Impacts of a Stochastic Subgrid-scale Mixing Scheme in Deep Convection Simulations for Application to the Convective Grey Zone

McKenna Stanford[1], Hugh Morrison[2], and Adam Varble[1,3]
[1]University of Utah, Salt Lake City, UT; [2]National Center for Atmospheric Research, Boulder, CO; [3]Pacific Northwest National Laboratory, Richland, WA
CONTACT: mckenna.stanford@utah.edu

1) Introduction & Overview

- Simulated "grey zone" (Δx = 1-2 km) updrafts are typically too undilute due to too little mixing (Bryan and Morrison, 2012; Lebo and Morrison, 2015)
- Under-mixing partly results from updrafts that are too wide compared to large eddy simulations (LES), leading to reduced horizontal gradients
- Allowing for variable mixing in time and space via a stochastic framework should conceptually allow some updrafts to mix with mid-tropospheric environmental air while allowing updrafts to remain relatively undilute at other times and locations

2) Theoretical Motivation

First-order closure to Reynolds-averaged scalar (C) conservation equation:

$$\left(\frac{dC_u}{dt}\right)_{mix} = -\frac{\partial(u'C')}{\partial x} = \frac{\partial}{\partial x}\left(-K_h\frac{\partial C}{\partial x}\right) \approx -\frac{2k^2\lambda w(C_u - C_{env})}{P_r \boxed{R^2}} \quad (1)$$

Equation (1) Variables:

- K_h: *horizontal* diffusion coefficient
- t: time
- u: horizontal velocity
- w: vertical velocity
- k: constant (~0.17)
- λ : turbulent mixing length
- C_u: updraft value of C
- C_{env}: updraft value of C
- P_r :Prandtl number
- ': perturbations from grid mean

$\uparrow R \quad C_u > C_{env} \quad \downarrow \left(\frac{dC_u}{dt}\right)_{mix}$

3) Stochastic Framework

Stochastically vary K_h to yield perturbed value (K'_h):

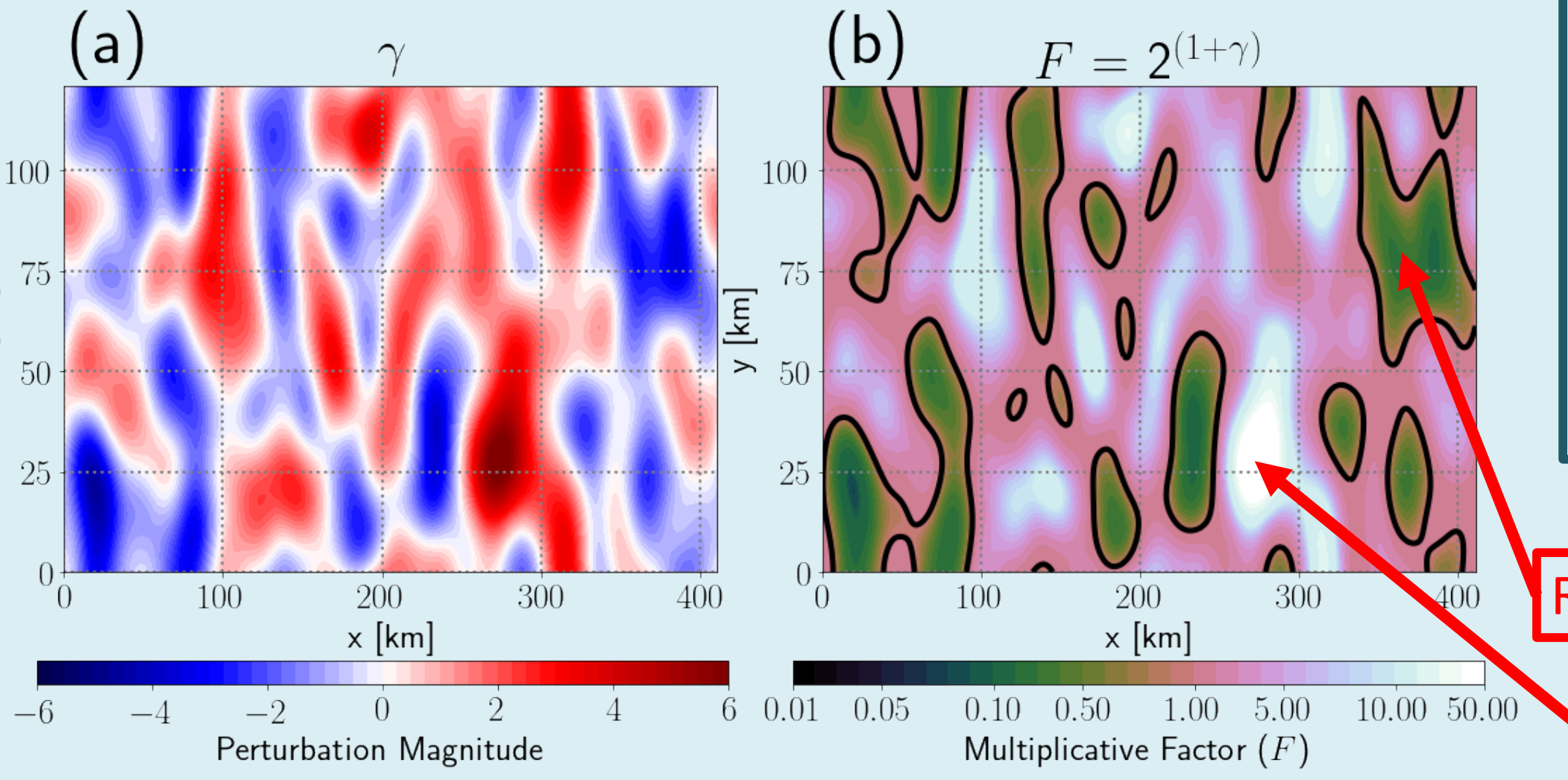
$$K'_h = K_h\left(2^{1+\gamma}\right) \quad (2)$$

γ: perturbation value sampled from Gaussian distribution

$F \equiv 2^{1+\gamma}$: F is a "multiplicative factor"

Perturbations correlated in time and space:

Time scale: 10 min.
Spatial scale: 10 km



Median $F = 2$

Mixing is more often enhanced than reduced

Reduced mixing

Enhanced mixing

Figure 1. (a) Spatial pattern of stochastic patterns produced by the stochastic pattern generator. (b) Spatial pattern of stochastic multiplicative factor, F, that is applied to K_c.

4) Model Setup

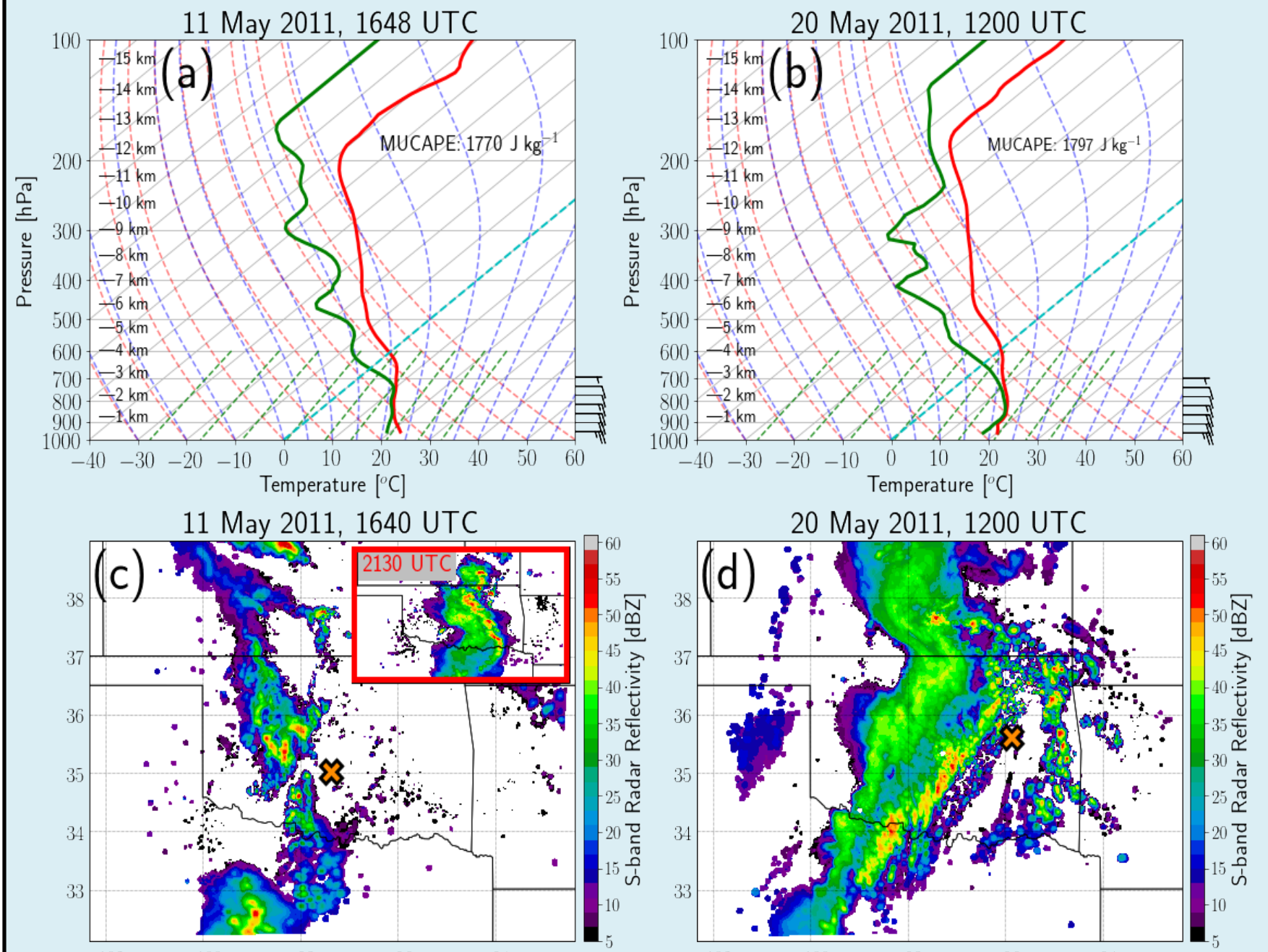


Figure 2. Skew T - log P diagrams of (a) the 11 May 2011 simulation and (b) the 20 May simulation. Horizontal cross sections of gridded NEXRAD radar reflectivity at 2.5 km AGL for (c) 11 May and (d) 20 May 2011 at 1200 UTC.

- WRFV3.9.1
- Δx = 0.125 (LES), 0.5, 1, & 2 km
- Smagorinsky 1st order closure w/ anisotropic mixing length
- 2 squall line simulations using 11 and 20 May soundings from the Midlatitude Continental Convective Clouds Experiment (MC3E; Jensen et al., 2016)
- All modifications to mixing applied after 2-hr spinup

5) Results: Sensitivity to diagnostically altering mixing

Simulation Name	Simulation Description	Line Color & Style
BASELINE	Standard Smagorinsky mixing; Δx = 1 km	**Black**, solid
4X_FULL_DEPTH	Horizontal diffusion coefficient increased by a factor of 4 throughout full tropospheric depth; Δx = 1 km	**Blue**, solid
4X_ABOVE_4KM	Horizontal diffusion coefficient increased by a factor of 4 only above 4 km AGL (standard mixing in bottom 4 km); Δx = 1 km	**Blue**, dashed
NO_MIXING_FULL_DEPTH	Horizontal mixing turned off throughout full tropospheric depth; Δx = 1 km	**Red**, solid
NO_MIXING_ABOVE_4KM	Horizontal mixing turned off only above 4 km AGL (standard mixing in bottom 4 km) ; Δx = 1 km	**Red**, dashed
LES	Standard Smagorinsky mixing; Δx = 0.125 km	Grey, solid
LES_DEGRADED	Standard Smagorinsky mixing; LES averaged to 1-km grid	Grey, dashed

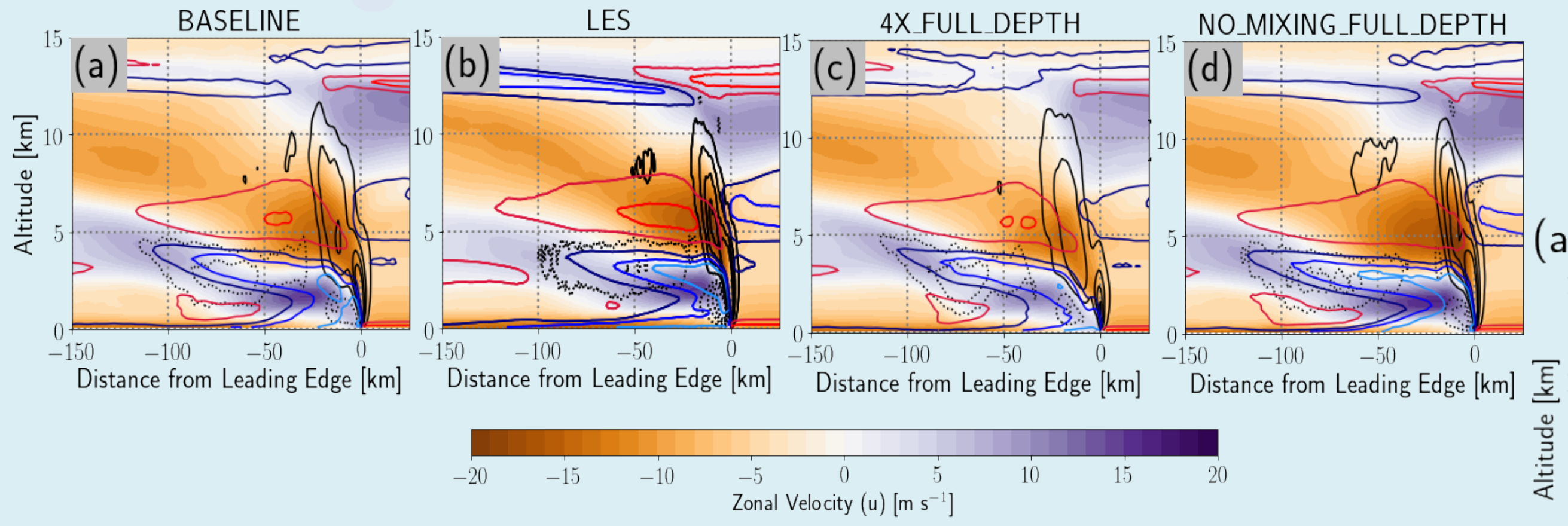


Figure 3. Line averaged cross sections from 4-6 hours of zonal velocity (color fill), buoyancy perturbation (blue and red contours for negative and positive perturbations, respectively), and vertical velocity (solid and dotted black contours for positive and negative velocities, respectively). All simulations are from the 11 May sounding.

- 4X_FULL_DEPTH: weakens cold pool, rear inflow jet, and front-to-rear flow
- NO_MIXING_FULL_DEPTH: strengthens cold pool, rear inflow jet, and front-to-rear flow
- Mesoscale structure of NO_MIXING_FULL_DEPTH is most similar to LES
- Zonal momentum transported further vertically by 4X_FULL_DEPTH—RKW-theory "balance"

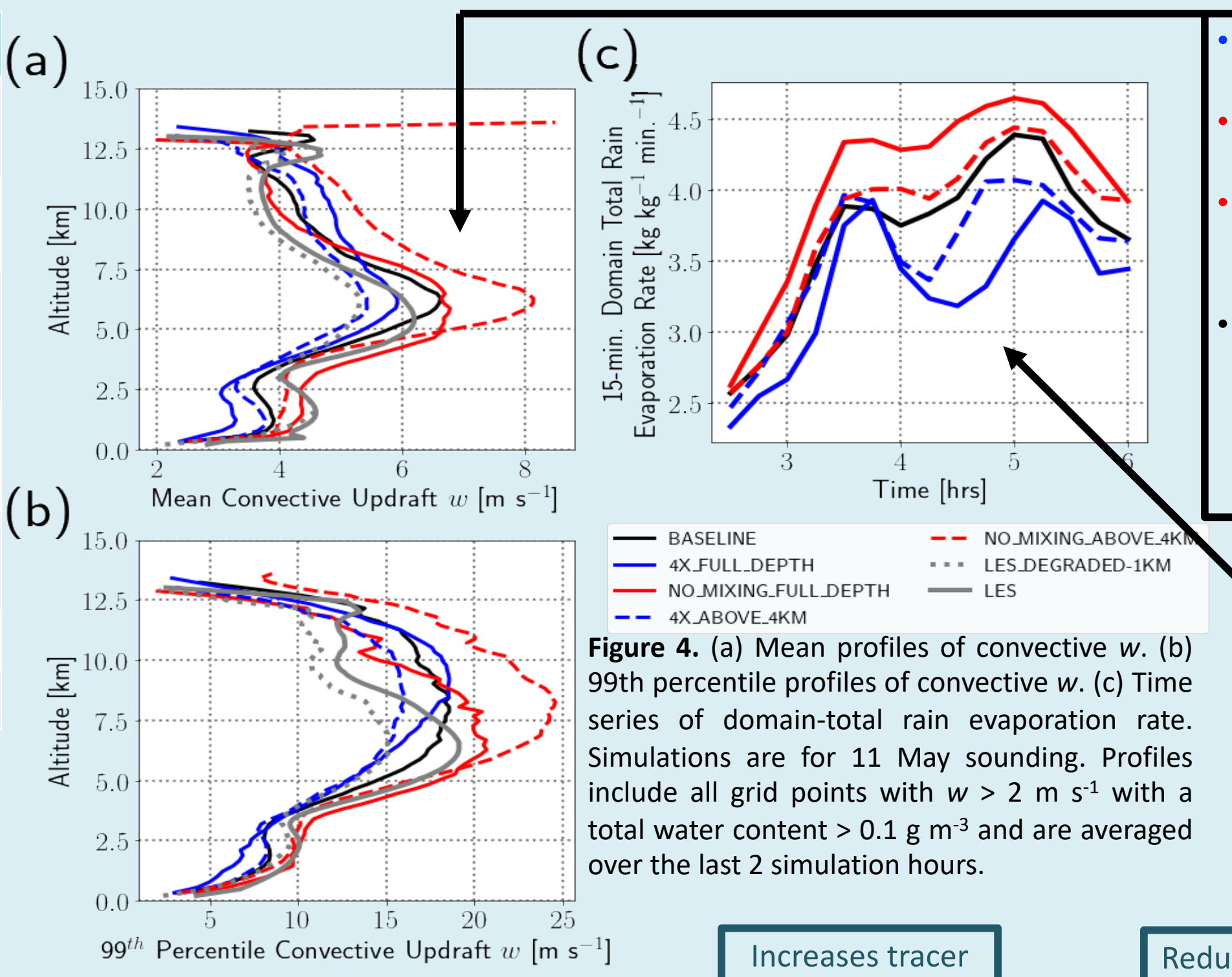


Figure 4. (a) Mean profiles of convective w. (b) 99th percentile profiles of convective w. (c) Time series of domain-total rain evaporation rate. Simulations are for 11 May sounding. Profiles include all grid points with $w > 2$ m s^{-1} with a total water content > 0.1 g m^{-3} and are averaged over the last 2 simulation hours.

- 4X_ABOVE_4KM: reduces w
- NO_MIXING_ABOVE_4KM: increases w
- NO_MIXING_FULL_DEPTH w structure closest to LES
- Limiting mixing to be only ABOVE 4KM limits influence of cold pool strength on w structure

Altering mixing only ABOVE 4KM indirectly changes cold pool strength via updraft-downdraft-cold pool interactions

Increases tracer

Reduces tracer (closer to LES)

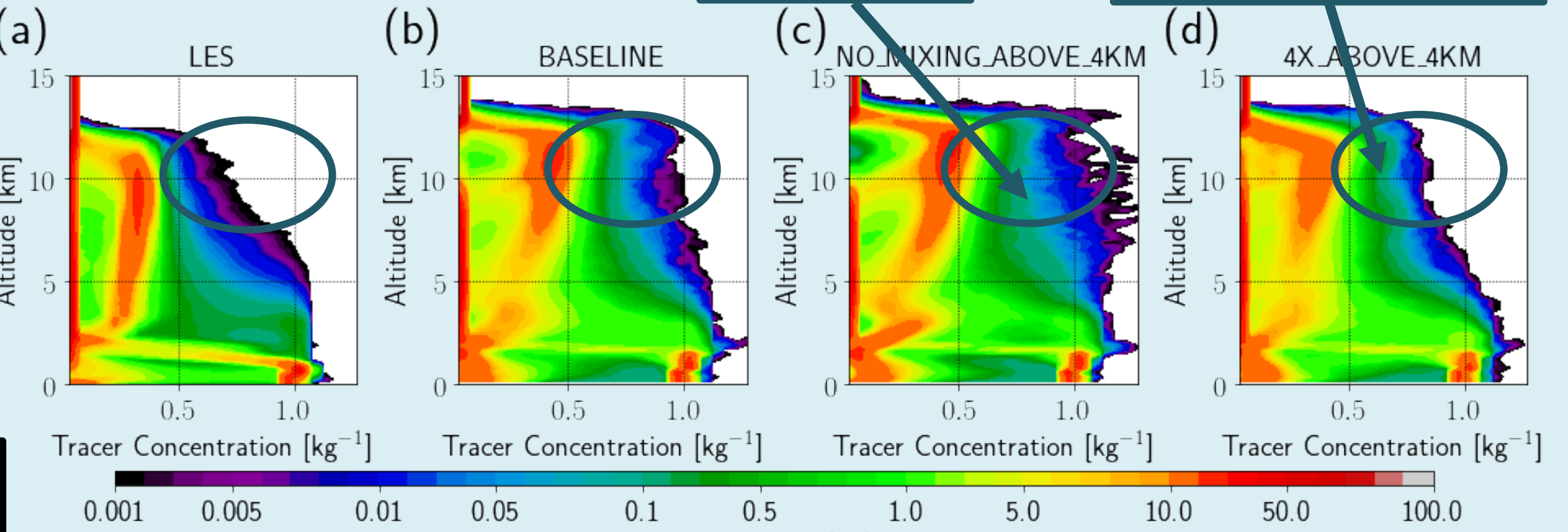


Figure 5. Contoured frequency by altitude diagrams (CFADs) of a passive fluid tracer, initialized in the bottom 1.5 km at 3 hours, composited over the last hour of the simulations, for the 11 May sounding.

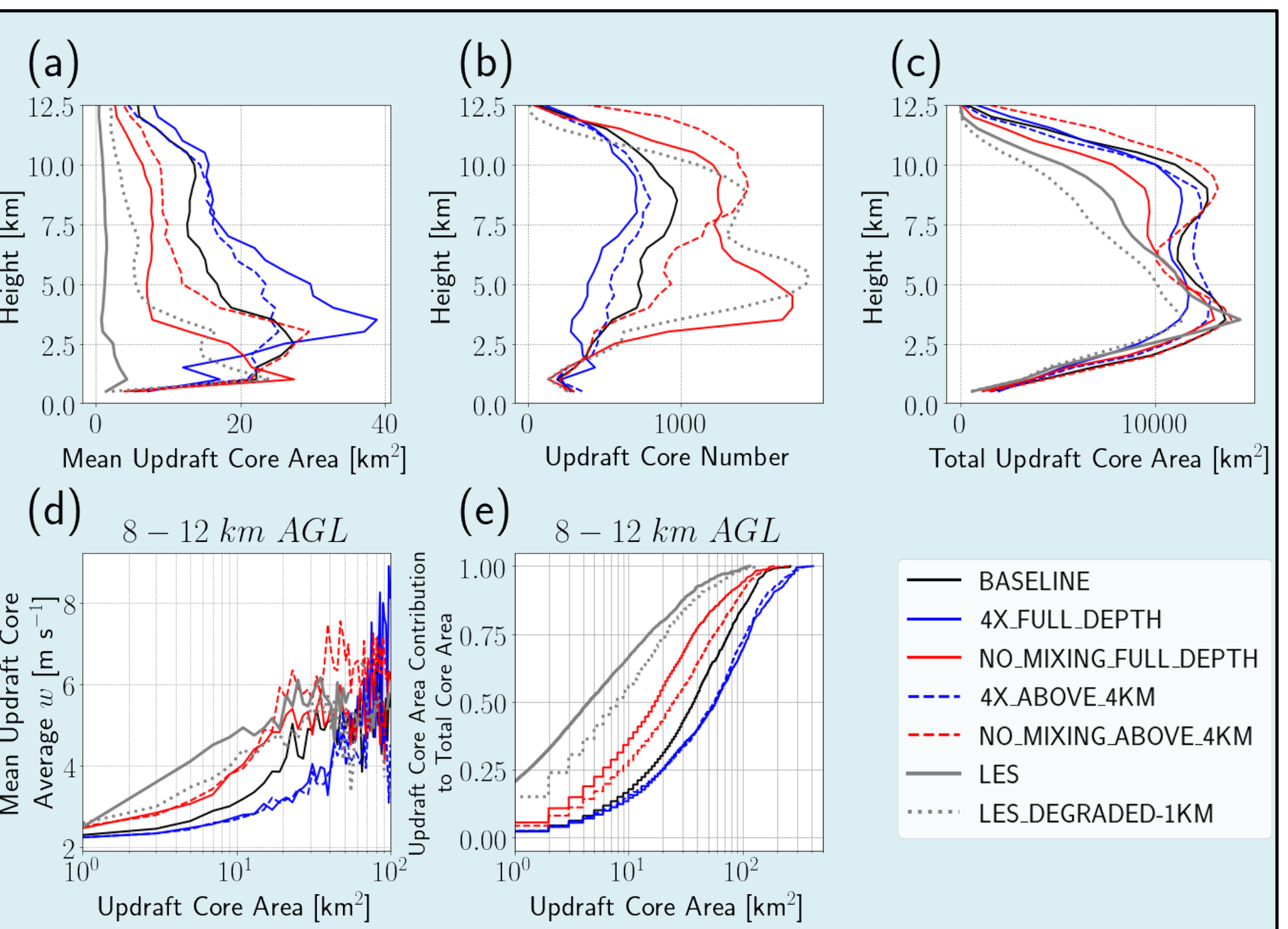


Figure 6. Vertical profiles of (a) mean convective updraft core area, (b) updraft core number, and (c) total updraft core area. (d) Mean updraft core average w for cores between 8 and 12 km altitude. (e) Cumulative distribution function of updraft core area contribution to total core area for altitudes between 8 and 12 km. Convective updraft cores are defined as contiguous points with $w > 2$ m s^{-1} and total water content > 0.1 g m^{-3}.

- 4X_FULL_DEPTH & 4X_ABOVE_4KM: increases core size, decreases core number, weakens average core w for a given core area, and increases contribution of large cores to total core area
- NO_MIXING_FULL_DEPTH & NO_MIXING_ABOVE_4KM: decreases core size, increases core number, strengthens average core w for a given core area, and decreases contribution of large cores to total core area
- In all updraft core metrics, NO_MIXING_FULL_DEPTH produces statistics closest to LES

6) Results: Stochastic mixing scheme

Simulation Name	Simulation Description	Line Color & Style
STOCH	Stochastic mixing **applied above 4 km AGL**; standard, non-stochastic mixing below 4km ; Δx = 0.5, 1, & 2 km; Note that the median F for STOCH simulations is 2X	**Cyan**, solid
θ-pert	Standard Smagorinsky mixing applied, but with white noise applied to lower-level θ field at 2-hr restart	**Purple**, thin solid

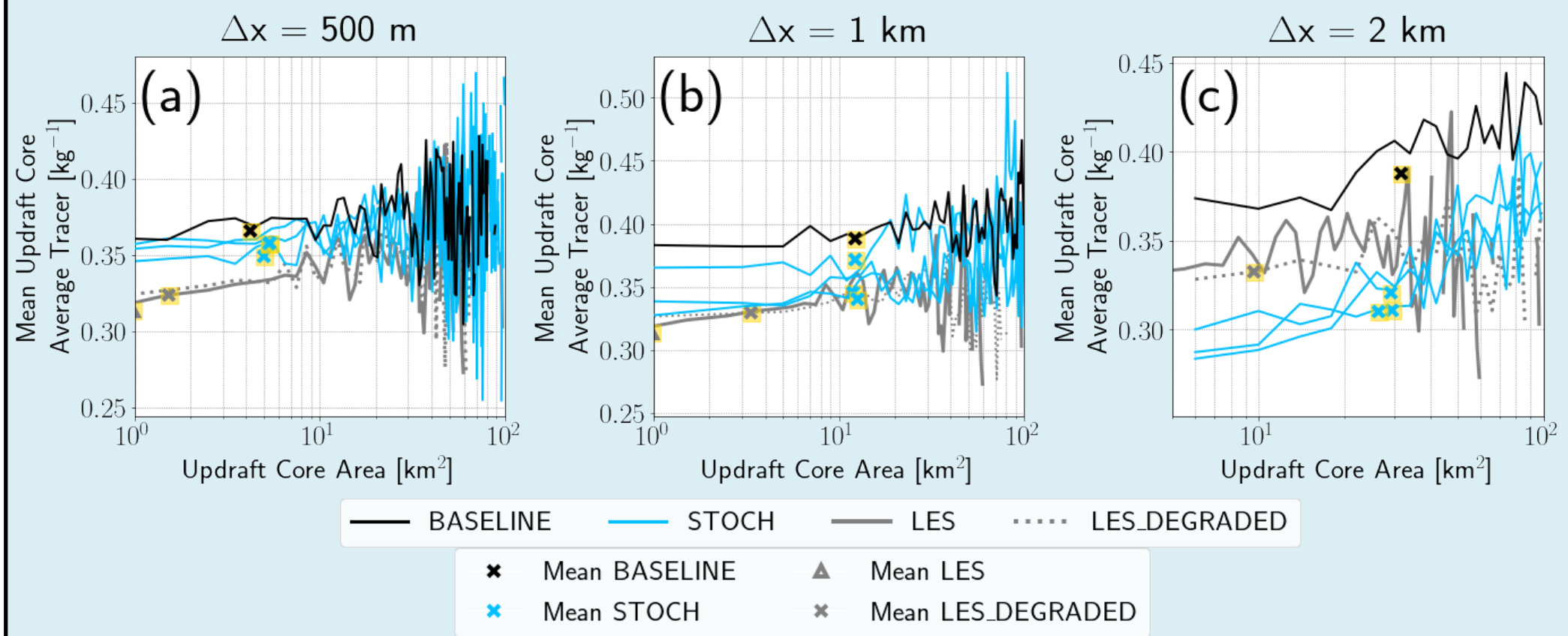


Figure 7 . Mean updraft core average tracer concentration as a function of updraft core area, composited over the last 2 hours of the simulation, for altitudes between 8.5 and 12 km, for the 11 May sounding. . Convective updraft cores are defined as contiguous points with $w > 2$ m s^{-1} and total water content > 0.1 g m^{-3}.

STOCH simulations produce less average core tracer concentrations for a given core area compared to **BASELINE**, indicating more dilution, shifting concentrations closer to **LES**

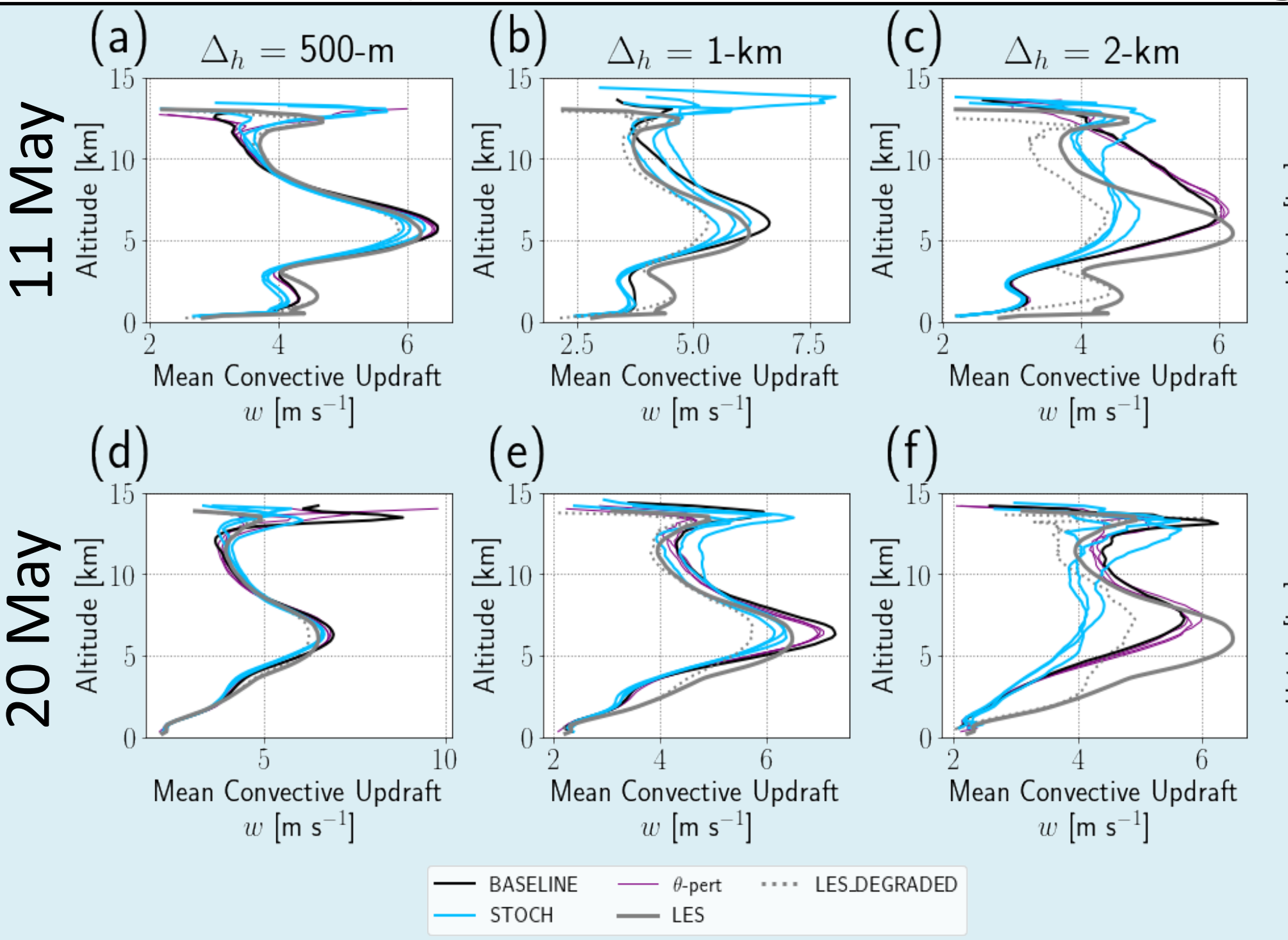


Figure 8. Vertical profiles of mean convective vertical velocity for (a)-(c) 11 May simulations and (d)-(f) 20 May simulations. Leftmost panel is for 500-m grid spacings, middle panel is for 1-km grid spacings, and right-most panel is for 2-km grid spacings. Profiles include all grid points with $w > 2$ m s^{-1} with a total water content > 0.1 g m^{-3} and are averaged over the last 2 simulation hours.

- **STOCH** simulations produce weaker w relative to **BASELINE** above 4 km, shifting profiles closer to **DEGRADED-LES**
- The stochastic scheme is more impactful as grid spacing is coarsened from **LES** to 2 km

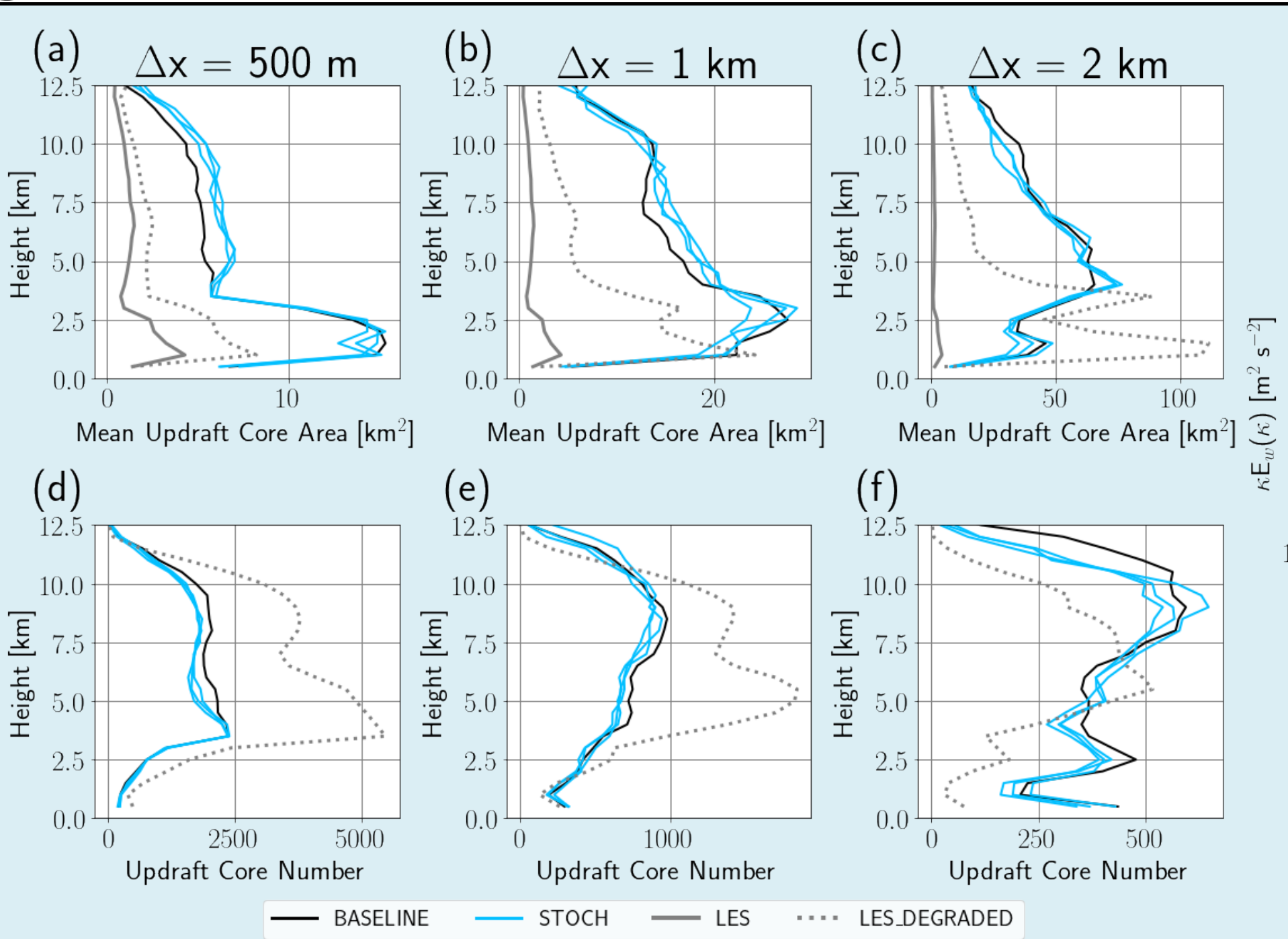


Figure 9. Vertical profiles of (a)-(d) mean updraft core area and (d)-(f) updraft core number, composited over the last 2 hours of simulations, for the 11 May sounding. Convective updraft cores are defined as contiguous points with $w > 2$ m s^{-1} and total water content > 0.1 g m^{-3}.

Updraft core properties of **STOCH** simulations do not vary significantly from **BASELINE**, signifying that the stochastic scheme largely acts to alter updraft core dynamical properties but NOT updraft core size and number distributions

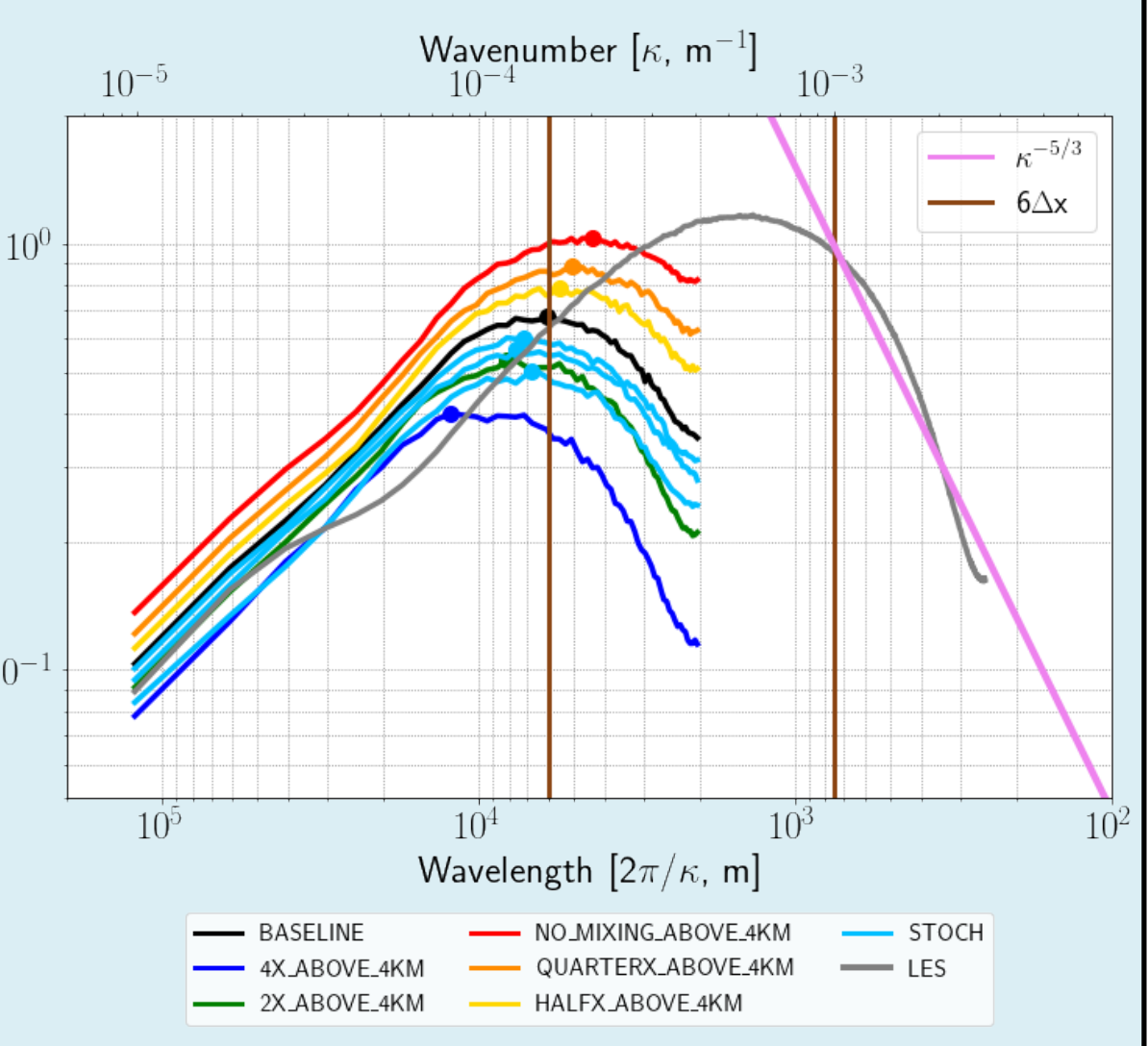


Figure 10. 2D vertical velocity energy spectra composited over the final 2 hours of simulations and between altitudes of 4 and 7 km.

Peak of vertical velocity energy spectra for **STOCH** occurs at slightly smaller wavelengths (i.e. higher effective resolution) relative to peak for simulations with same (constant) multiplicative factor (**2X**)

7) Conclusions

- Diagnostically reducing (enhancing) mixing produces smaller (larger) updraft cores and a higher (lower) effective resolution
- Enhancing mixing dilutes updraft cores and decreases the amount of tracer transported to upper levels
- Enhancing (reducing) mixing weakens (strengthens) the cold pool, rear inflow jet, and front-to-rear flow, altering mesoscale structure in a manner similar to RKW theory
- Stochastic scheme dilutes updraft cores, weakening vertical velocities, but shows no significant changes to updraft core size and number distributions
- Stochastic scheme produces an effective resolution slightly higher (lower) than 2X (BASELINE)

8) Future Work

- Extend stochastic framework to full-physics, real case study simulations & compare w/ observations
- Investigate stochastic scheme in tropical convection simulations (more purely buoyancy-forced updrafts)
- Examine impact of stochastic scheme on convective initiation
- Due to arbitrary "cut-off" of stochastic mixing below 4-km and competing benefits of reduced vs. enhanced mixing, additional stochastic formulations will be tested

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