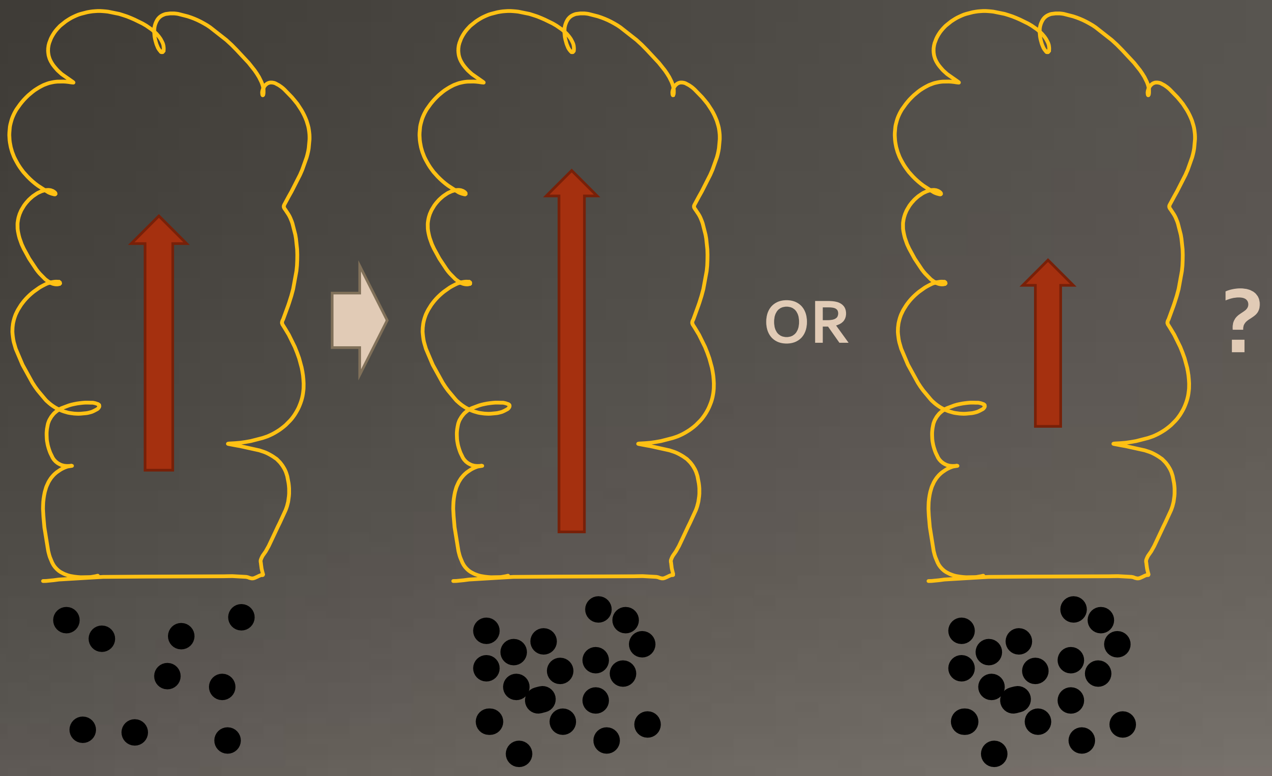
Invigoration or Enervation of Convective Clouds by Aerosols?



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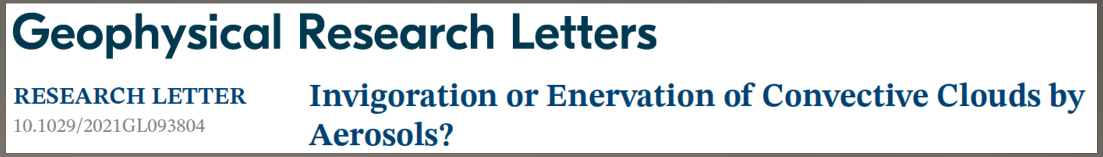

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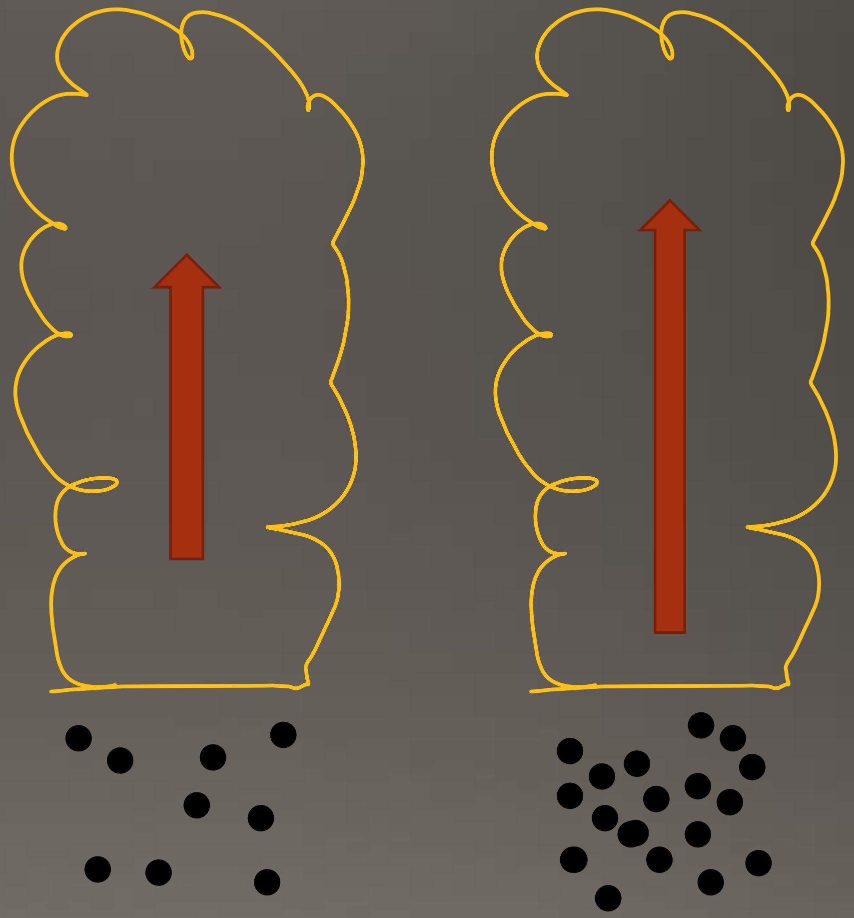
Invigoration or Enervation of Convective Clouds by Aerosols?

Aerosol-Induced Invigoration

- "Invigoration" here refers to the idea that convective storms that ingest higher aerosol particle concentrations will develop **stronger updrafts**
- Lots of proxies for updraft strength, here we use CAPE.



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“Cold-phase” invigoration hypothesis

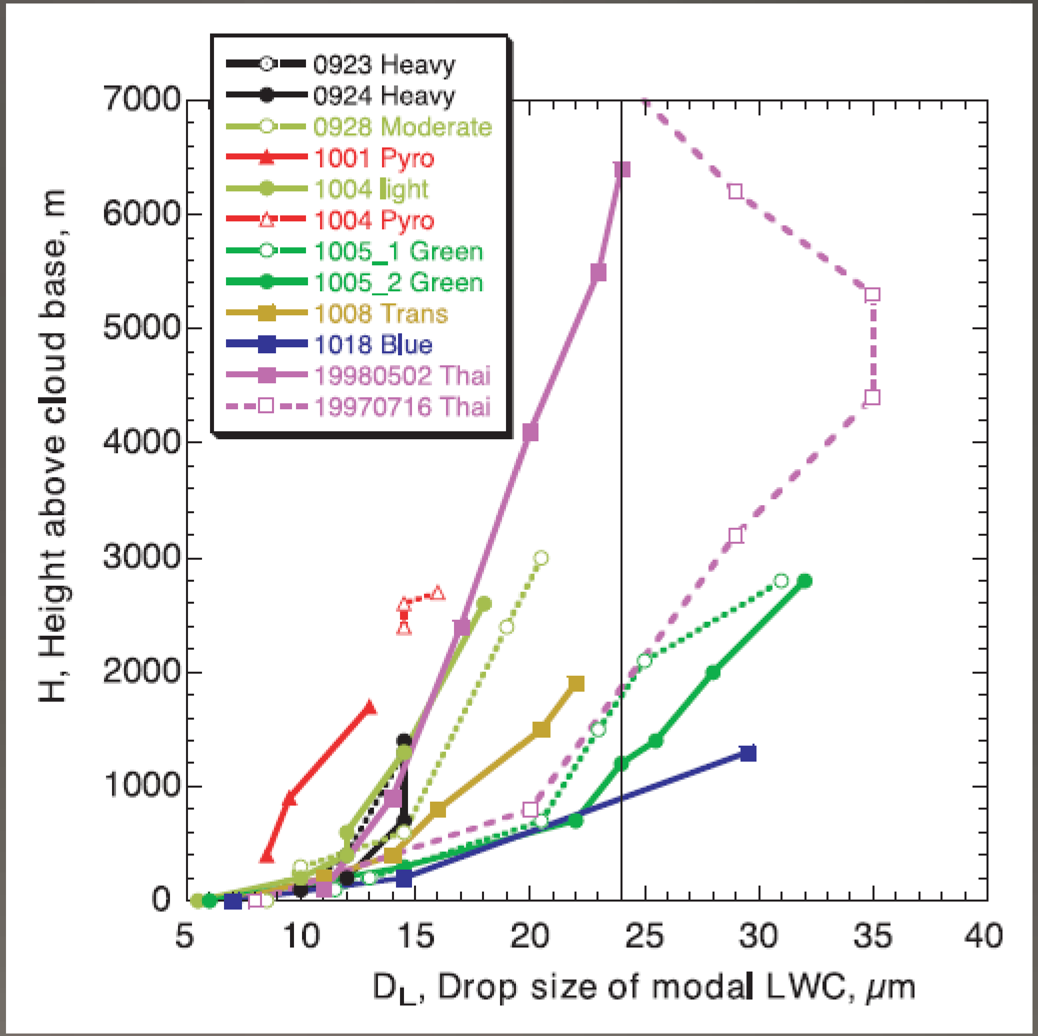
- The common explanation:
- More cloud droplets suppresses rain formation and precipitation

→ As a result, more liquid water is lofted above the freezing level

→ The extra liquid freezes and releases latent heat, increasing buoyancy of the updraft

→The updraft strengthens

- Prominently described by Rosenfeld et al. (2008)



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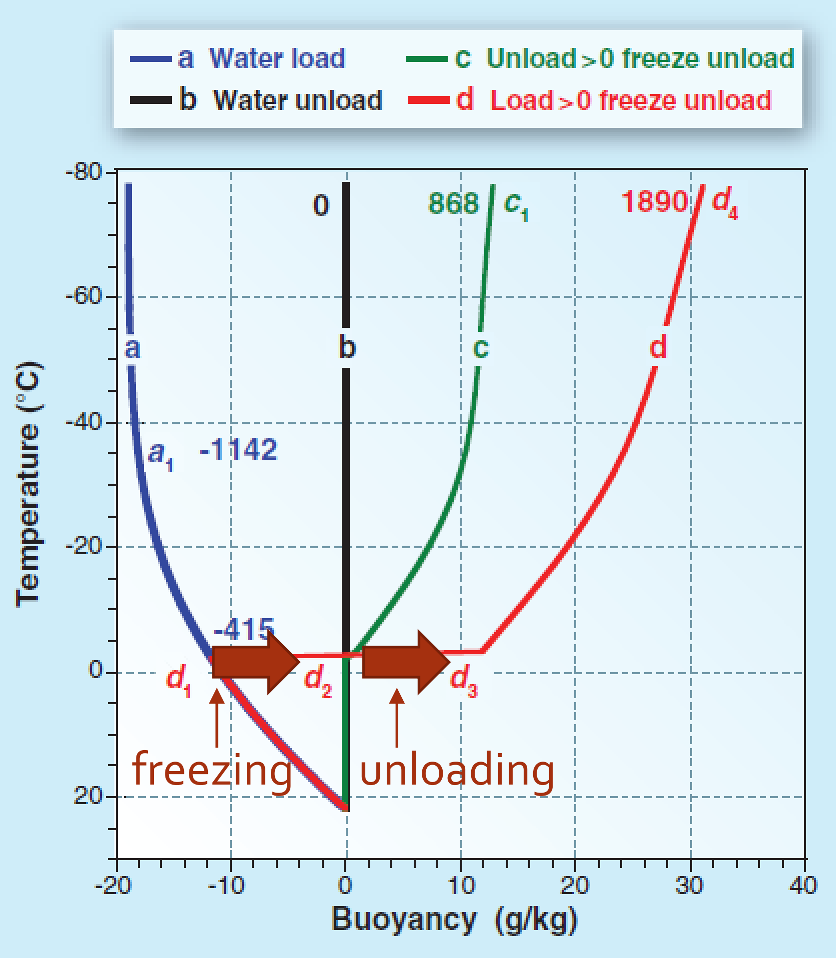
Andreae et al. (2004)

“Cold-phase” invigoration hypothesis

- This common explanation misses a key point from Rosenfeld et al. (2008)
- “Freezing all the cloud water would warm the air and add thermal buoyancy by an amount that would almost exactly balance the condensate load (d2). When the ice hydrometeors precipitate from a parcel, it becomes more positively buoyant because of its reduced weight (d3).”



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Rosenfeld et al. 2008

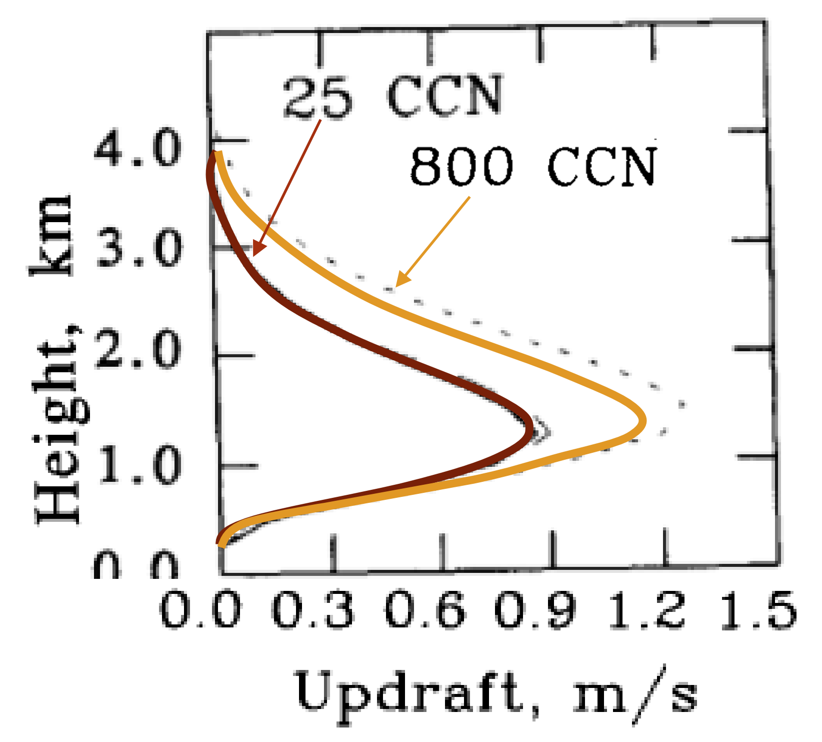
"Warm-phase" invigoration hypothesis

- Smaller, more numerous droplets grow by condensation faster.
  - $condensation \propto N\bar{D}$

→ More latent heat is released and increases the buoyancy of the updraft.

→ Also, supersaturation is reduced.

→The updraft strengthens.



Kogan and Martin 1994

Igel and van den Heever (2021)

GOAL

To theoretically assess the magnitude of the cold-phase and warm-phase invigoration hypotheses

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Use Parcel Theory to Evaluate the Hypotheses

- Updraft speed is related to CAPE: CAPE=½ w^2
- CAPE depends on the parcel properties and the environment:

$$CAPE = \int_{p_{LFC}}^{p_{EL}} R_d \frac{T_{\rho,ENV} - T_\rho}{p} dp$$

- Conveniently, **DIFFERENCES in CAPE** between two parcels A and B in the same environment are independent of the environment:

$$\Delta CAPE = \int_{p_{LFC}}^{p_{EL}} R_d \frac{T_{\rho,A}(p) - T_{\rho,B}(p)}{p} dp$$

To calculate $\Delta CAPE$, we need to specify $T_\rho(p)$ → need an equation for $\frac{dT}{dp}$ that accounts for freezing, condensate loading, and supersaturation

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A New Lapse Rate Equation

- A new equation for dT/dp was derived that accounts for the three necessary processes of supersaturation, freezing, and condensate loading

$$\frac{dT}{dp} = \frac{\frac{TR_0}{p_0} + \frac{L_{F1}r_1}{p_0}\left(1 - \frac{d\ln S}{d\ln p}\right)}{c_p + L_{32}r_F\frac{d\xi}{dT} + L_{F1}r_1\frac{p}{p_0}\frac{d\ln p^{21}}{dT}}$$

Supersaturation change with pressure

Condensate loading impacts these two terms

Freezing term; ξ is frozen fraction

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A New Lapse Rate Equation

- The equation is numerically integrated to arrive at profiles of temperature, water vapor, liquid, and ice
- To solve, several assumptions must be made:

  1. Condensate loading as a function of pressure $r_F(p)$
  2. Frozen fraction as a function of temperature $\frac{d\xi}{dT}$
  3. Supersaturation as a function of pressure $\frac{d\ln S}{d\ln p}$

- These assumptions can be varied in ways that are consistent with aerosol effects

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Unrealistic Condensate Loading and Freezing Assumptions

	Clean	**Polluted**
Condensate loading assumption	No condensate loading	Condensate loading until freezing, then complete unloading
Freezing assumption	100% ice starting at -4°C	100% ice starting at -4°C

Condensate unloading may not be complete – partial unloading may occur

Condensate unloading is not instantaneous – it may occur gradually instead

Freezing is not instantaneous at -4°C – it is gradual down to -40°C

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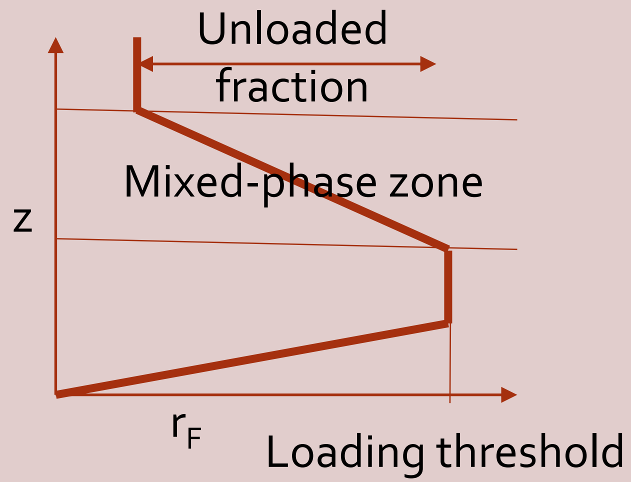
More Realistic Condensate Loading and Freezing Assumptions

	Clean	**Polluted**
Condensate loading assumption	No loading	
Freezing assumption	Linearly freeze between -4 and -40 °C	Linearly freeze between -4 and -40 °C

The unloaded fraction and loading threshold are both varied.

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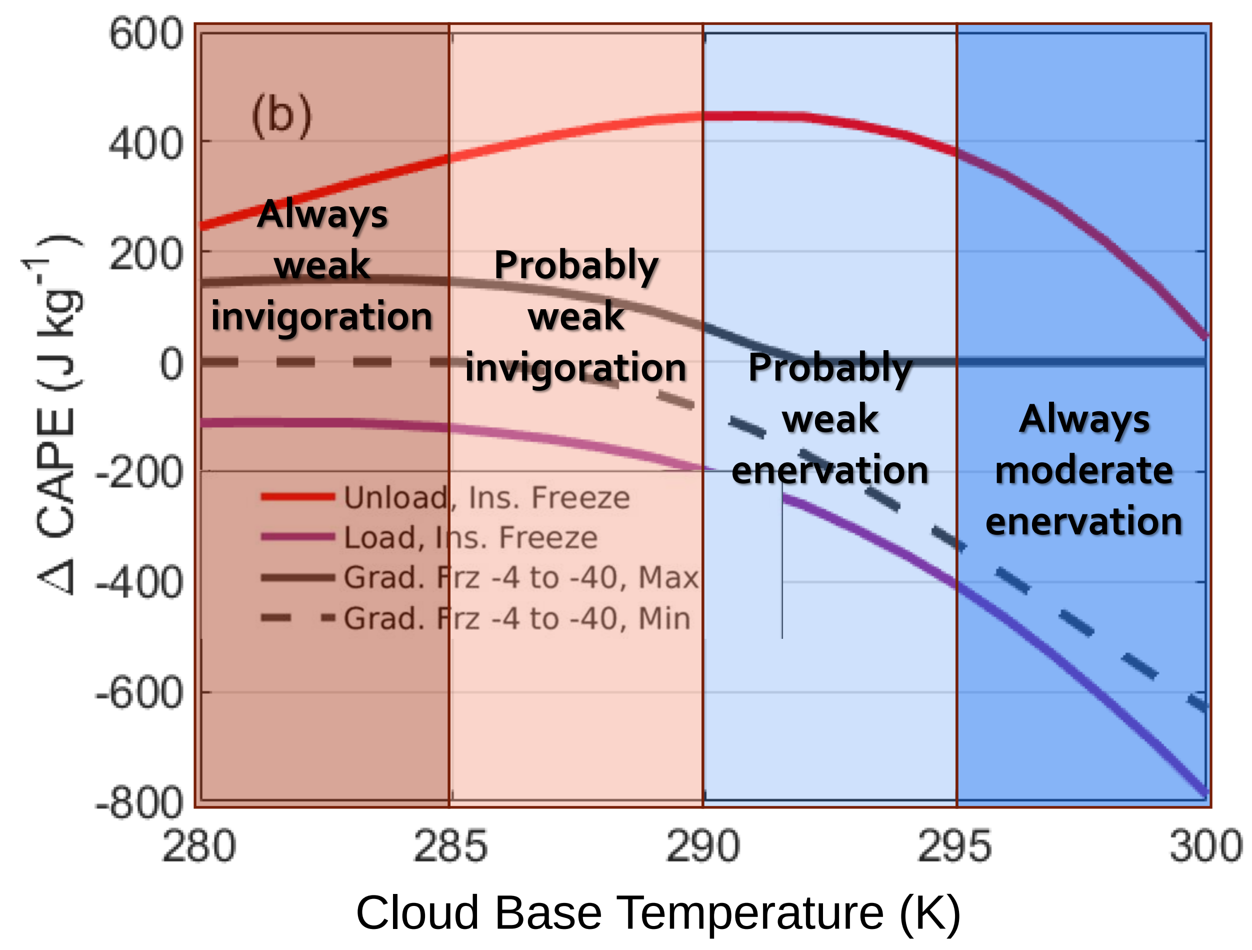
More Realistic Assumptions



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Warm-Phase Invigoration

	Clean	**Polluted**
Condensate loading assumption	No condensate unloading	No condensate unloading
Freezing assumption	Linearly freeze between -4 and -40 °C	Linearly freeze between -4 and -40 °C
Supersaturation assumption	Equilibrium SS of 20%	Equilibrium SS < 20%

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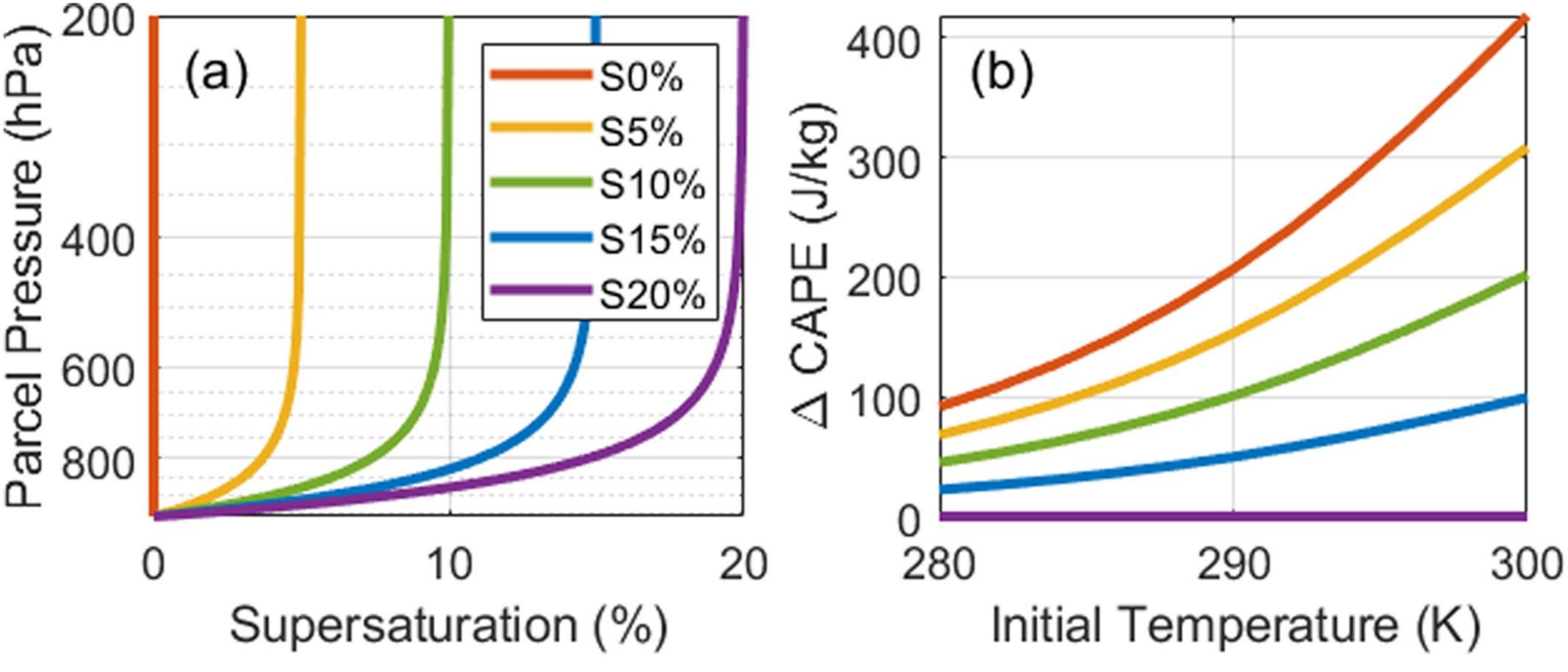
Warm-Phase Invigoration

- ΔCAPE of up to ~100 J/kg for every 5% change in supersaturation
- Can't say from this study what a realistic change in SS is.



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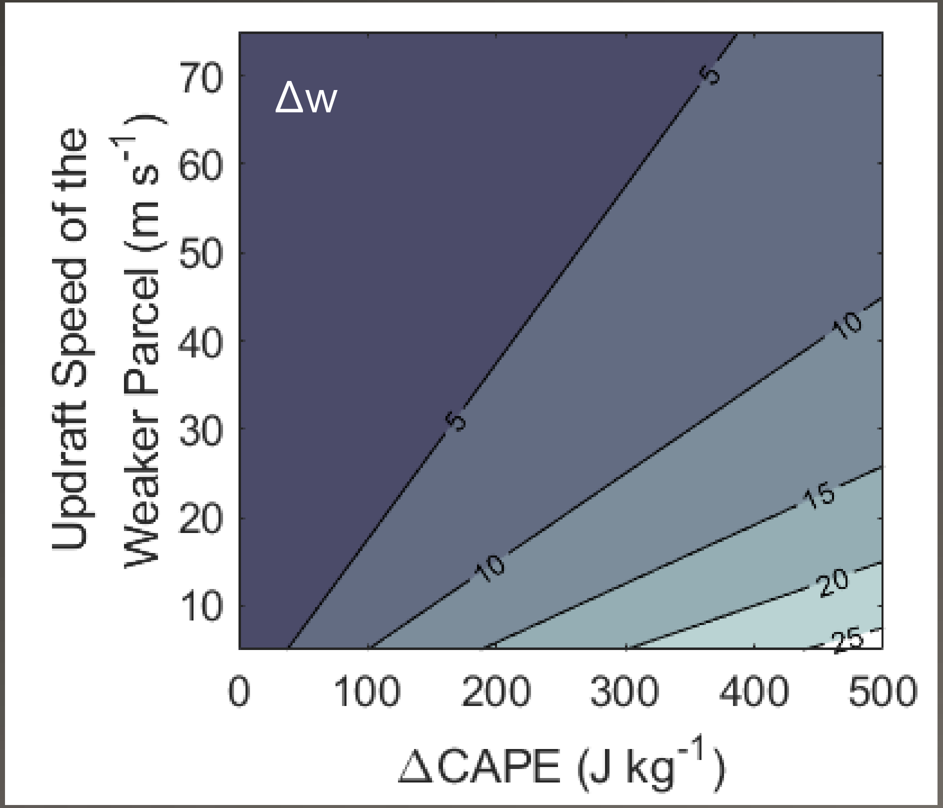
CAPE and Updrafts

- CAPE=1/2 w^2 (we know this equation overestimates *w*)



- Naturally weak storms are most susceptible to invigoration/enervation
- For ΔCAPE ~ 400 J/kg, maximum Δw ~ 10 m/s assuming that values are too large by a factor of 2
- May be hard to observe

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Take-Home Points

- Cold-phase invigoration relies on condensate unloading, not just freezing
  - For storms with bases > 290K, aerosol-induced changes to cold-phase processes may result in enervation, not invigoration
- Warm-phase invigoration is plausible but requires very large changes in supersaturation to be important
- Aerosol-induced changes in updraft speed are likely ~10 m/s or less in naturally weak storms and ~5 m/s or less in naturally strong storms

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