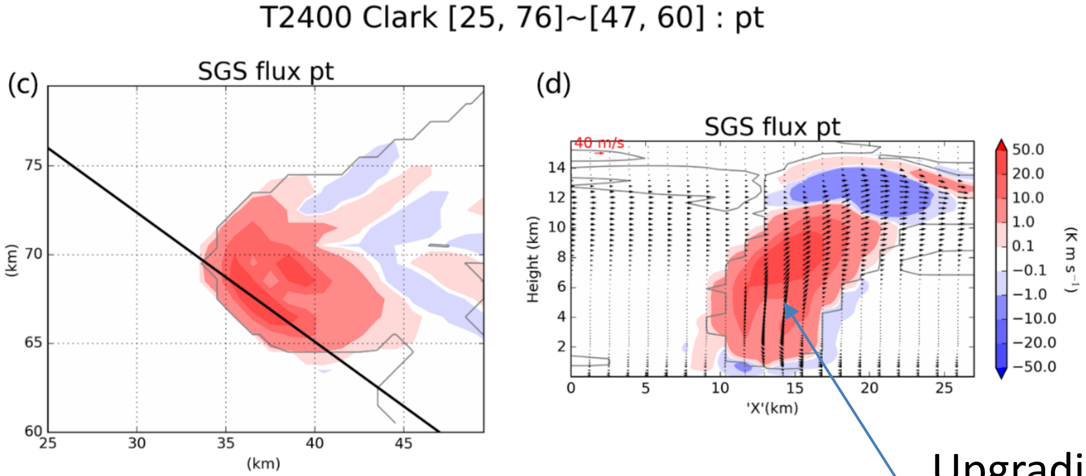


Results of actual 1 km simulations using different schemes

TKE scheme

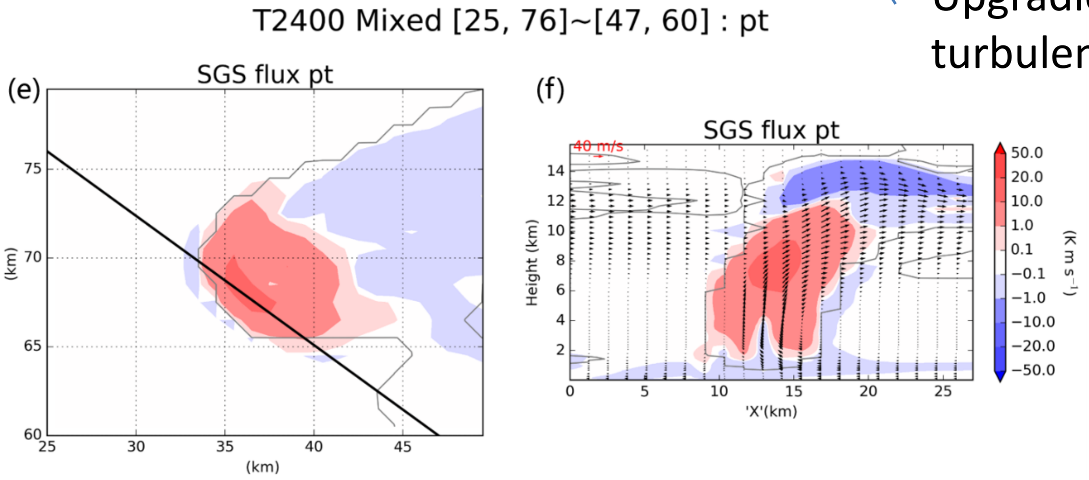

T2400 TKE1.5 [25, 76]~[47, 60] : pt

Series Expansion


T2400 Clark [25, 76]~[47, 60] : pt

Upgradient SGS turbulent fluxes

Mixed scheme


T2400 Mixed [25, 76]~[47, 60] : pt

PBL Parameterizations

- Prediction of convective weather has great sensitivity to PBL parameterization, because it directly affects boundary layer structures and therefore important low-level storm environment;
- There exists a high level of uncertainties with PBL parameterization, leading to a proliferation of PBL schemes.
- WRF model alone has at least ten PBL schemes (MRF, YSU, MYJ, QNSE, MYNN, BouLac, GBM, UW, ACM, ACM2, TEMF) – see review by Cohen et al. (2015);
- These schemes can be classified as local, non-local, hybrid local/non-local schemes;
- PBL schemes are closely coupled with surface layer fluxes, which have their uncertainties.

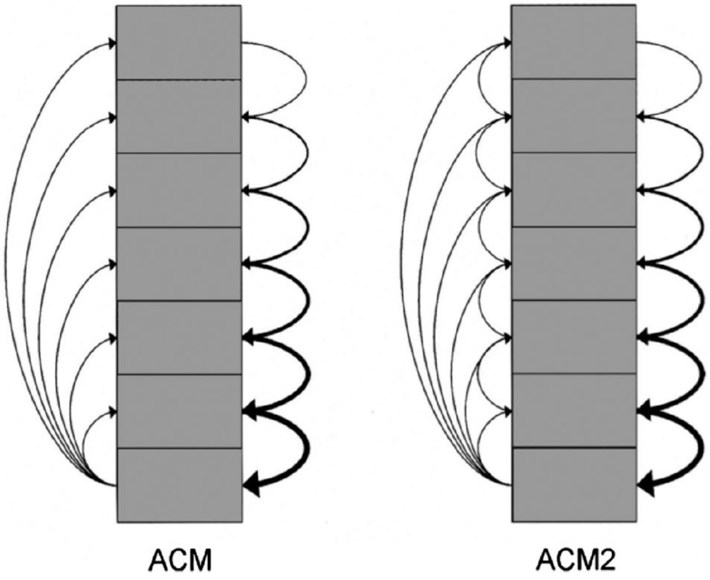


FIG. 2. Depiction of the mechanics of the ACM and ACM2 schemes regarding PBL interactions [from Pleim (2007a)]. Arrows depict exchanges of atmospheric quantities between various layers within the simulated PBL.

PBL Parameterizations

- It is well known that in convective boundary layer, there exists upgradient heat fluxes in the upper portion of the BL, corresponding to slightly stable theta profile;
- A counter-gradient γ term is included in, e.g., the 'Non-local' YSU scheme to account for the effect;

$$\overline{w'\theta'} = -K_h \cdot (\frac{\partial\overline{\theta}}{\partial z} - \gamma)$$

- When BL eddies are partially resolved, we fall into the gray zone or terra incognita – scale aware PBL schemes have been designed that parametrizes increasingly less eddy mixing;
- A new PBL scheme was developed by Shin and Hong (2015), which inherited YSU's treatment for local downgradient eddy fluxes, but the counter-gradient heat flux term was replaced with the nonlocal heat flux profile fitted to LES results. Scale-awareness is added by scaling both local and nonlocal eddy fluxes based on normalized grid spacing ($\Delta_* = {}^{\Delta}/_{z_i}$).

Nonlocal and Local heat fluxes derived from LES data for different grid spacing

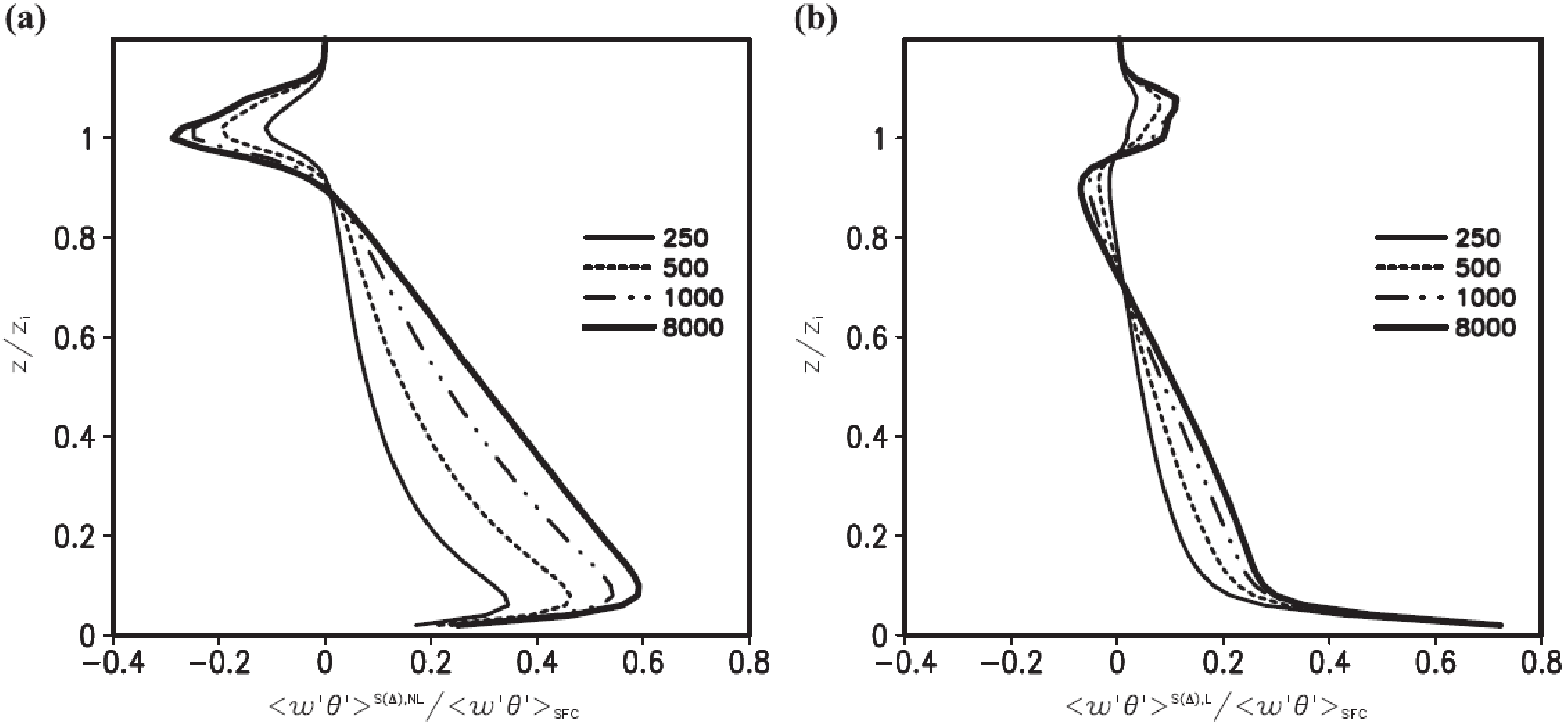
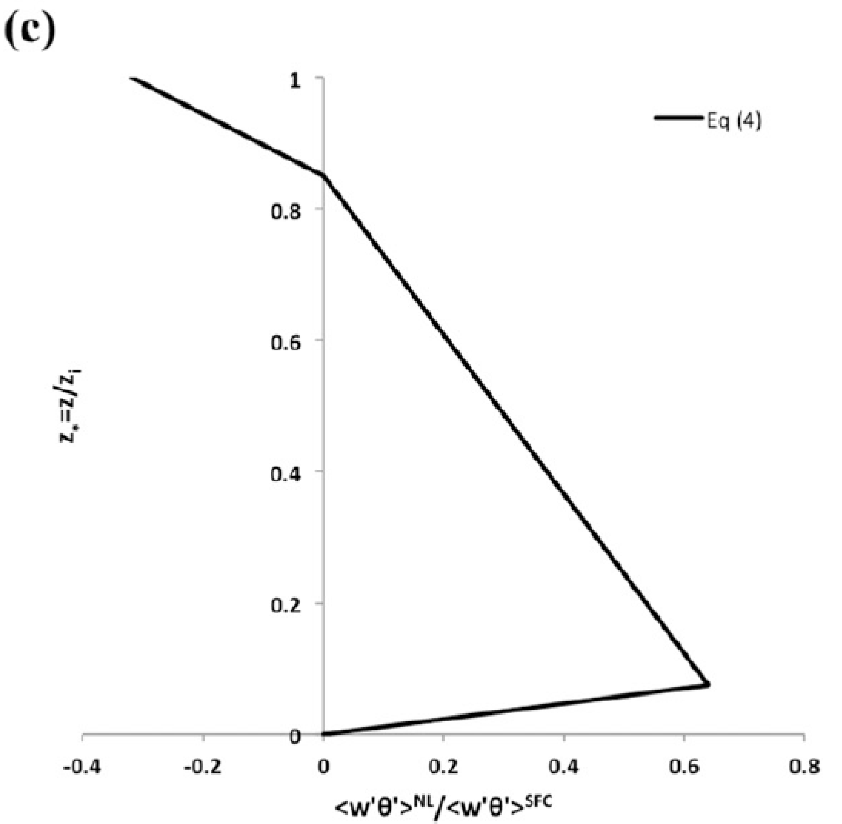


FIG. 1. Vertical profiles of the domain-averaged (a) SGS nonlocal and (b) SGS local heat transports for $\Delta = 250$ m (thin solid), 500 m (thin dotted), 1000 m (thin dot–dot–dashed), and 8000 m (thick solid), normalized by surface heat flux.

Shin and Hong (2015)

Fitted nonlocal heat flux profile and grid-size dependency function and of Shin and Hong (2015) scheme



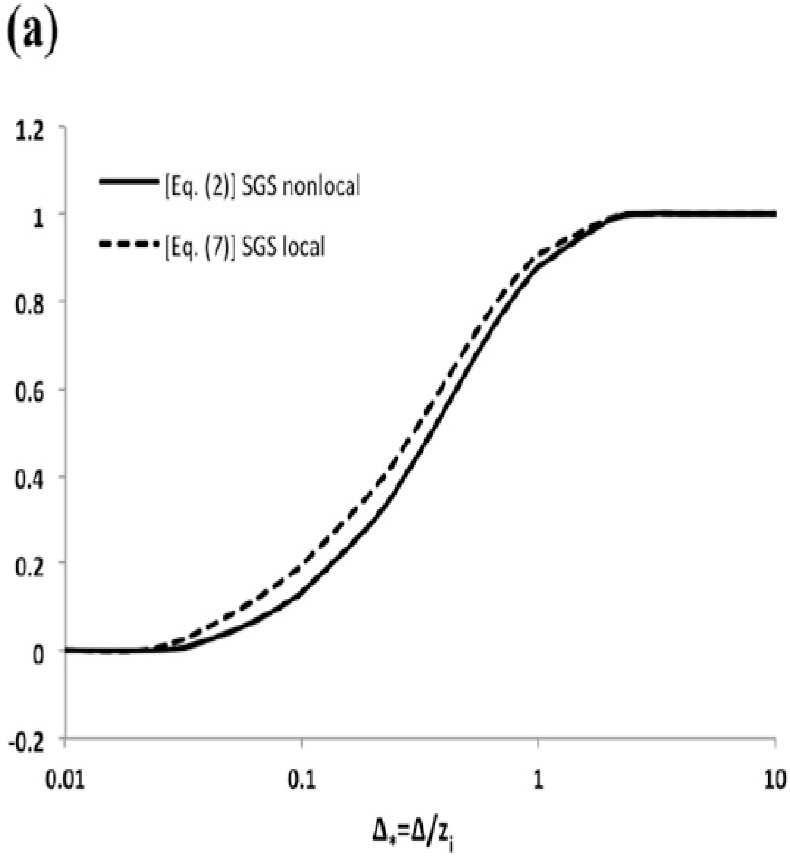


FIG. 2. (a) Grid-size dependency functions for SGS nonlocal [$P_{NL}(\Delta_{*cs})$ for $C_{cs}=1$: solid, Eq. (2)] and local [$P_L(\Delta_*)$: dotted, Eq. (7)] vertical heat transports, (b) stability dependency function [C_{cs}: Eq. (3)], and (c) total nonlocal vertical heat transport profile [Eq. (4)].

Sensitivity to Nonlocal Flux Profile

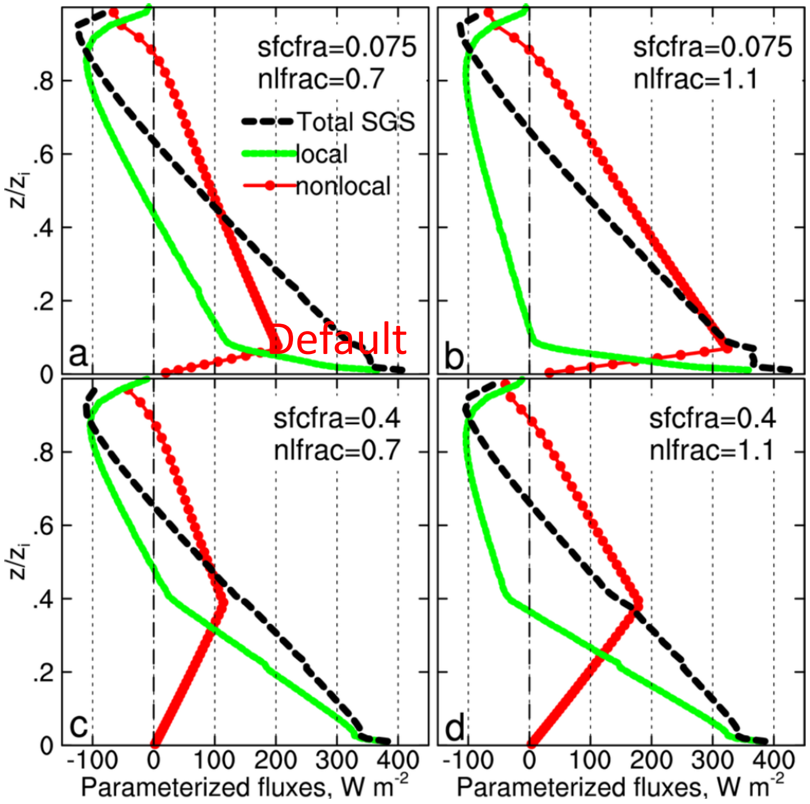


Figure 6. Flux profiles simulated with the SH scheme with different *sfcfra* and *nlfrac*.

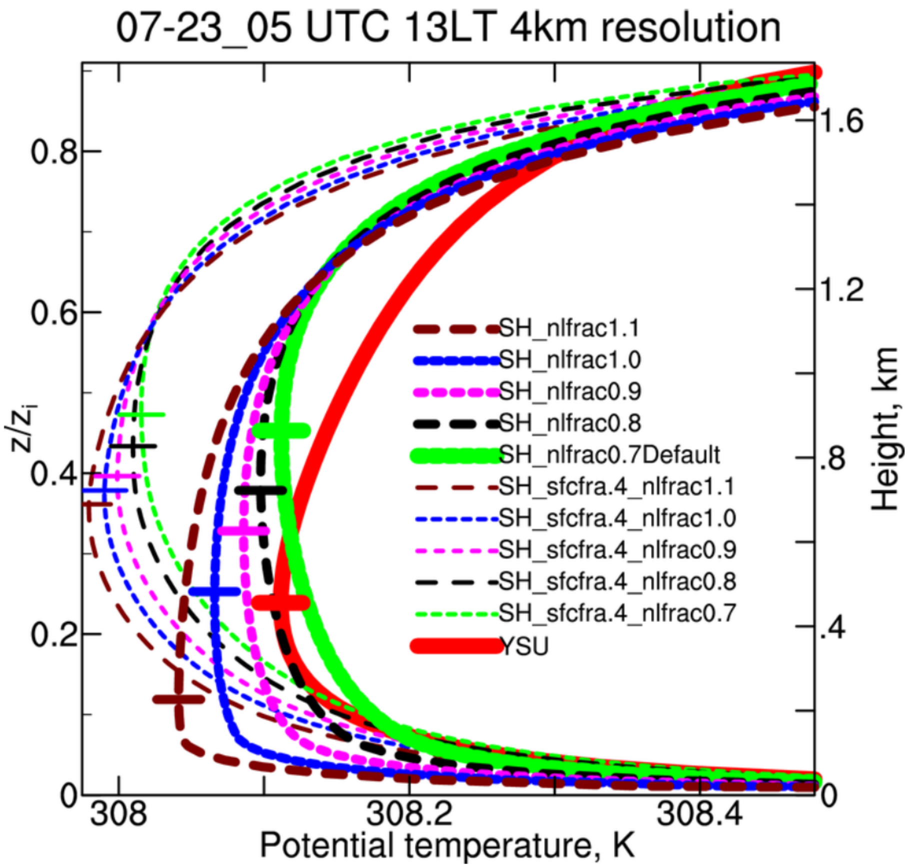


Figure 5. Simulated profiles of potential temperature using the WRF single-column model with the YSU, SH schemes and SH variants with adjusted *sfcfra* and *nlfrac*. The adjusted values are shown in the legend.

sfcfra : normalized height of the surface layer where nonlocal flux increases linearly with height.
nlfrac : ratio of nonlocal heat flux to total heat flux at the top of the surface layer.

Xiaoming Hu et al. (2018)

3D WRF Simulations for 14 Cases over Beijing in 2010 at 27/9/3 km grid spacings

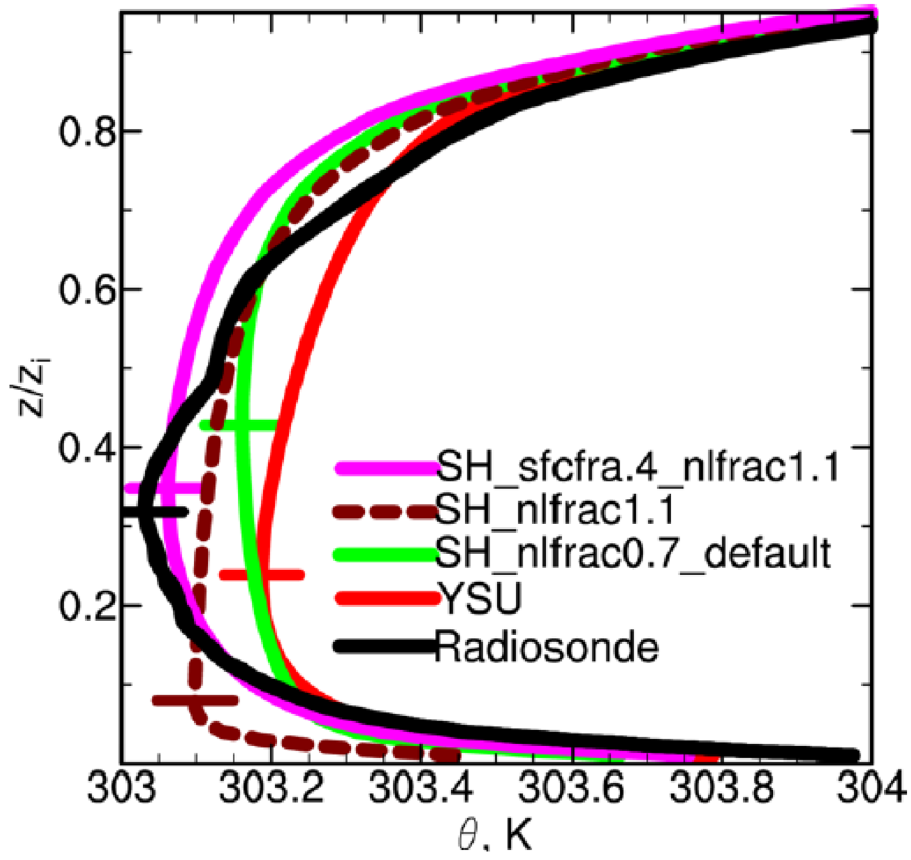


Figure 10. Simulated and observed composite profiles of potential temperature (θ) for all the 14 cases in 2010

Xiaoming Hu et al. (2018)

PBL and SGS Turbulence Parameterizations

- There exist large uncertainties with PBL and SGS Turbulence Parameterizations;
- Modeling of deep moist convection at O(1km) grid spacing calls for more realistic SGS turbulence closure schemes that can correctly model upgradient fluxes;
- Newer scale-aware PBL schemes can introduce additional uncertainties that require further tuning and testing;
- Stable boundary layer parameterization is an even bigger challenge;
- A unified 3D scale-aware PBL/SGS turbulence closure that include fluxes in all three directions should be developed;
- Given that uncertainties may be unavoidable, carefully designed stochastic perturbations may be necessary to facilitate ensemble forecasting.

Comparisons between downscaled IC, Multiple Physics, SKEB and SPPT perturbations for a squall line case

- Multiple physics had been commonly employed in convective-scale ensemble, and have been shown to clearly improve ensemble spread.
- Stochastic kinetic energy backscatter (SKEB) had been shown to produce ensemble spread comparable to those produced by multiple physics, for CAM-resolution forecasts, and the combination of SKEP and multiple physics yield better results in Duda et al. (2012) although the study did not include IC and LBC perturbations.
- The relative contributions to spread growth from IC, PHY, SKEB and SPPT within CAM ensembles need to be better studied.
- Johnson and Wang (2016) studied the role of IC perturbations generated by a convective-scale EnKF and suggested positive contributions of convective-scale IC perturbations on first few hours of forecasting.

Man Zhang, et al (2018 under preparation)