Non-monotonic Convective Response to Vertical Wind Shear

A Closer Look from Cloud Resolving Model Simulations

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Vertical wind shear is important for convective development

- Vertical wind shear (vertical shear of the horizontal wind) plays a critical role in organizing convection

- Existing literatures are mostly focused on a single squall-line case or idealized warm bubble experiments (e.g., Rotunno et al. 1988; Rotunno and Klemp 1982; Klemp 1987; Skamarock et al. 1994)

- We propose to get an ensemble convective response in a less storm-like and more realistic environment, and inform a physically-based convective organization-wind shear relationship to be used in climate models

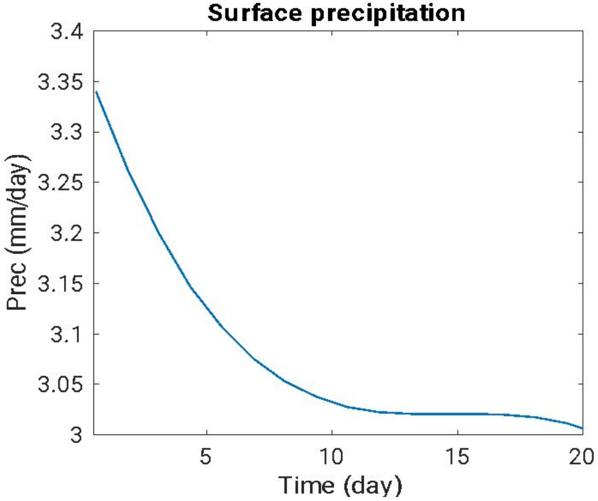
Scientific questions

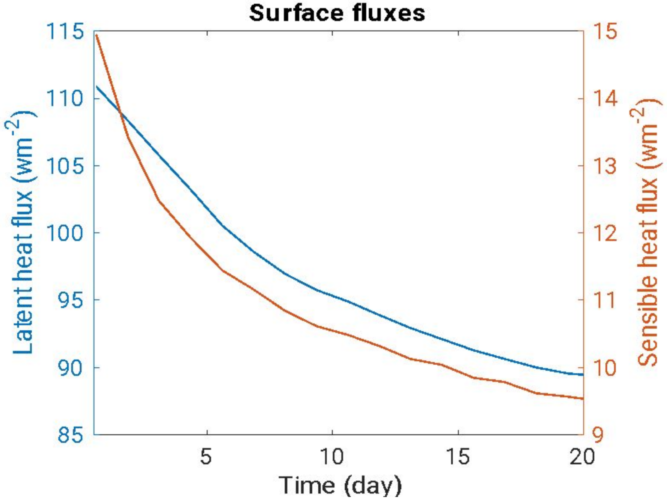
- Do convective characteristics respond to vertical wind shear monotonically or non-monotonically, and why?
- What drives differences in the surface precipitation response with different wind shear magnitudes?
- Does organization occur under a particular wind shear magnitude?

Model setup

- Cloud-resolving model: SAM 6.11.6
- Radiative Convective Equilibrium (RCE) configurations, no large-scale forcing, except for the added zonal winds
- Resolutions: 64 stretching vertical levels; 500m horizontal; 256 x 256 grid boxes; 10s temporal resolution
- Create 20 ensemble members with initial conditions that were generated by output from the quasi-equilibrium run every 12 hours, each ensemble was run for additional 3 hours

Ensemble members are branched from RCE basic state

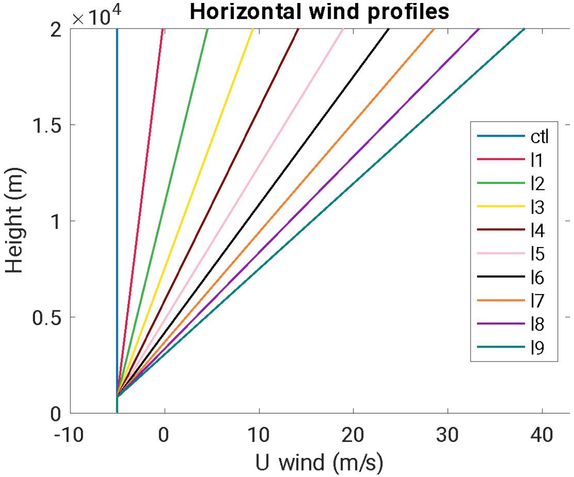


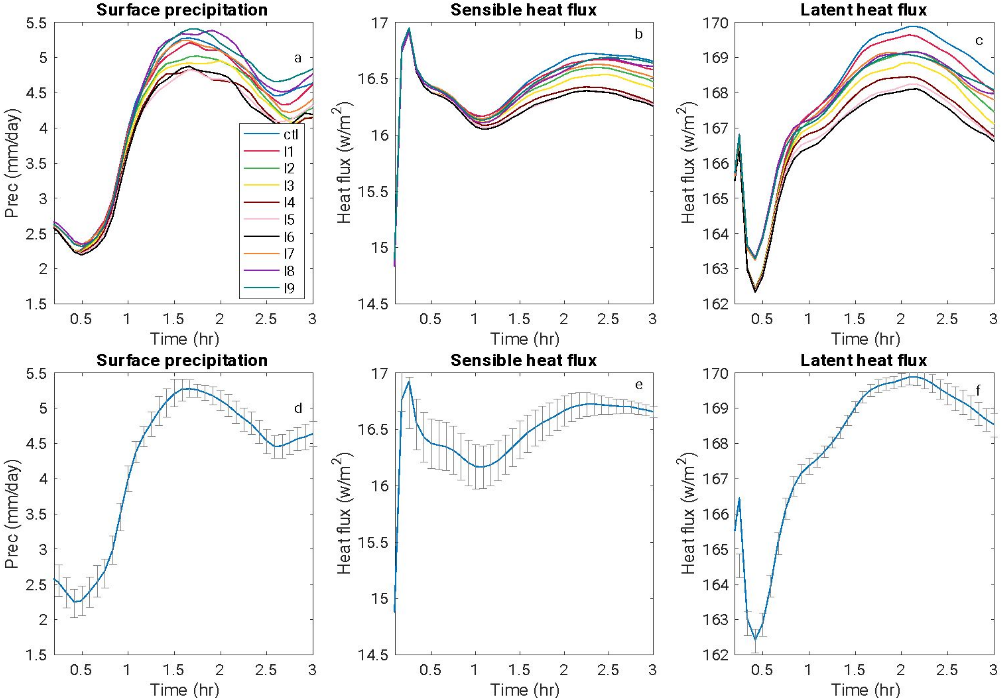


- The domain-mean surface precipitation stays around 3 mm day^{-1}, and latent and sensible heat fluxes slowly decrease to about 90 W m^{-2} and 9.5 W m^{-2}, respectively

- Analysis results are averages of 20 ensemble members

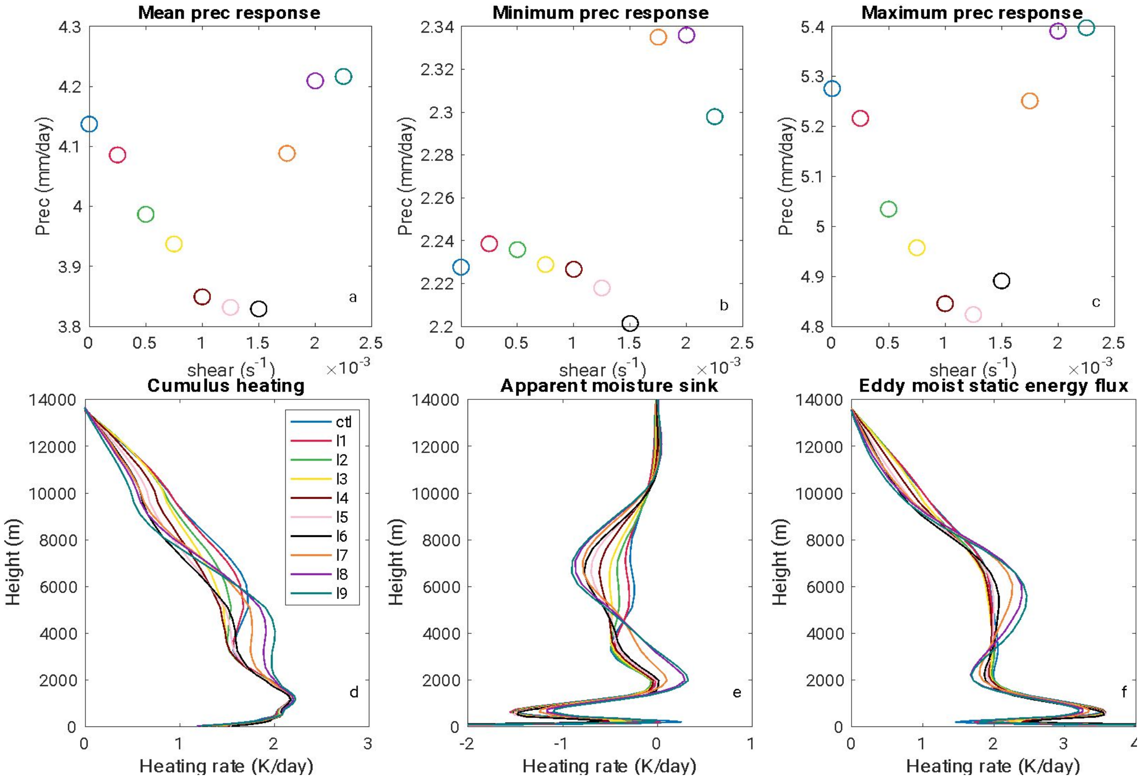
Vertical wind shear profiles and ensemble responses





- Domain-mean precipitation exhibits non-monotonic response, spread cannot be explained by fluxes

Ensemble responses in convective heating and moistening



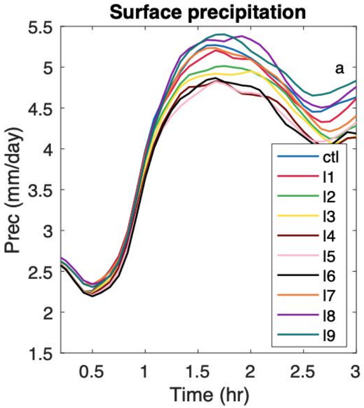
- Non-monotonic behavior in mean, min, and max response as well
- Consistent pattern in vertical heating and moistening

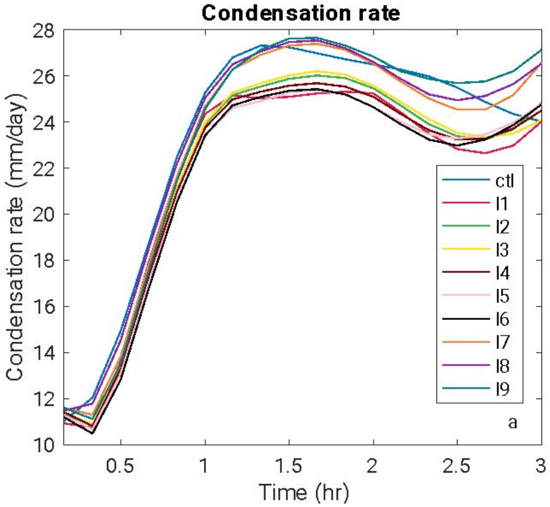
Spread in condensation rate explains spread in precip better

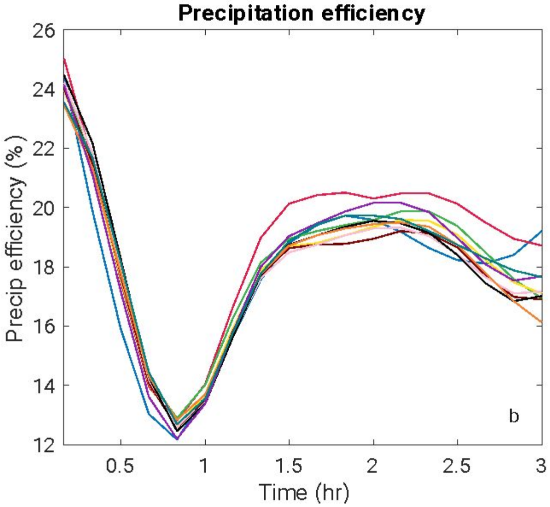
$$\frac{d\langle\overline{q_{cond}}\rangle}{dt} = \langle\overline{COND}\rangle - \langle\overline{EVAP}\rangle - \overline{PREC} \qquad \langle x\rangle = \int_{surf}^{top} \rho x dz$$

$$PE \equiv \overline{PREC}/\langle\overline{COND}\rangle$$

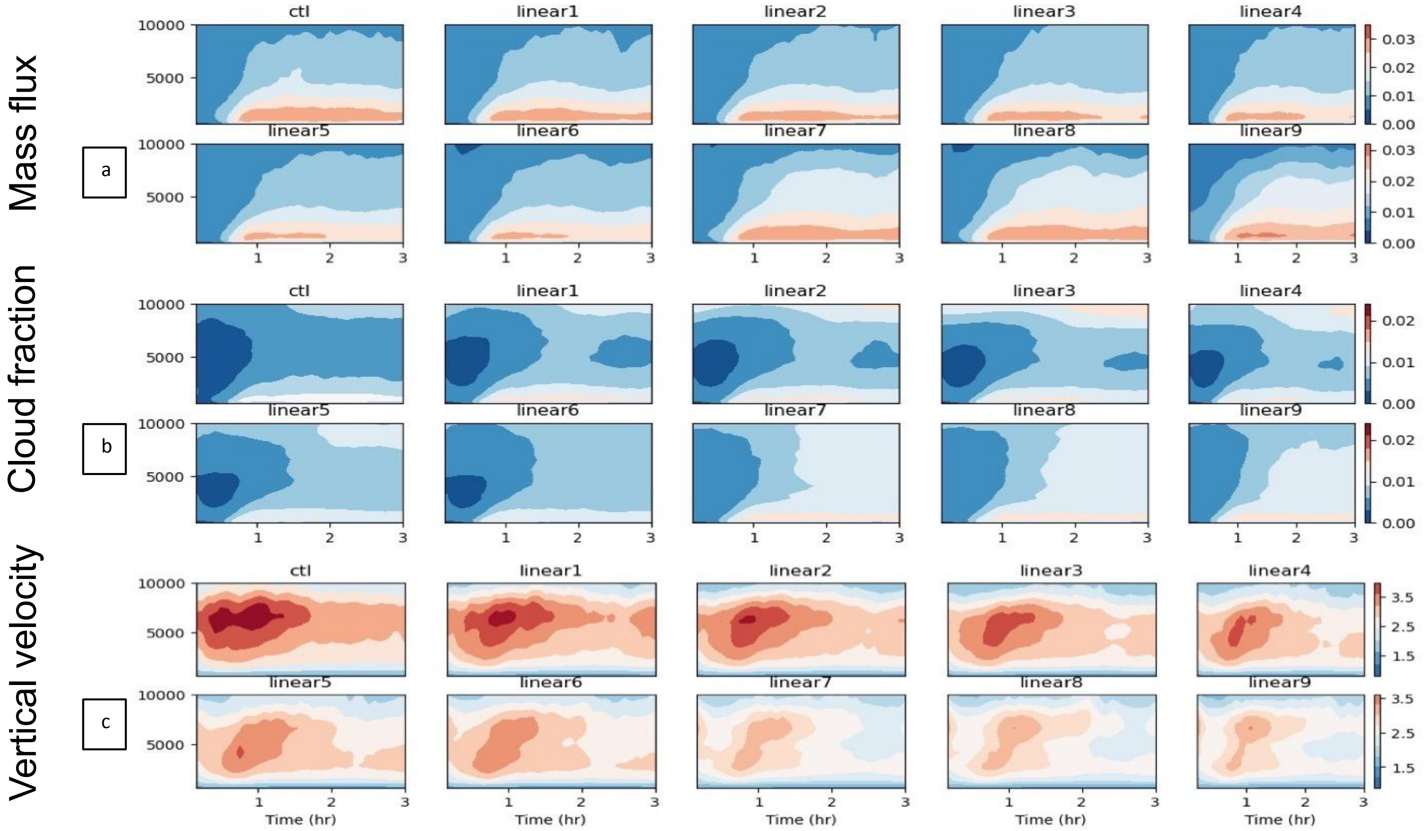
$$EE \equiv \langle\overline{EVAP}\rangle/\langle\overline{COND}\rangle \approx 1 - PE$$



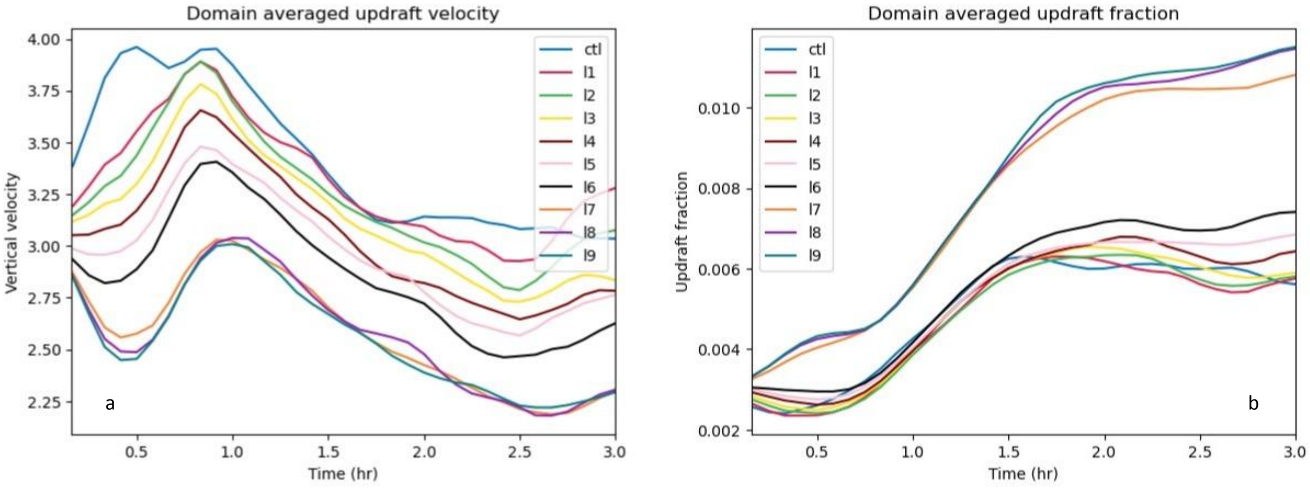




Responses in mass flux, cloud fraction and vertical velocity



Responses in domain averaged updraft velocity and fraction



- Interplay between changes in mean cloudy updraft velocity and fraction with increasing shear magnitude explains the non-monotonic convective response

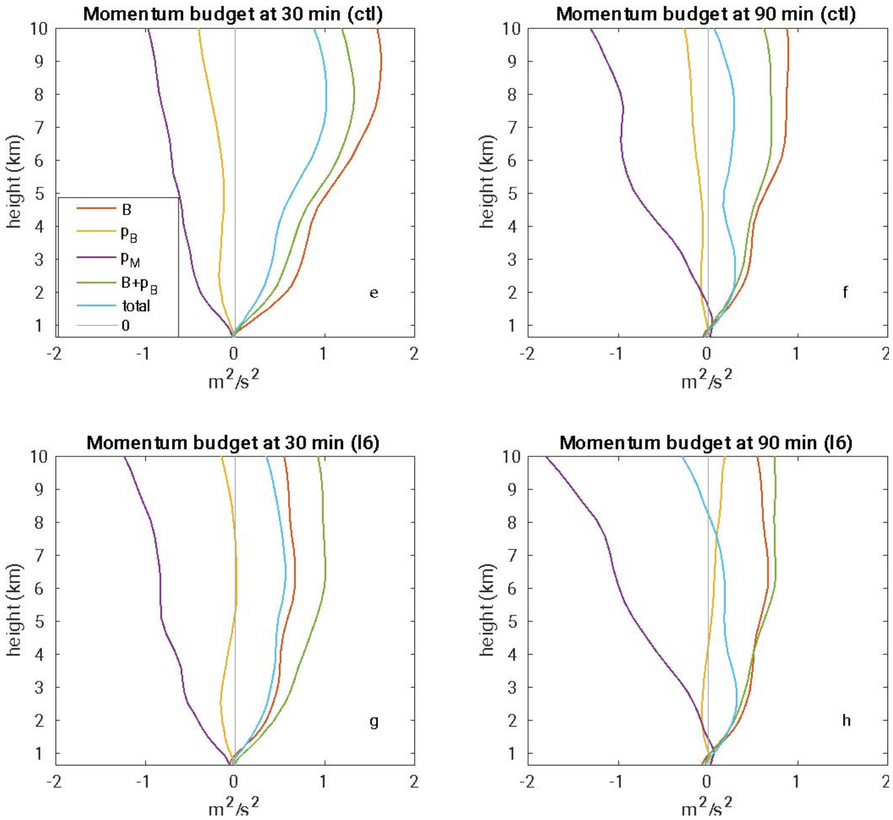
Vertical momentum budget decomposition

$$\frac{1}{2}\frac{dw^2}{dz} = B - \frac{1}{\rho_0}\frac{\partial p_B{}'}{\partial z} - \frac{1}{\rho_0}\frac{\partial p_M{}'}{\partial z} - \epsilon w^2$$

$$\nabla^2 p_B' = \partial_z(\rho_0 B),$$

$$\nabla^2 p_M' = -\nabla \cdot (\rho_0 \vec{v} \cdot \nabla \vec{v}).$$

- Weaker updrafts in moderate shear condition is partly explained by stronger negative dynamic pressure

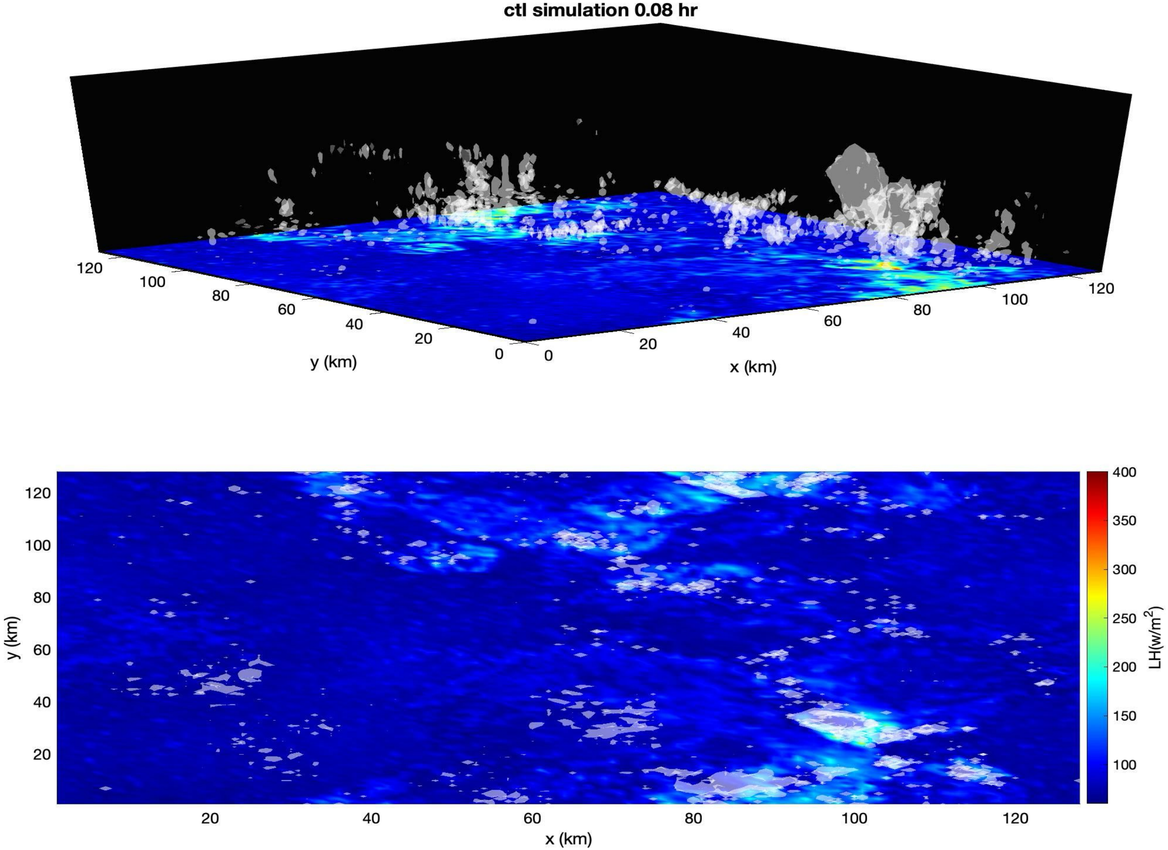


Momentum budget at 30 min (ctl)

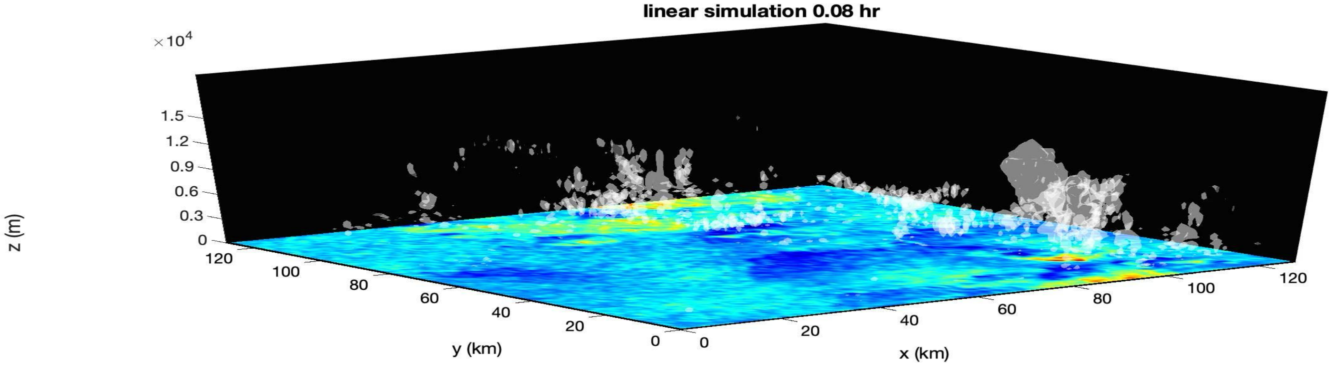
Momentum budget at 90 min (ctl)

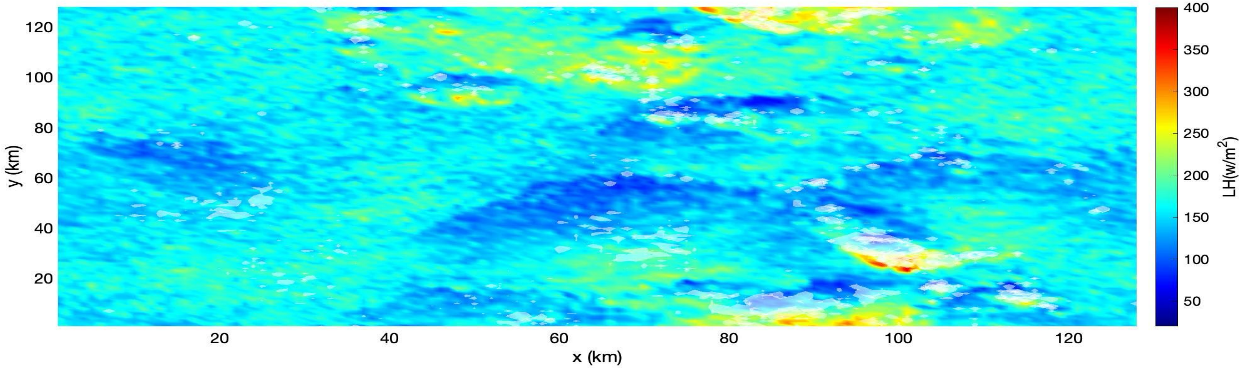
Momentum budget at 30 min (l6)

Momentum budget at 90 min (l6)



- For control scenario, cloud updrafts are comparatively upright and circular



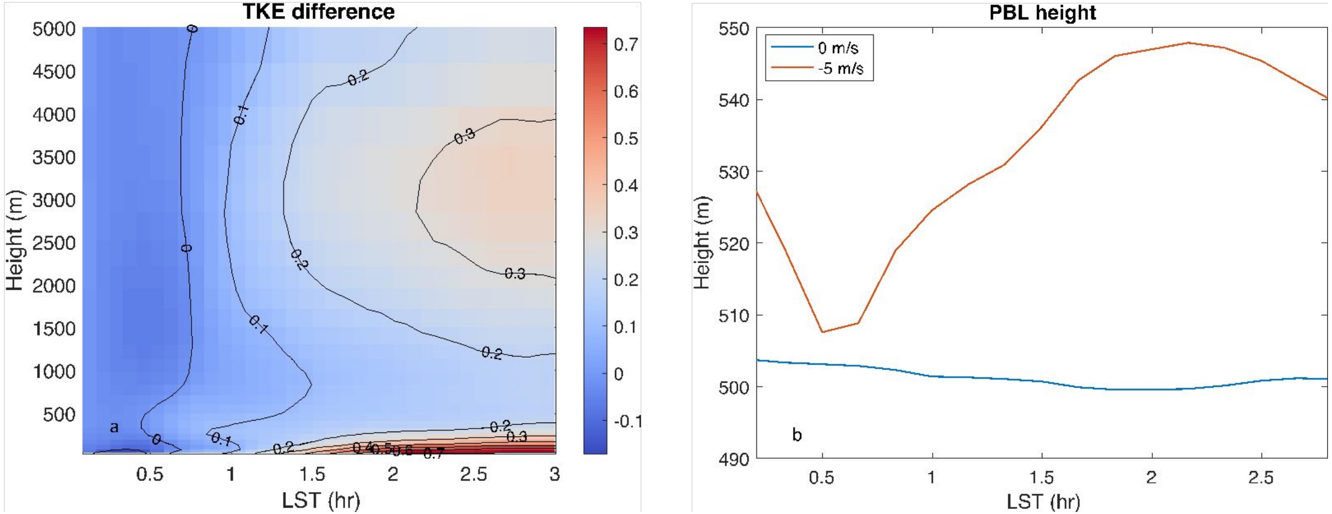


- For linear scenario, cloud updrafts are more vertically tilted and linear

Conclusions and future work

- Convection responds to wind shear magnitude in a non-monotonic manner
- This behavior is primarily driven by variations in the updraft mass flux and condensation rate
- Wind shear tends to decrease updraft vertical velocity while simultaneously increasing the updraft fraction
- Finer resolution and optimal wind shear profile or setting for convective organization in future studies

Boundary layer turbulence strength



Increased surface drag and a stronger momentum flux to the surface
Higher wind velocities lead to greater damping

$$COND = gw\left(\frac{dq_s}{c_p dT} - \frac{\rho q_s}{p - e}\right)\left(\frac{1}{1 + \frac{L_v}{C_p}\frac{dq_s}{dT}}\right)$$