A dynamics viewpoint of cloud-aerosol interactions in convective storms

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ASR ADCI Breakout

March 18, 2013

*NCAR is sponsored by the National Science Foundation

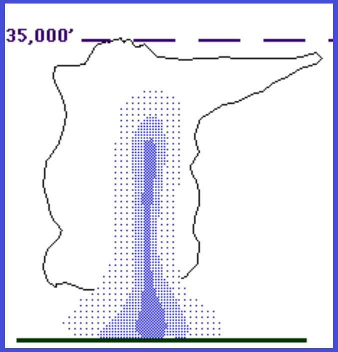
Previous studies have shown strong sensitivity of aerosol effects on deep convection to environmental RH and vertical wind shear (Fan et al. 2009; Khain 2009).

- "Increasing aerosols always suppresses convection under strong wind shear and invigorates convection under weak wind shear…" (Fan et al. 2009, JGR)

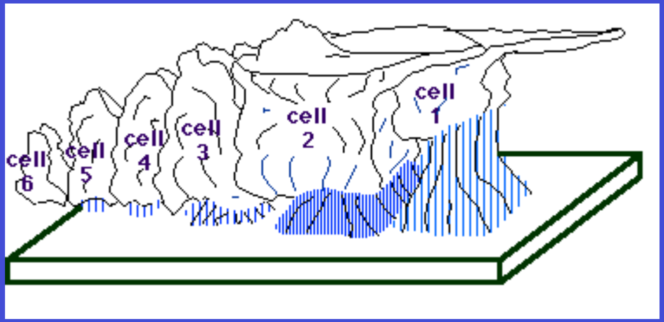
Dynamically, what might explain sensitivity of aerosol effects to vertical wind shear?

Shear exerts a dominant influence on storm type:

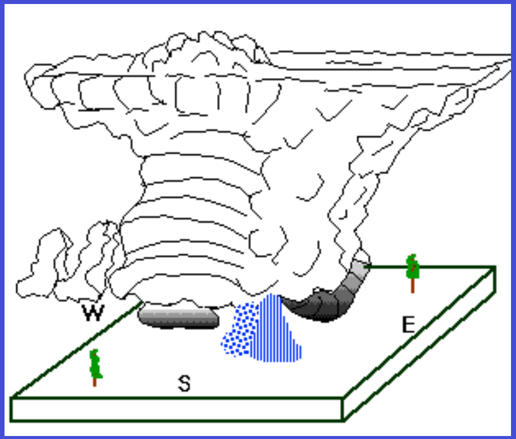
Single cell



Multicell



Supercell



INCREASING ENVIRONMENTAL SHEAR →

Images from www.icsrc.org

Environmental wind shear has two key effects on the vertical velocity of updrafts:

1) Impact via cold pool-shear interactions leading to less/more tilting of updrafts

→ ***more sensitive to aerosols***

2) Generation of dynamic pressure perturbations, p_d

→ ***less sensitive to aerosols***

$$\frac{\partial w}{\partial t} = -\vec{v} \bullet \nabla w - \frac{1}{\rho}\frac{\partial p}{\partial z} + B$$

BUOYANCY

$$\frac{\partial p}{\partial z} = \frac{\partial p_d}{\partial z} + \frac{\partial p_B}{\partial z}$$

BUOYANCY PRESSURE PERTURBATION

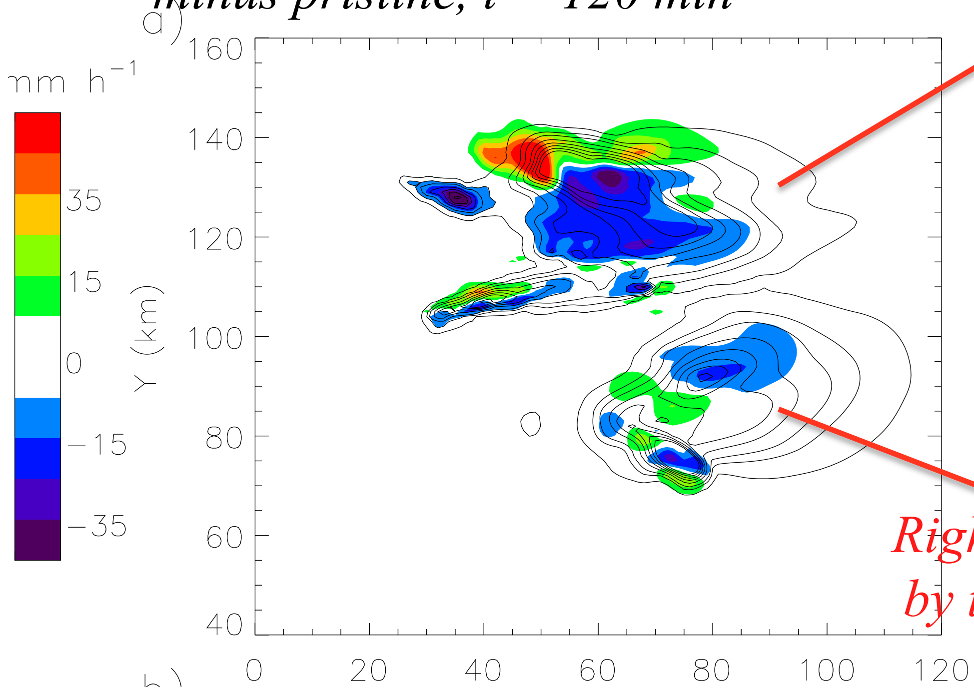
DYANMIC PRESSURE PERTURBATION: CRITICAL IN A STRONGLY SHEARED ENVIRONMENT

- **Aerosols effects via microphysics can potentially affect cold pools and buoyancy.**

- **Updrafts of systems strongly driven by dynamic pressure perturbations (e.g., supercells) should in principle be less sensitive to aerosols.**

- **This is seen in recent supercell simulations (Storer et al. 2010; Lebo et al. 2012; Morrison 2012).**

Change in surface precipitation, polluted minus pristine, t = 120 min



Left-moving "bow echo" dominated by cold pool-shear interactions

Right-moving mesocyclone dominated by tilting/stretching of environmental shear

Morrison (2012)

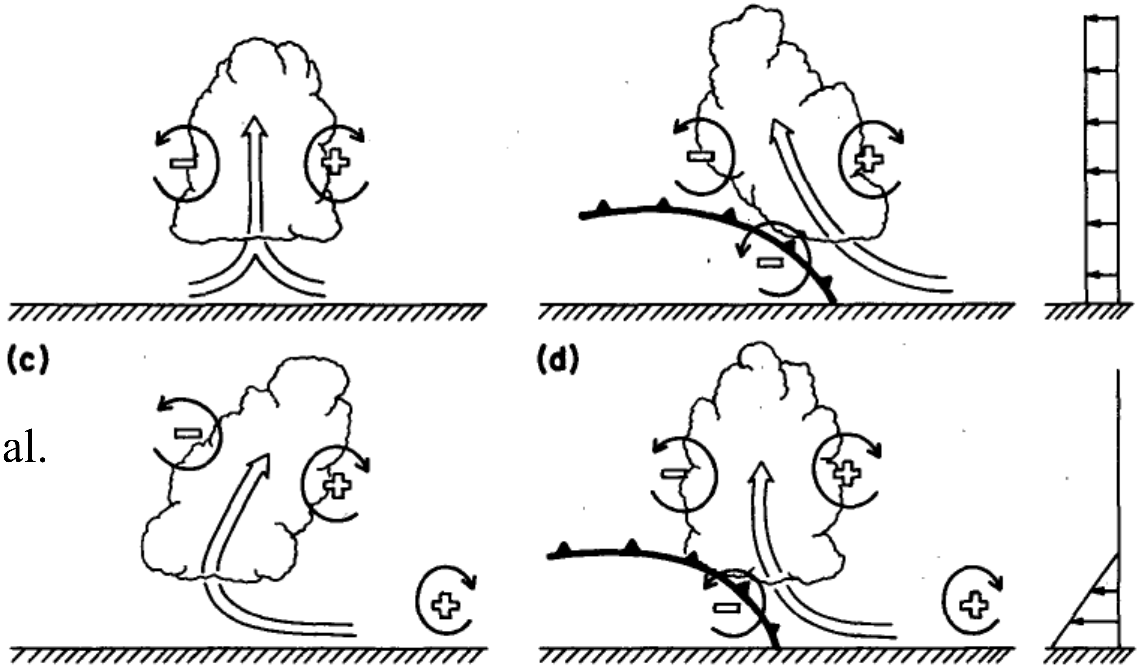
- **Other studies have shown larger effects (Khain and Lynn 2009; Lebo and Seinfeld 2011), but it is unclear if this is associated with supercellular or secondary convection.**

- **Aerosol effects are expected to be stronger in more cold pool/buoyancy dominated systems with relatively smaller p_d.** ***Shear is still very important because of impacts on updraft tilting!***

- **A widely-cited conceptual model of the dynamics of these systems is "RKW" theory (Rotunno et al. 1988).**

$$c^2 = -2\int_0^H B_L \, dz$$

$$\frac{c}{\Delta u} = \frac{\text{cold pool contribution to vorticity}}{\text{shear contribution to vorticity}}$$



Rotunno et al. (1988)

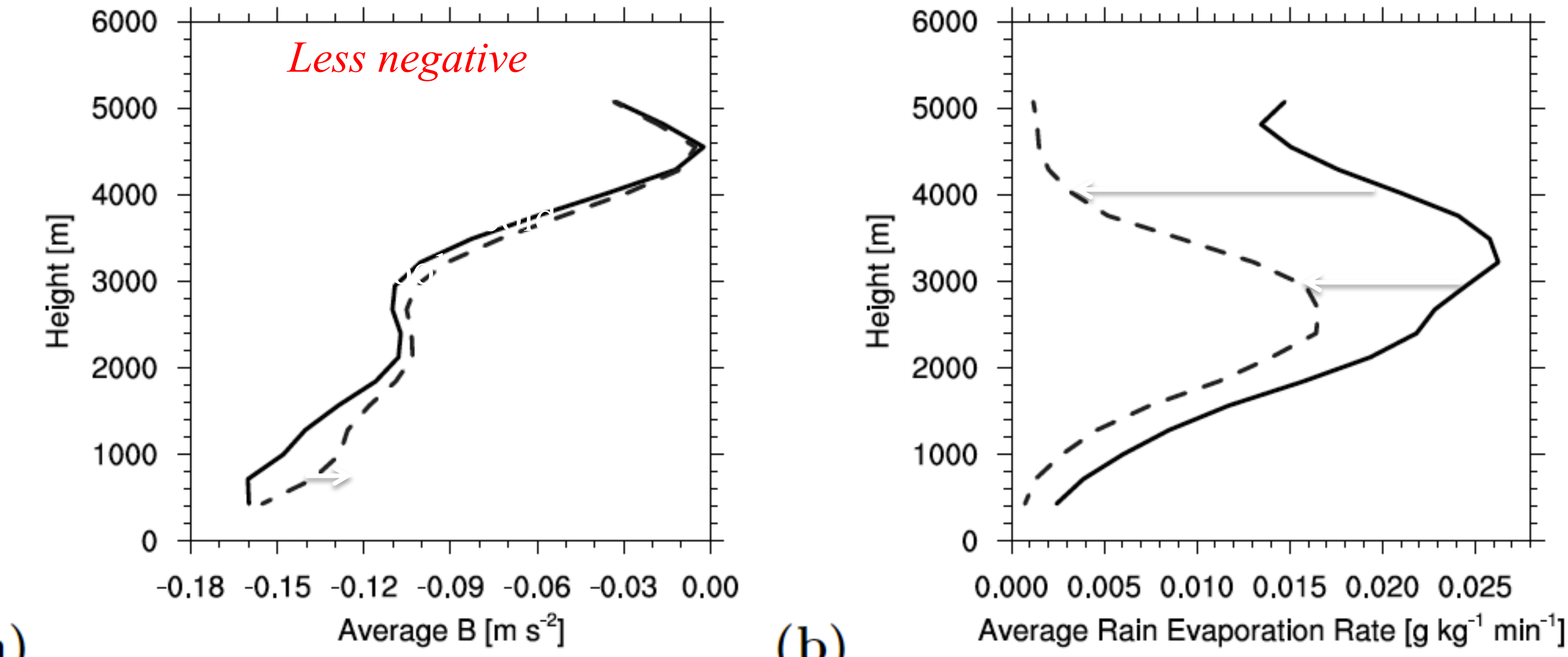
Squall Line Simulations

(Lebo and Morrison 2013)

- Loosely based off of 8th WMO Cloud Modeling Workshop Case 2 [Muhlbauer et al., 2013 (*BAMS, in press*)]
- N_{CCN} = 100, 200, 500, 1000, 2000 cm^{-3}
- Δu = 8, 12, 16, 20, 24, 28, 32 m s^{-1} over 5 km
- Morrison et al. (2009, *MWR*) bulk microphysics as modified in Lebo et al. (2012, *ACP*) including explicit treatment of supersaturation and binned aerosols.
- Forced *w* to initiate convection (applied first 1 h).
- 8 hr simulations

Cold Pool Sensitivity: weak shear case

Smaller rain evaporation rate in the lowest 5km

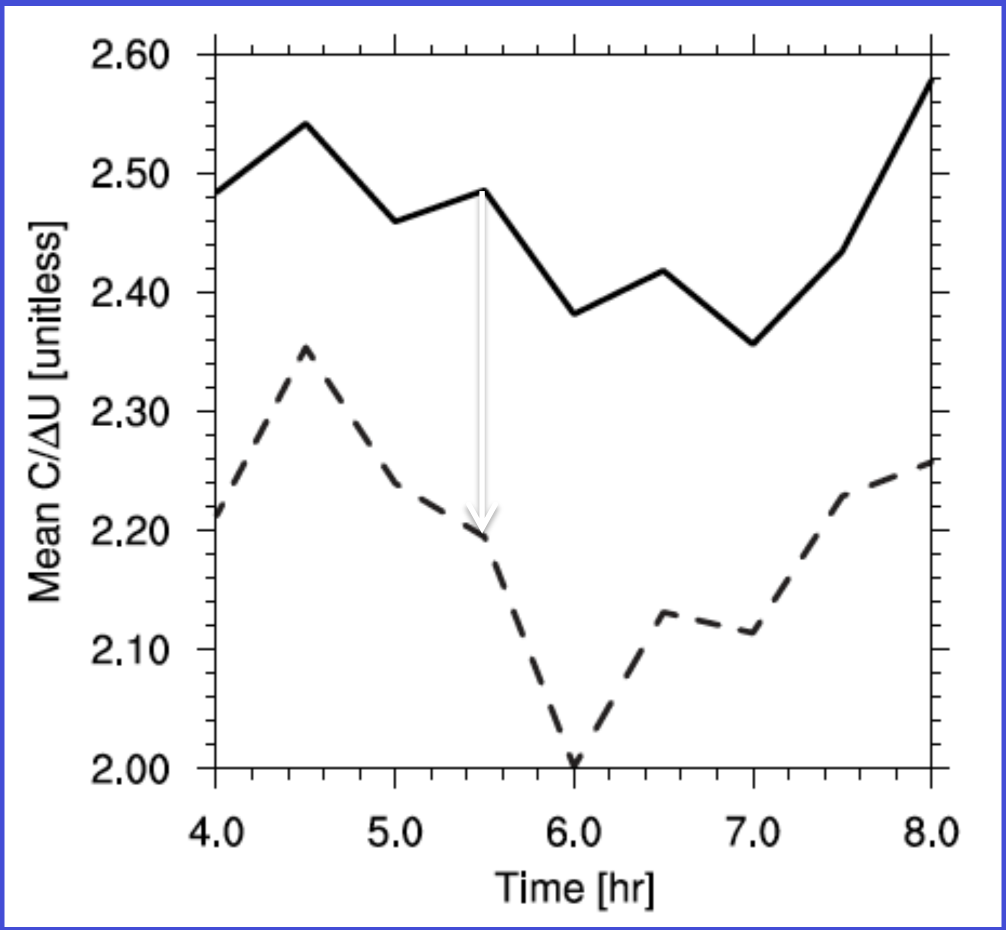


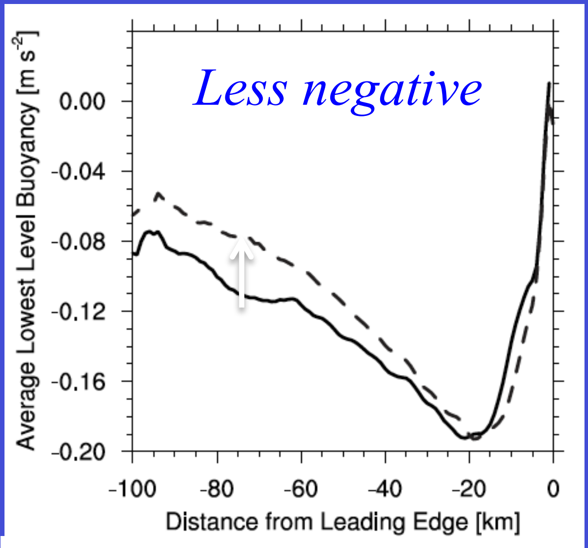
______ "Clean" = 100 cm^{-3}

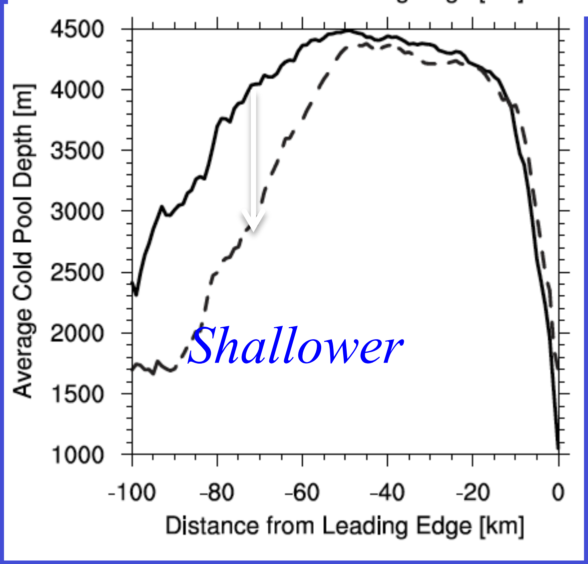
- - - - - - "Polluted" = 1000 cm^{-3}

Temporal averages between 5-7 hours and zonal average 100 km behind gust front

Cold Pool Sensitivity







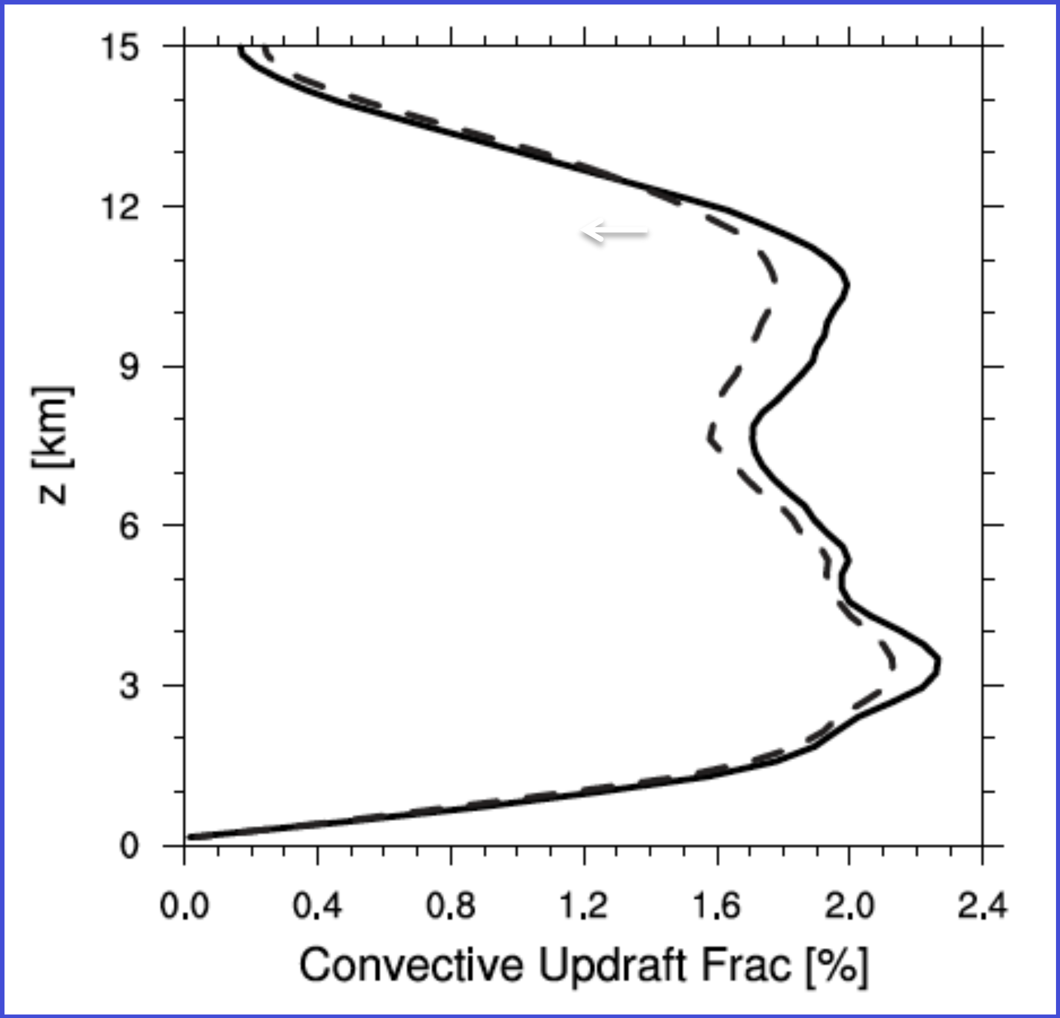
_______ "Clean" = 100 cm^{-3}

- - - - - - "Polluted" = 1000 cm^{-3}

Temporal averages between 5-7 hours

Convective structure

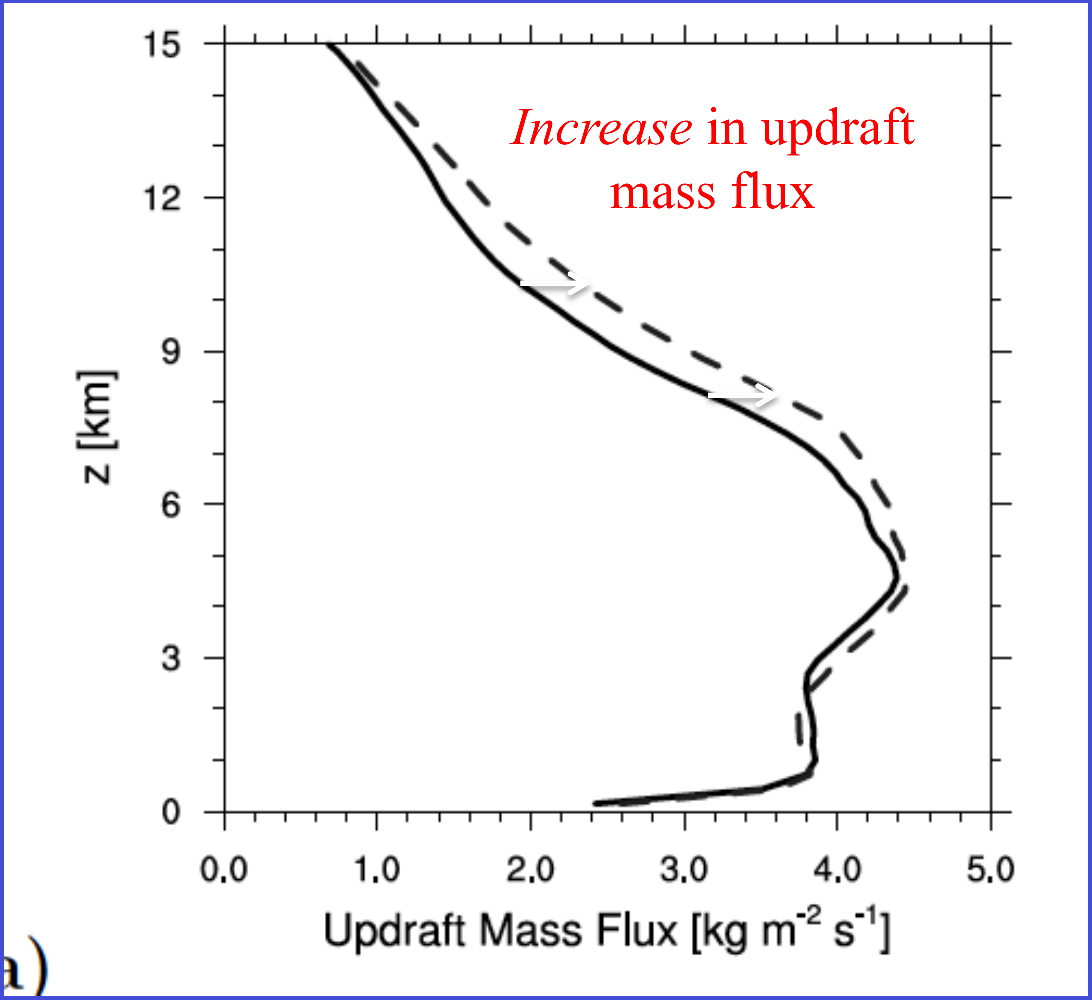
More upright updrafts in polluted conditions



_______ "Clean" = 100 cm^{-3}

- - - - - - "Polluted" = 1000 cm

Convective invigoration

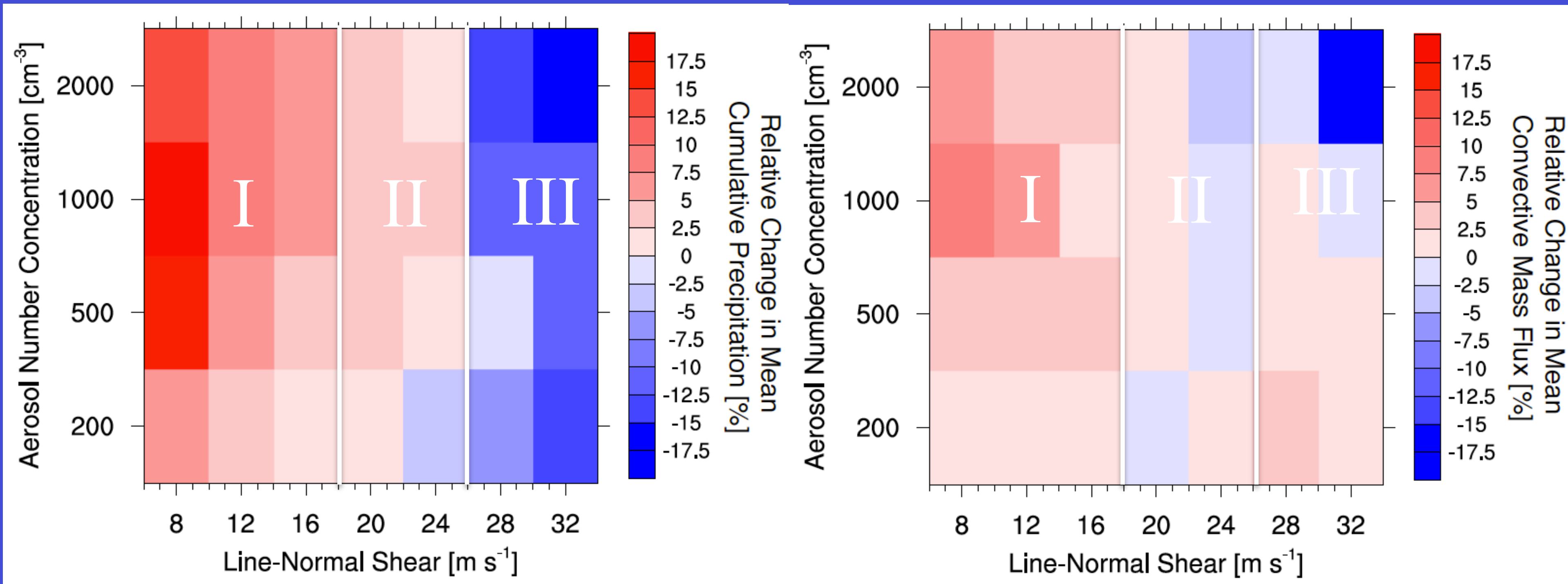


______ "Clean" = 100 cm^{-3}

- - - - - - "Polluted" = 1000 cm^{-3}

- **Under stronger shear, when $C/\Delta U \sim 1$ or < 1, the opposite occurs: C is weaker in polluted conditions and the updrafts become more tilted in the "forward" (downshear) direction and weaken.**

Summary of results



For weaker shear (region I), C/ΔU >> 1 and the decrease in C in polluted conditions leads to *more* upright updrafts and *more* precip and convective mass flux.

For stronger shear (regions II/III), C/ΔU ~ 1 or C/ΔU < 1, and the decrease in C in polluted conditions generally leads to *more* tilted updrafts and *less* precip and convective mass flux.

Conclusions

• Studies have shown strong case dependence of aerosol effects on deep convection, especially in term environmental wind shear and RH. This is broadly consistent with the fact that mechanisms driving vertical velocity vary widely in different storm types/environments.

• Effects appear to be weaker in systems with strong forcing by tilting/stretching of environmental shear (supercells), but larger in systems driven by cold pool-shear interactions (multicells/squall lines).

• Aerosol effects on the dynamics of a squall line are consistent with RKW theory, providing a conceptual framework for aerosol effects on these systems.