Magnitude and timescale of liquid water path adjustment to cloud droplet number concentration for nocturnal non-precipitating marine stratocumulus

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Background

- LWP adjustment to seeding can be characterized with a slope

$$k = \frac{\delta l}{\delta n}$$

where

$$l = \ln L,\ n = \ln N$$

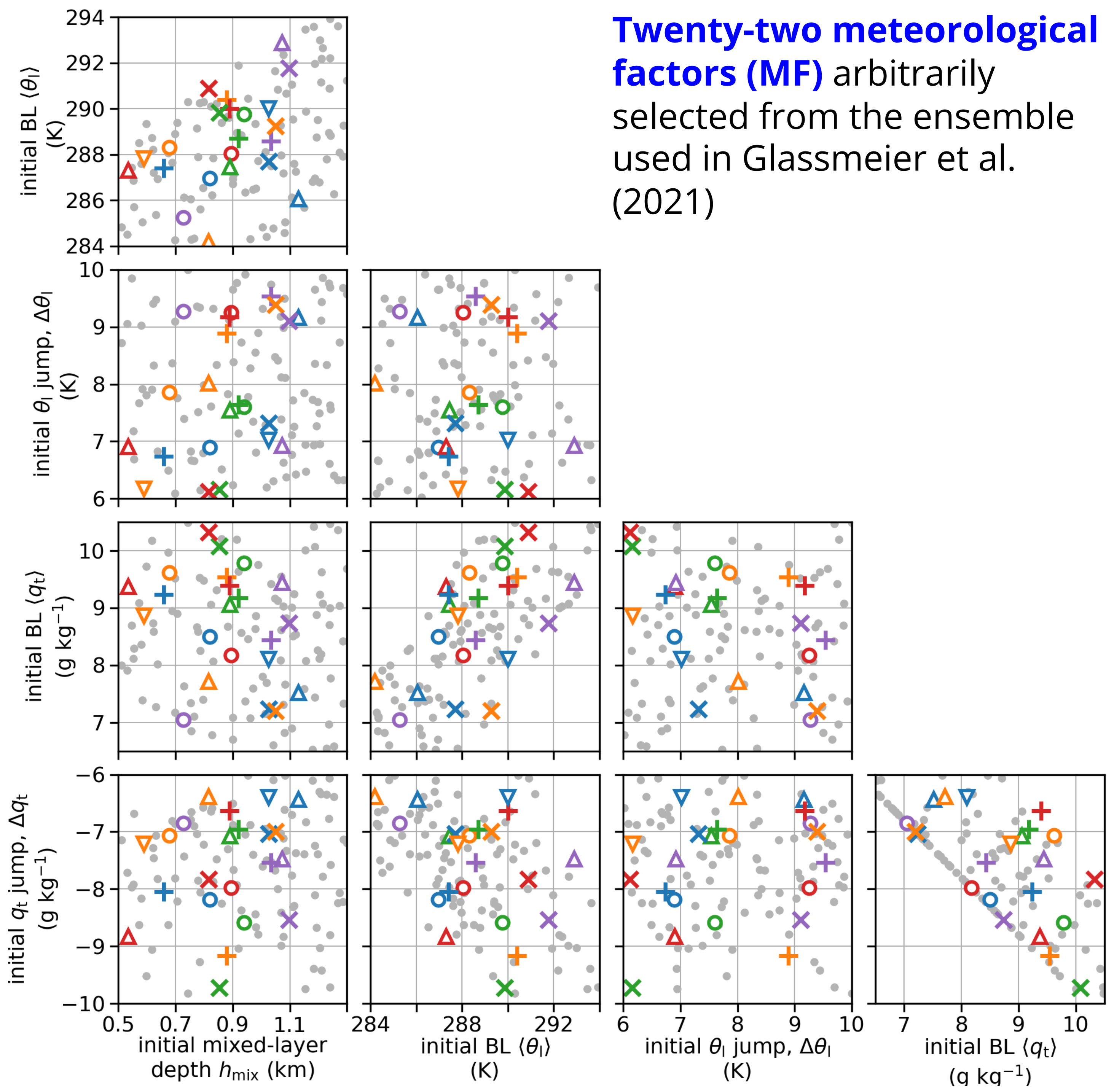
- (L: LWP; N: cloud droplet number concentration)

Objective

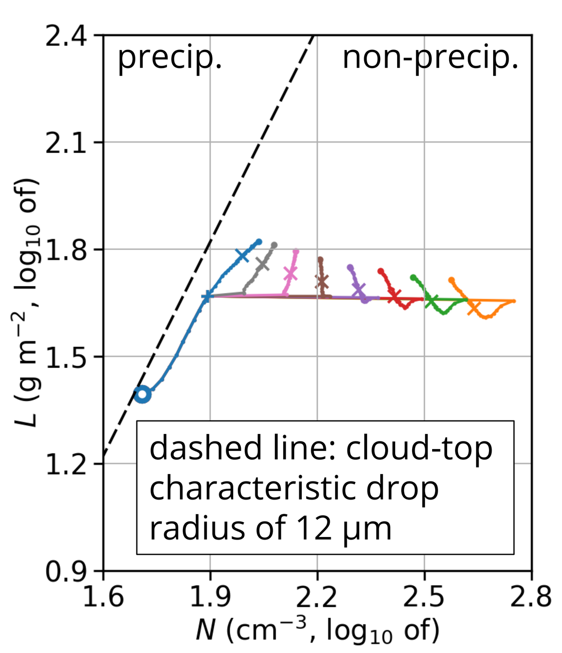
- Examine the magnitude and timescale of k for nocturnal non-precipitating marine stratocumulus using aerosol seeding

Method

- LES with the System for Atmospheric Modeling (SAM)



Twenty-two meteorological factors (MF) arbitrarily selected from the ensemble used in Glassmeier et al. (2021)

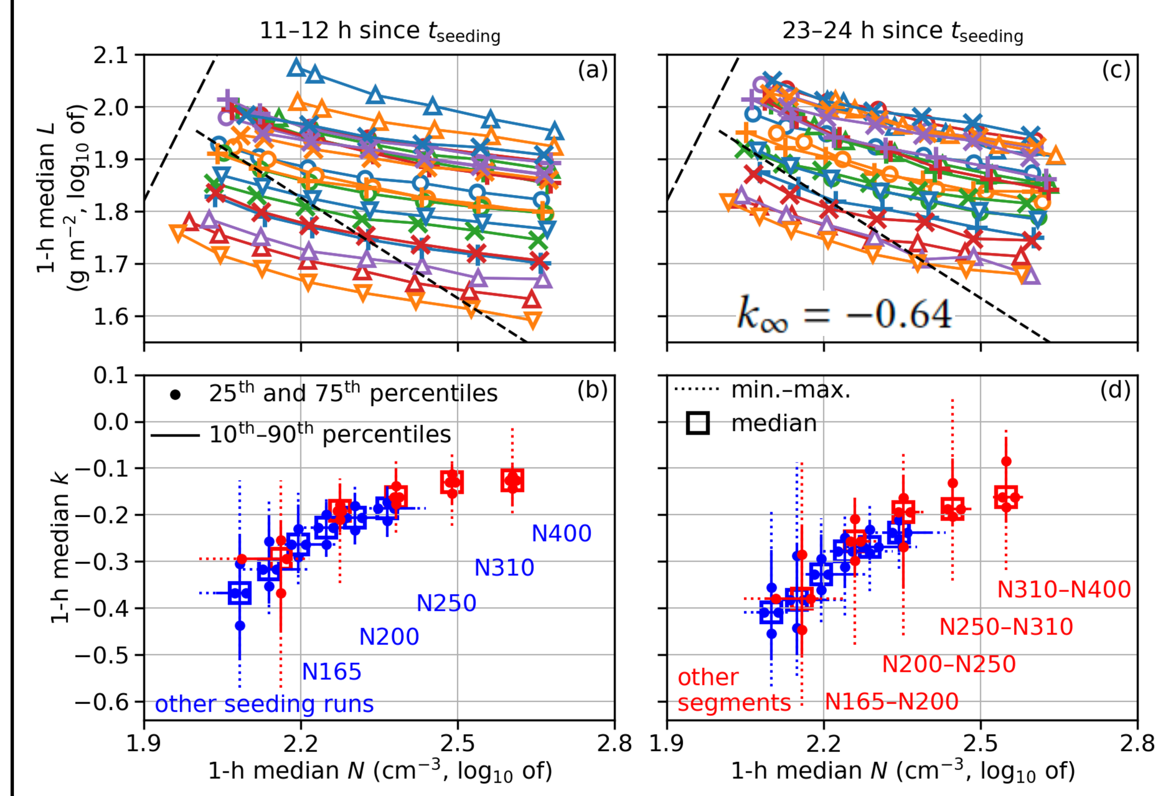


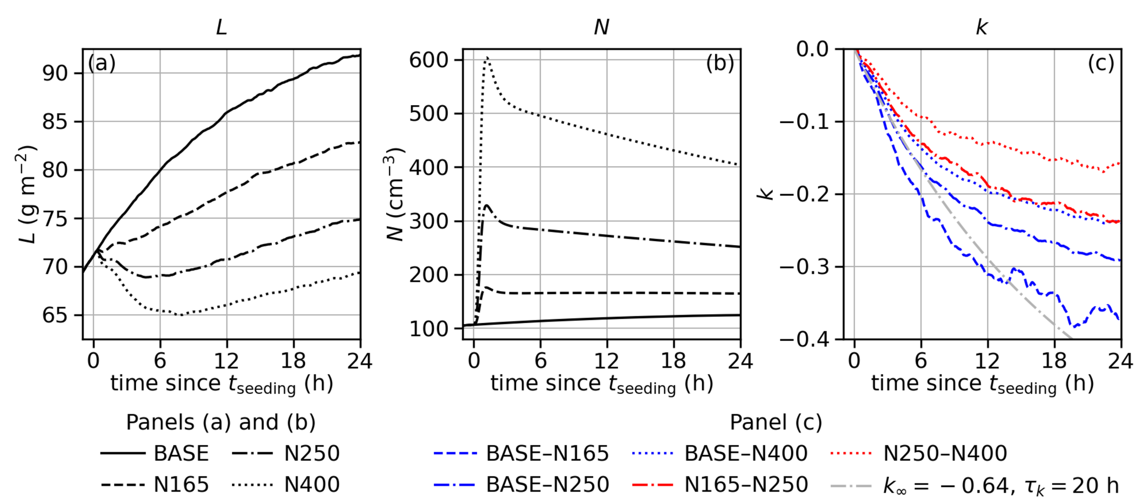
Example for experiment design

- BASE: relatively low N but remains non-precipitating
- Circle: 2-h from simulation start; "+": 12-h; "×": 24-h; dots: 36-h
- Full-domain subcloud seeding starts at 12-h (t_{seeding}), finishes after 30-min
- Multiple seeding amounts to sample the non-precipitating regime (Nnnn, where nnn is a three-digit N around 36-h)

- Other configurations
  - Shared: subsidence profile based on DYCOMS-II RF02; interactive surface fluxes
  - MF-dependent: SST 0.5 K warmer than initial surface air temperature

Overview



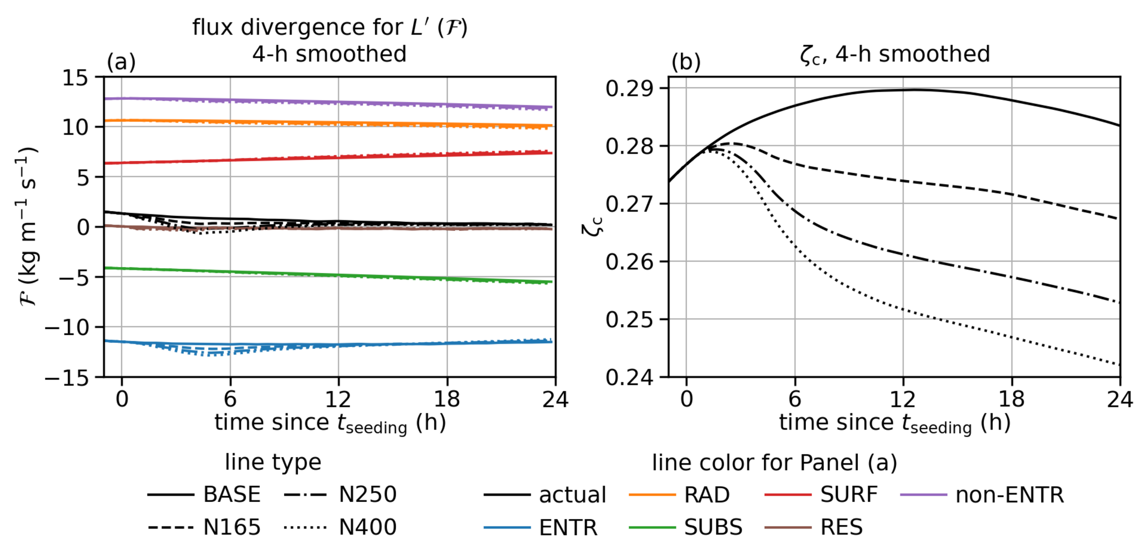


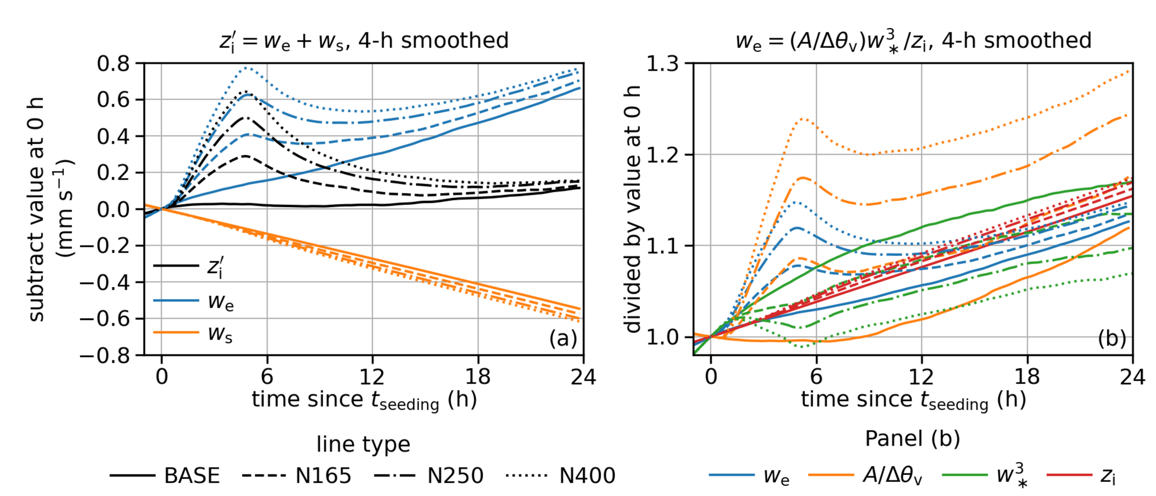
- (First based on all individual simulations and later on 22-MF composites for BASE and 3 seeding amounts)
- **k not very negative after 24-h**: needs to be around −0.45 by 24-h approach −0.64 with a timescale of 20 h
- **k less negative for high N**: consistent with Lu and Seinfeld (2005) and Chen et al. (2011); entrainment-enhancement by increasing N via several mechanisms should saturate at high N
- Both L evolution and N evolution contribute to k evolution; will elaborate later

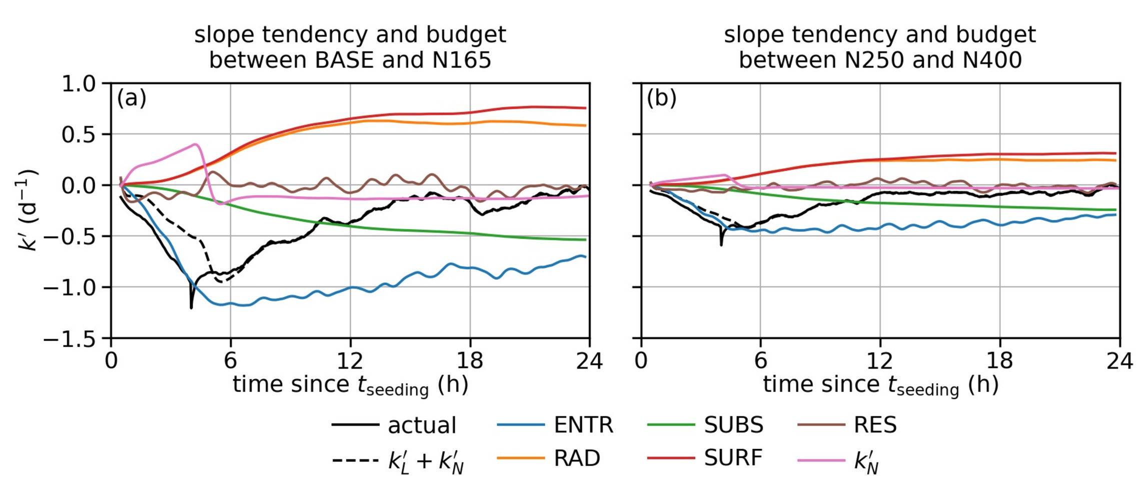
Budgets for L and k

- Define normalized cloud depth and flux divergence for L tendency (L')

$$\zeta_c = 1 - z_{\mathrm{cb}}/z_i,\quad \mathcal{F} = \langle\rho_0\rangle_{\mathrm{BL}} z_i \left[z_i' - \left(\frac{\partial z_{\mathrm{cb}}}{\partial\langle\theta_l\rangle}\langle\theta_l\rangle' + \frac{\partial z_{\mathrm{cb}}}{\partial\langle q_t\rangle}\langle q_t\rangle' \right) \right]$$







- **Response in ENTR flux divergence dominates the response in actual $\mathcal{F}$**: strong initial response, decays over time
- L budget and l budget can be calculated from

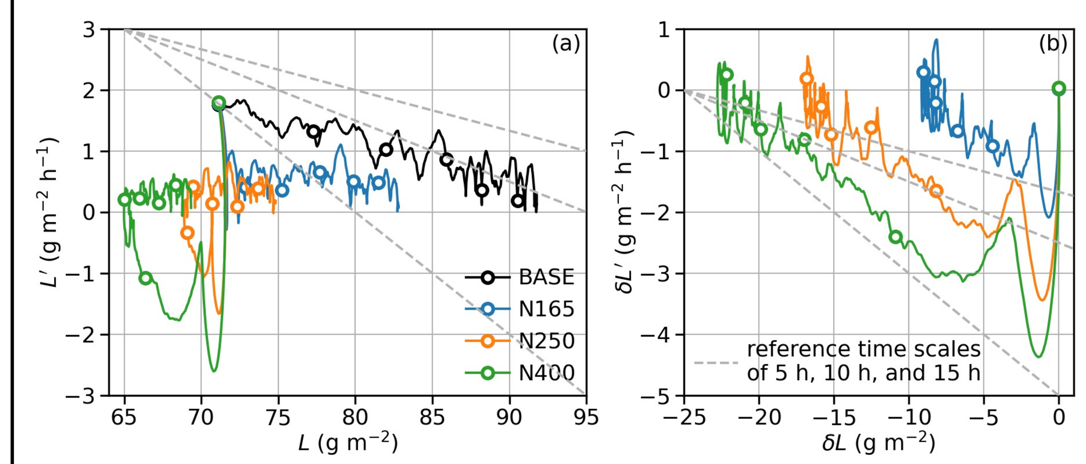
$$L' \propto \zeta_c \mathcal{F},\quad l' = \frac{L'}{L} \propto \zeta_c^{-1}\mathcal{F}$$

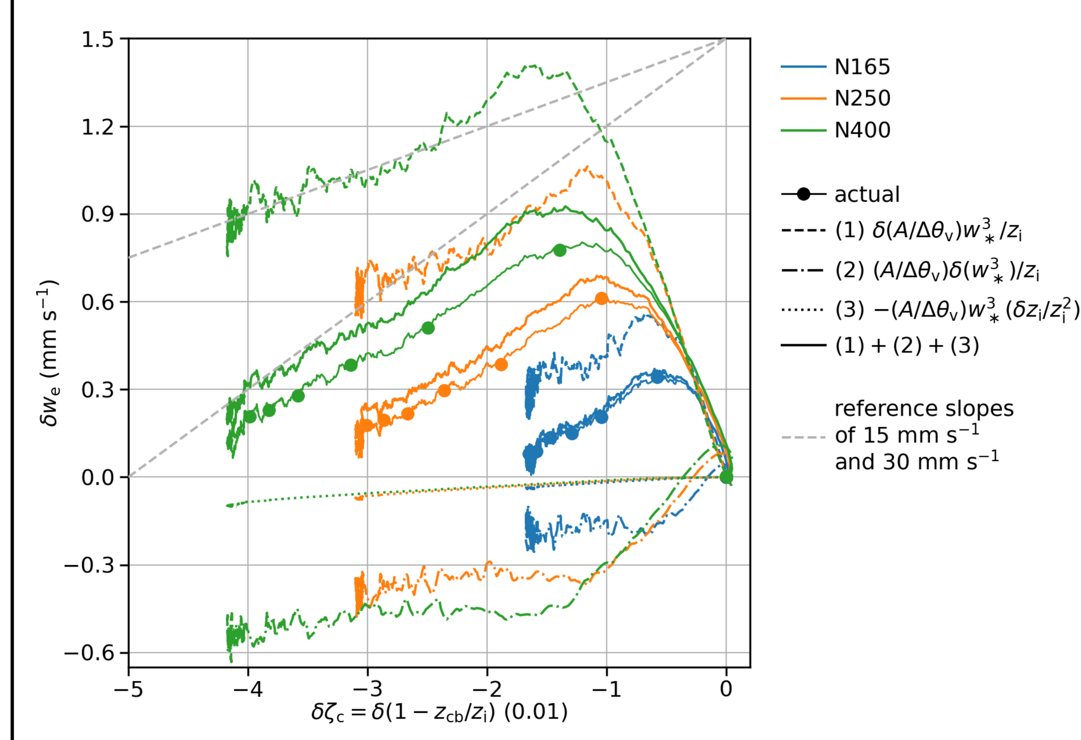
- **Both the responses in entrainment efficiency and buoyancy flux persist**
- k budget

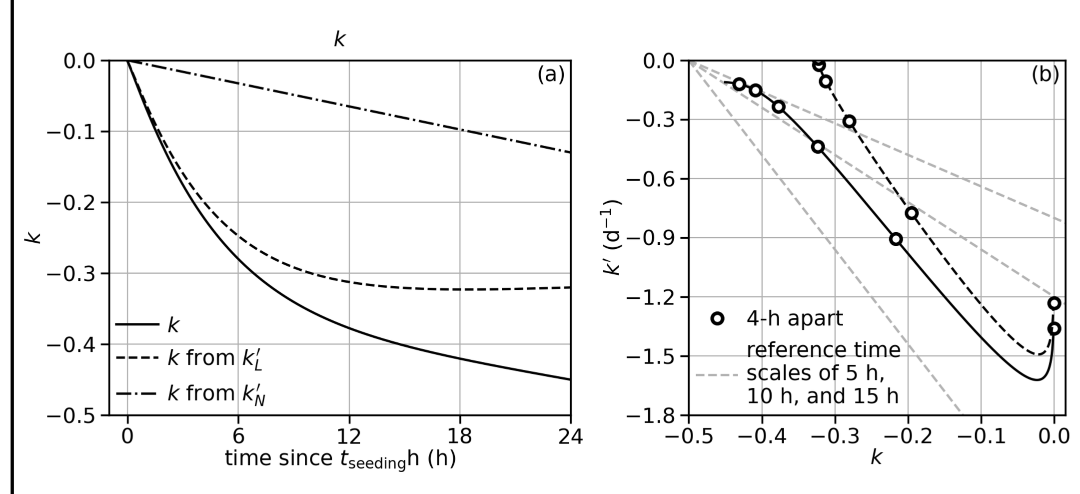
$$k' = k_L' + k_N' = \left(\frac{\delta l'}{\delta n}\right) + \left(-k\frac{\delta n'}{\delta n}\right)$$

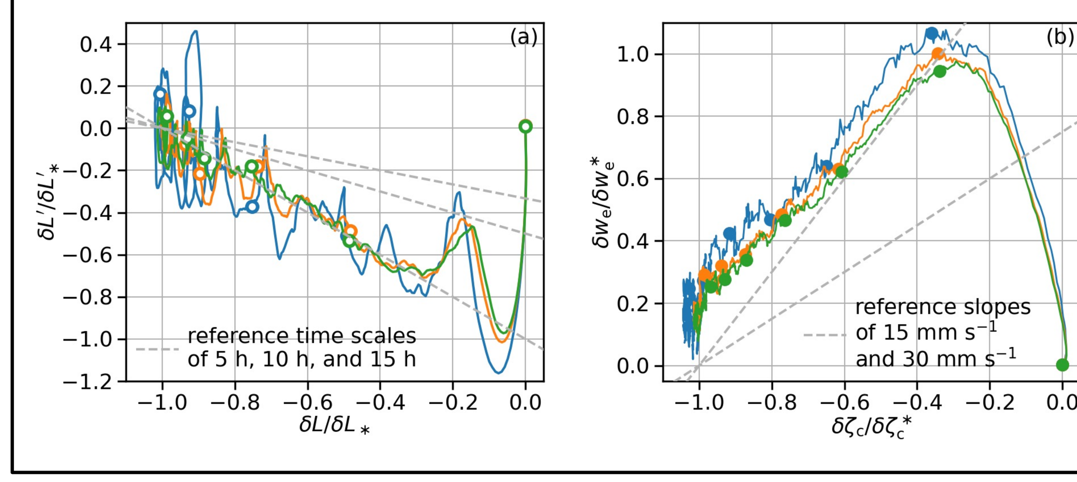
- **ENTR and SUBS terms make k more negative; RAD and SURF make k more positive**
- **N evolution could be important**
- **k budget between N250–N400 similar to but weaker than between BASE–N165**

Timescale









- **L for BASE evolves with a timescale between 10 and 15 h** towards the stage governed by the thermodynamic adjustment timescale (Schubert et al. 1979; Bretherton et al. 2010)
- Decompose L and L' for seeded runs

$$L = L_{\mathrm{BASE}} + \delta L$$
$$L' = L'_{\mathrm{BASE}} + \delta L'$$

- **δL evolves with a short timescale (~ 5 h) for 8–12 h**: consistent with the short timescale in Jones et al. (2014)
- **Steep δw_e–$\delta\zeta_c$ slope**: δw_e sensitive to $\delta\zeta_c$, meaning fast feedback between cloud depth (hence L) and w_e, consistent with Jones et al. (2014); also see Zhu et al. (2005); for our simulations, can derive simple equations to link δw_e and $\delta\zeta_c$
- **Timescale for k** mostly dominated by timescale for δL, hence **also short**
- **Similar δL evolution and δw_e–$\delta\zeta_c$ relation for different seeding amounts after scaling**: δL timescale insensitive to seeding amounts; consistent with linearized MLM in Jones et al. (2014)

Summary

- Based on unseeded (BASE) and seeded runs for an ensemble of 22 MFs:
  - k is not very negative 24-h after seeding; k becomes less negative at higher N
  - δL evolves with a short timescale (~ 5 h) for 8–12 h due to fast feedback between cloud depth (hence L) and w_e
  - Timescale for k mostly dominated by timescale for δL hence also short
- Implication: LWP adjustment over a large area of seeded clouds is unlikely to be very negative even during nighttime, and the adjustment could be relatively fast, although plume spreading in ship tracks and MCB applications may introduce additional timescales

References

- Two manuscripts in preparation: Chen et al. (2024), Hoffmann et al. (2024)