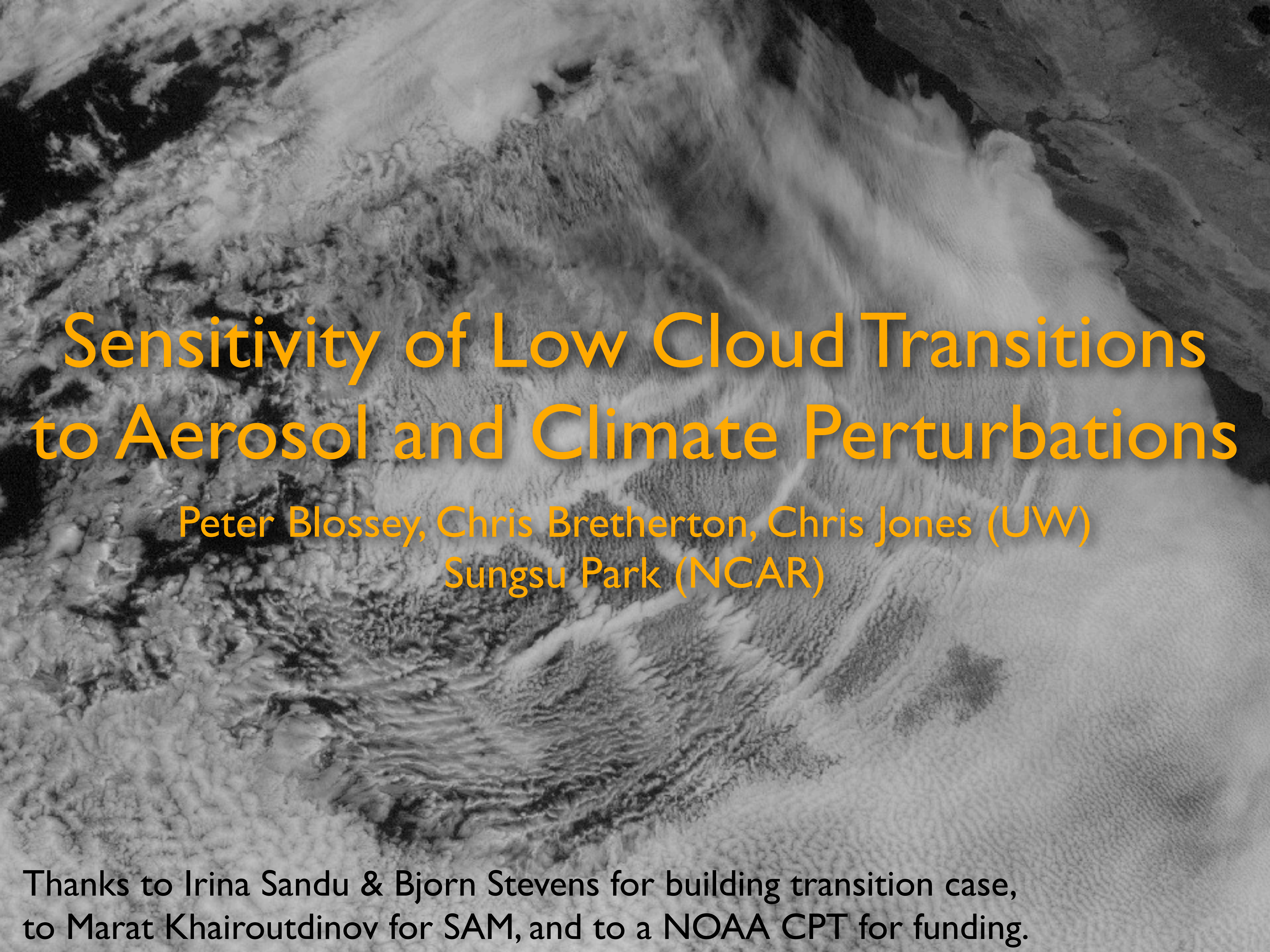


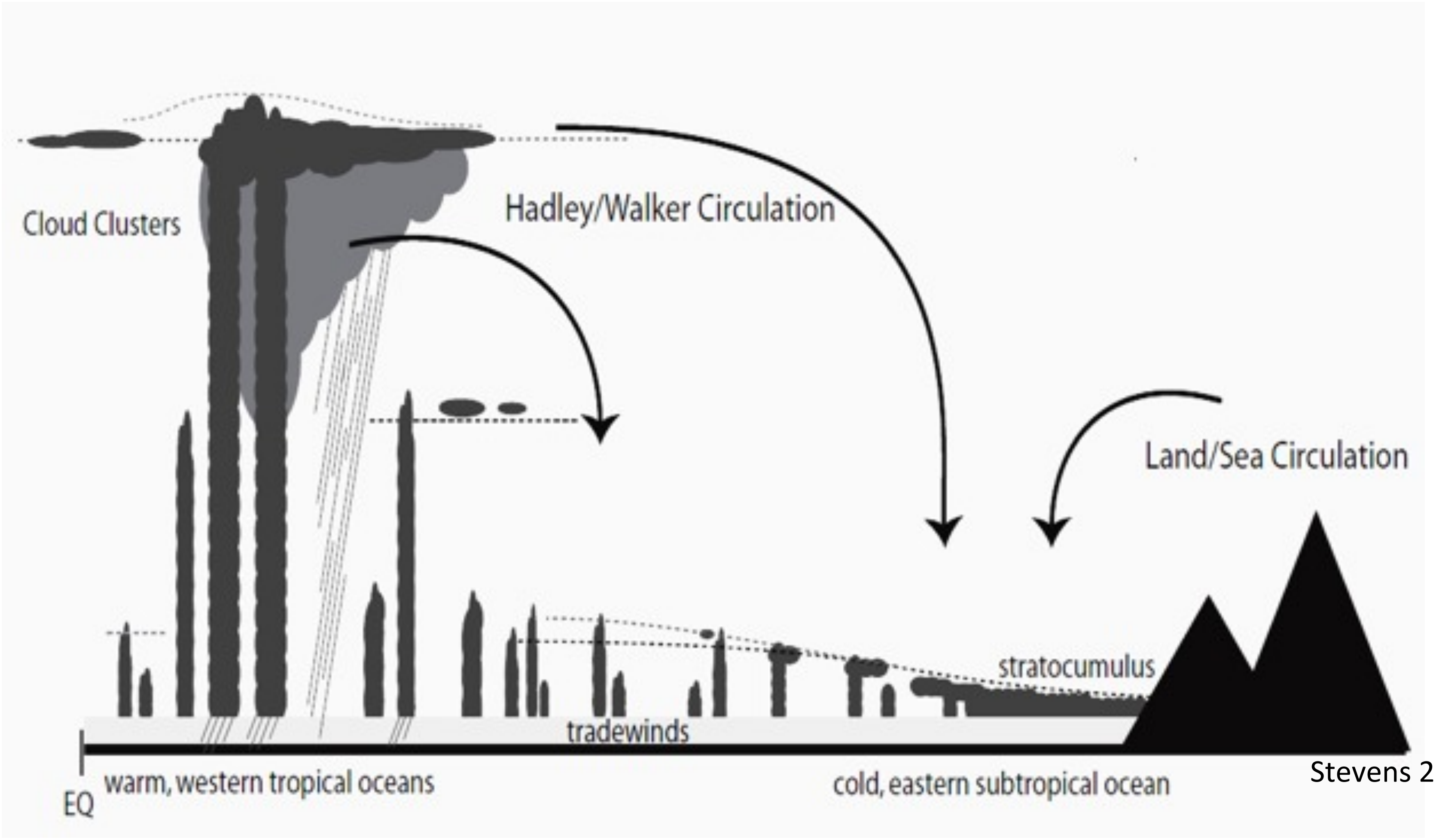
# Sensitivity of Low Cloud Transitions to Aerosol and Climate Perturbations

Peter Blossey, Chris Bretherton, Chris Jones (UW)
Sungsu Park (NCAR)

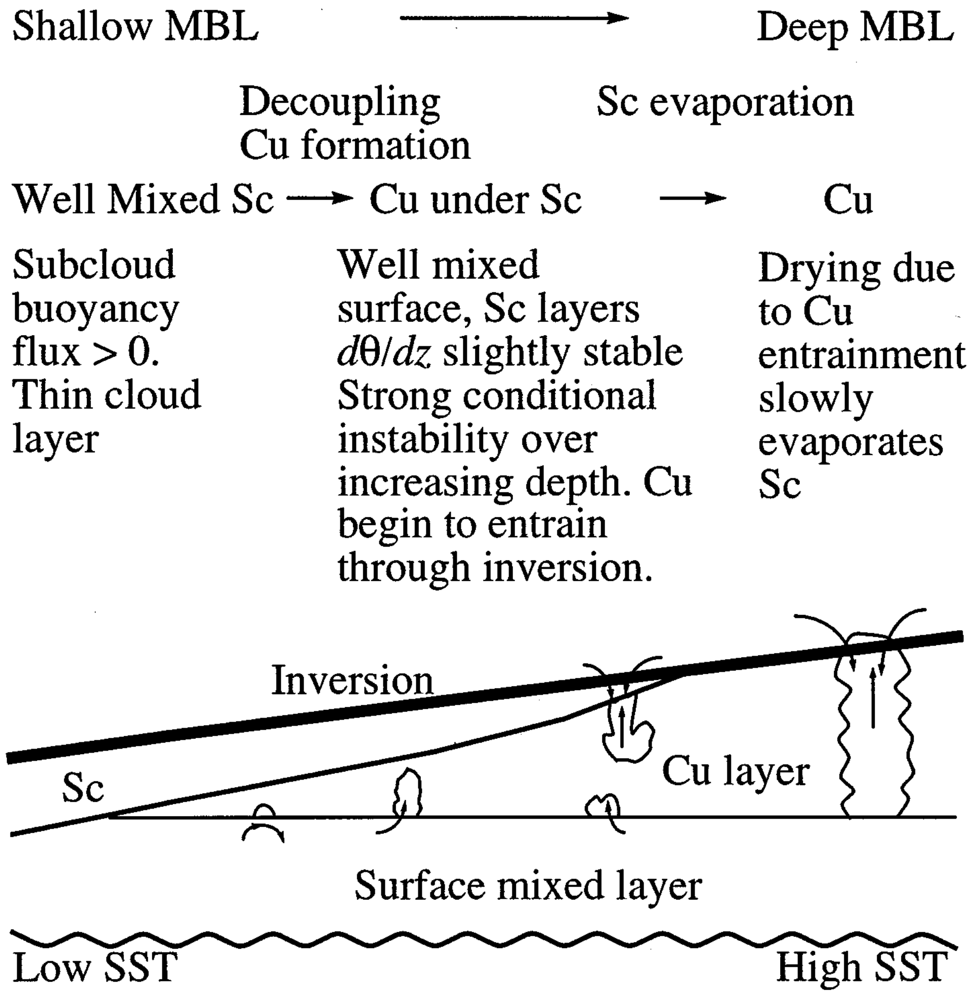
Thanks to Irina Sandu & Bjorn Stevens for building transition case, to Marat Khairoutdinov for SAM, and to a NOAA CPT for funding.

# Low Cloud Transitions

- Air masses associated with subtropical stratocumulus decks are advected over warmer SSTs by trade winds.
- Breakup of cloud is important for albedo both locally and globally.



Stevens 2006



Subcloud buoyancy flux > 0. Thin cloud layer

Well mixed surface, Sc layers $d\theta/dz$ slightly stable Strong conditional instability over increasing depth. Cu begin to entrain through inversion.

Drying due to Cu entrainment slowly evaporates Sc

Wyant et al (1997)

# Two studies related to cloud transitions in the Northeast Pacific

How do low clouds Northeast Pacific and their transitions respond to

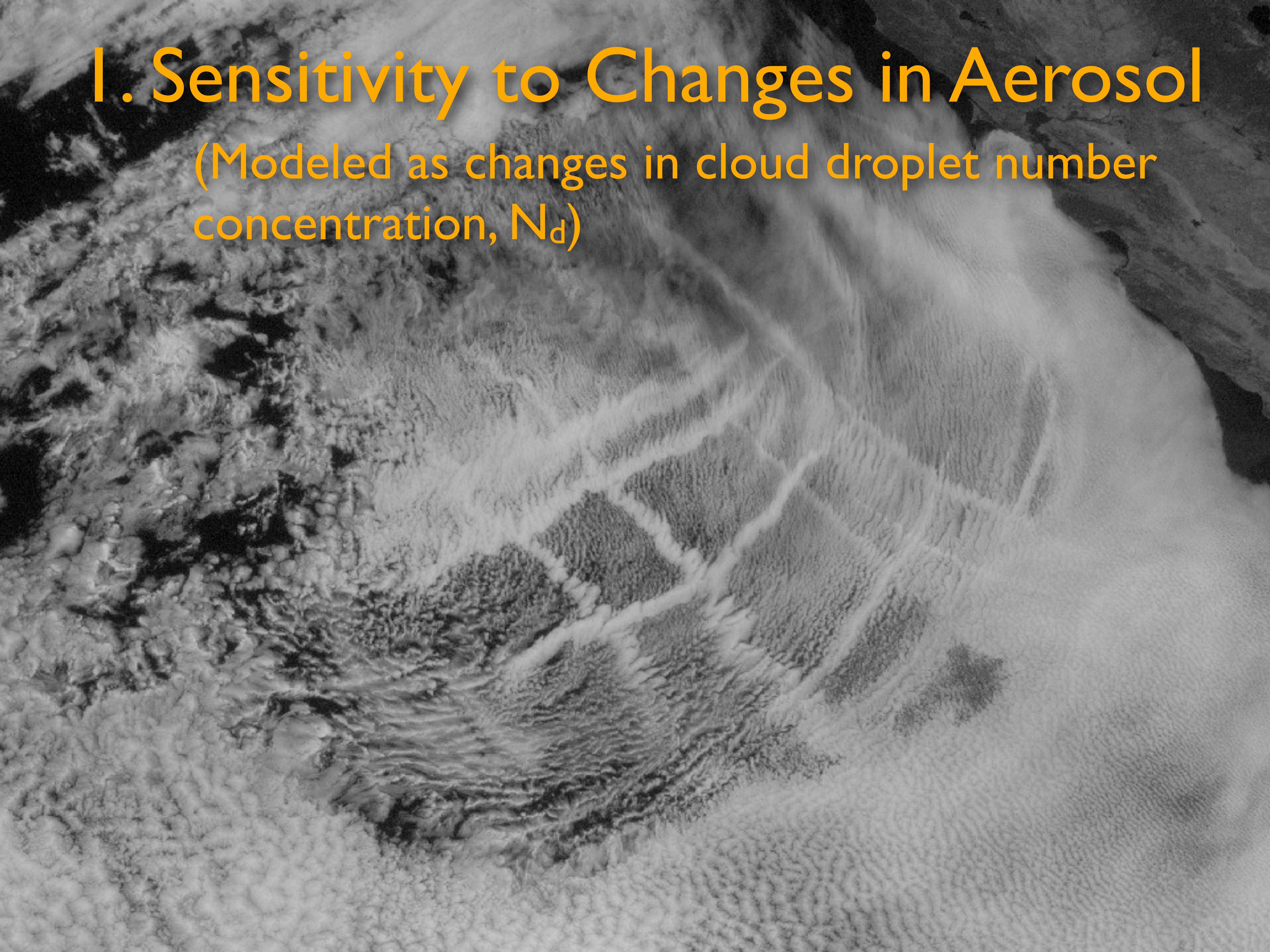
1. changes in aerosols?
2. climate perturbations?

Plan:

Study these along Lagrangian trajectories in the Northeast Pacific using Large Eddy Simulations and Single Column Models.

# 1. Sensitivity to Changes in Aerosol

(Modeled as changes in cloud droplet number concentration, $N_d$)



# Introduction: Aerosol Impacts on Clouds

- Aerosols can impact clouds through
  - cloud brightening (1st indirect effect) or
  - modification of cloud lifetime (2nd indirect effect).

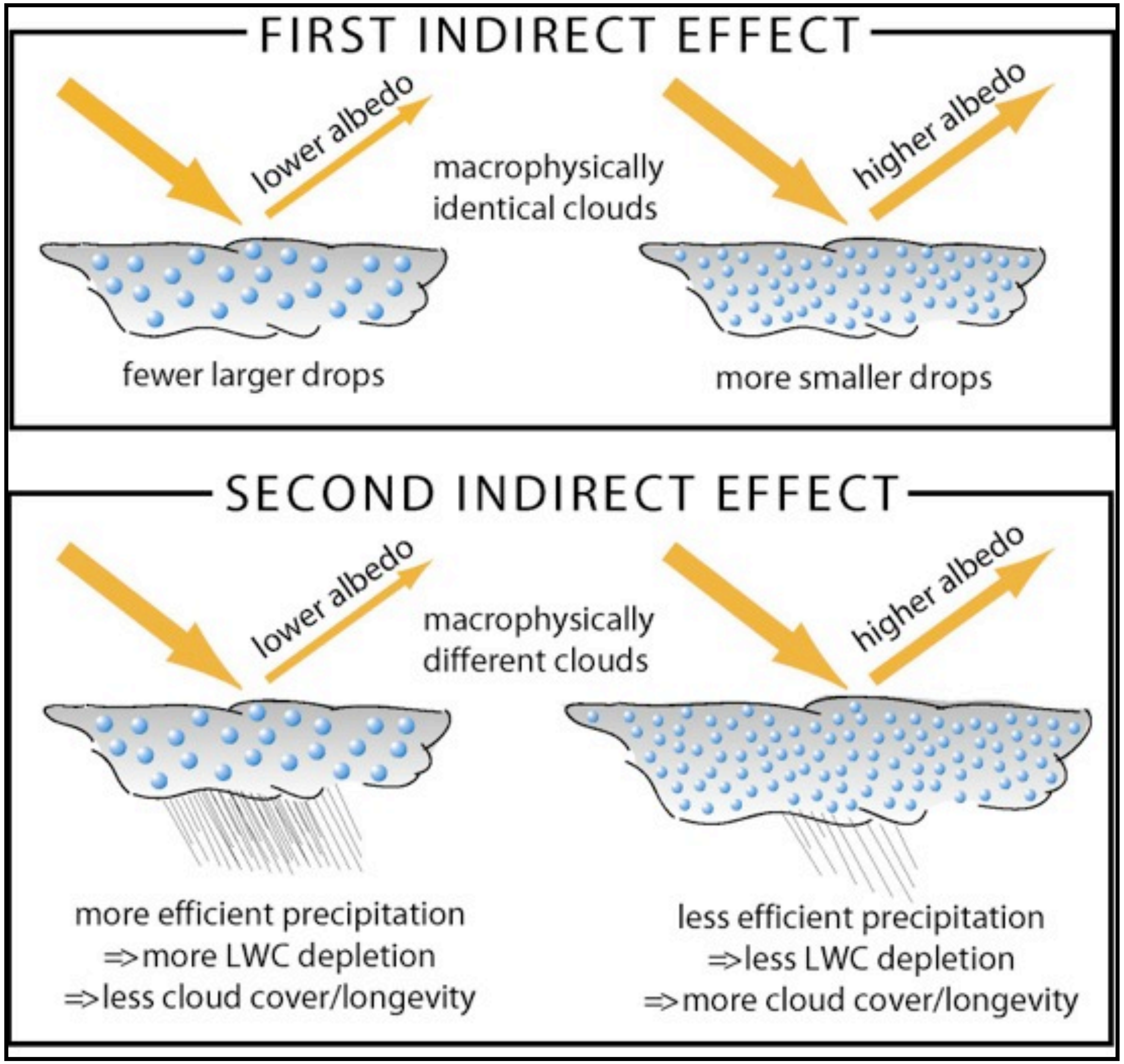
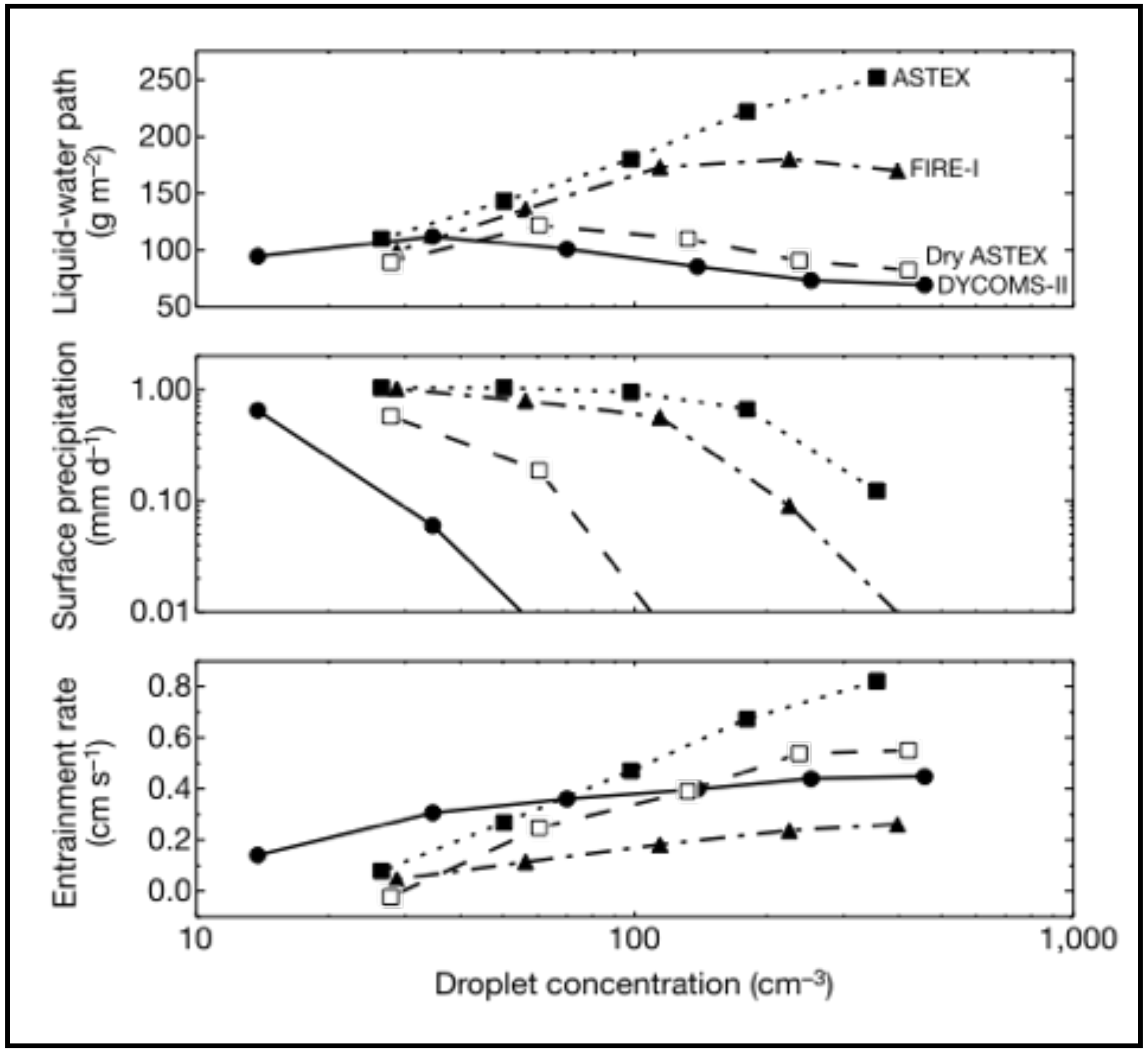
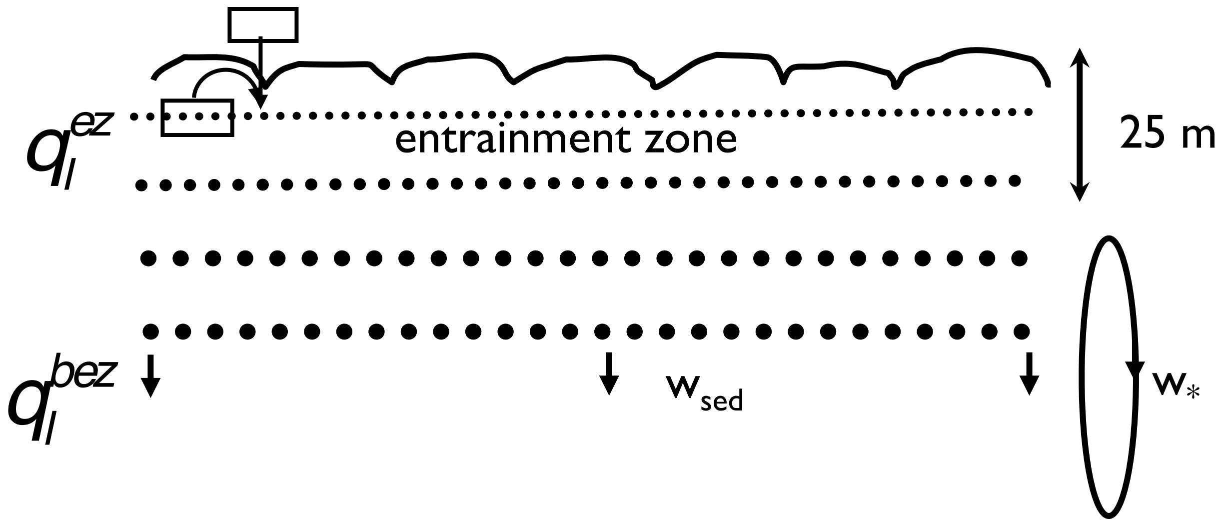


Figure courtesy of Rob Wood

# More aerosol thins nearly nonprecipitating Sc

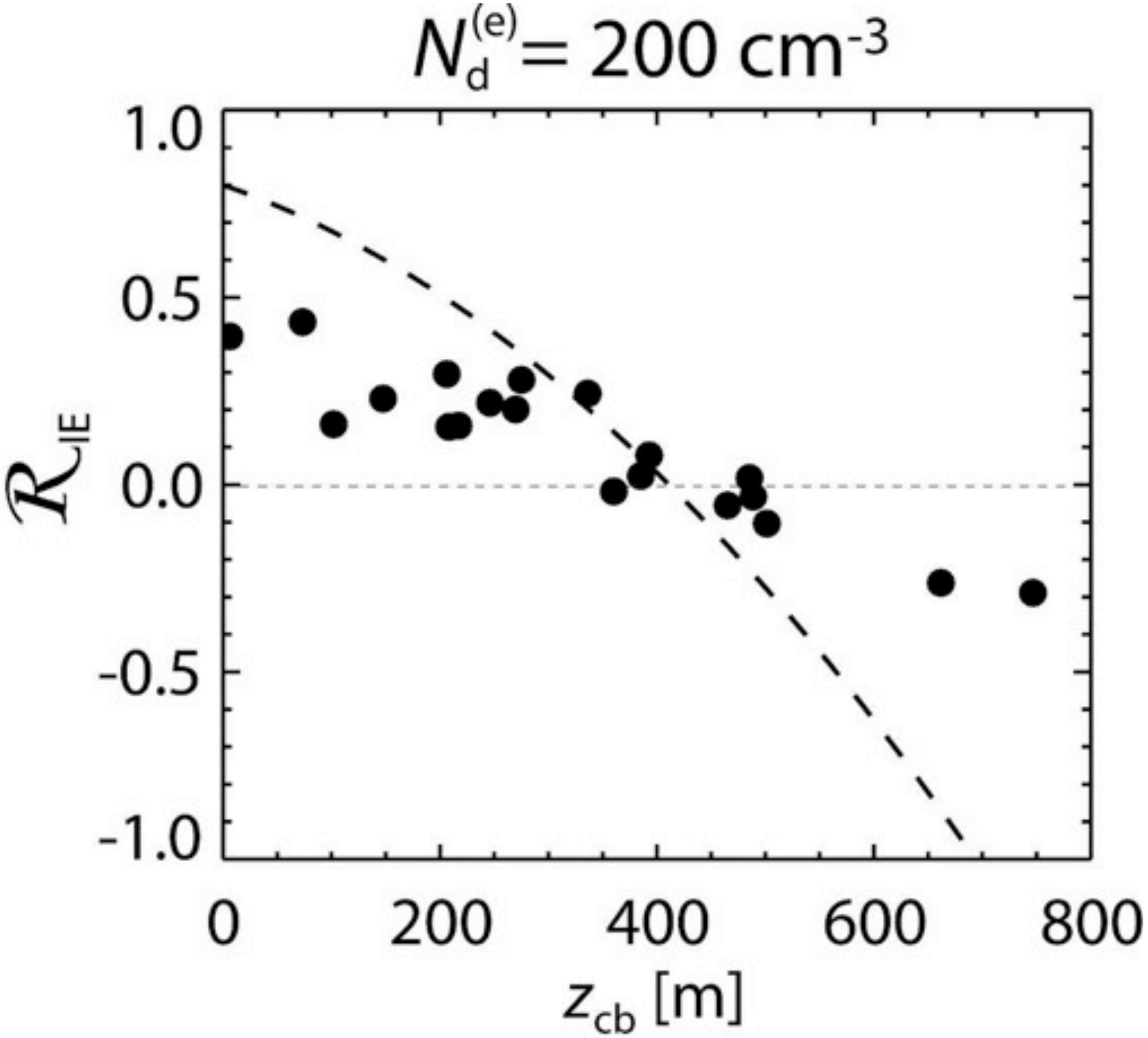
- Ackerman et al (2004) found that stratocumulus clouds only thicken with increasing cloud droplet concentration $N_d$ until surface precipitation rate becomes small (<0.1 mm $d^{-1}$).
- Due to enhanced entrainment of dry air with higher $N_d$.
- Bretherton et al (2007): Higher $N_d$ → Less sedimentation → more efficient entrainment, due to increased evaporation of liquid water in the entrainment zone.





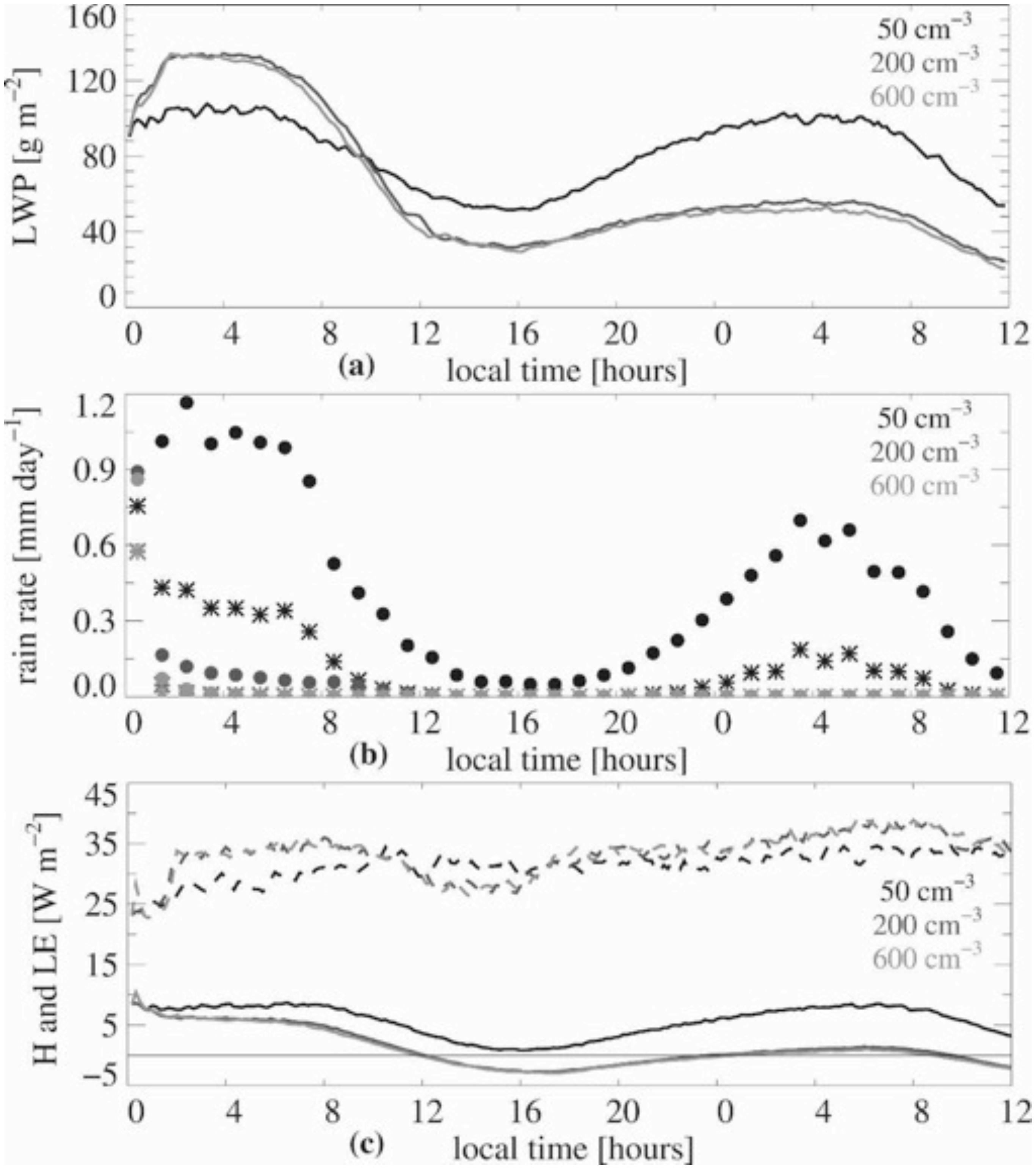
# Partial Cancellation of Aerosol Indirect Effects

- Wood (2007) looked at the cancellation of aerosol indirect effects in mixed-layer model (MLM) simulations of marine Sc.
- Over short times and for thinner clouds, the second indirect effect nearly canceled the first. $R_{IE}$ is their ratio (2nd to 1st).
- The sensitivity to aerosol perturbations decreased when the baseline Nd increased from 100 to 200.
- Caldwell and Bretherton (2009, also a MLM study) found a weaker sensitivity to aerosol perturbations and attributed this to low LWP.

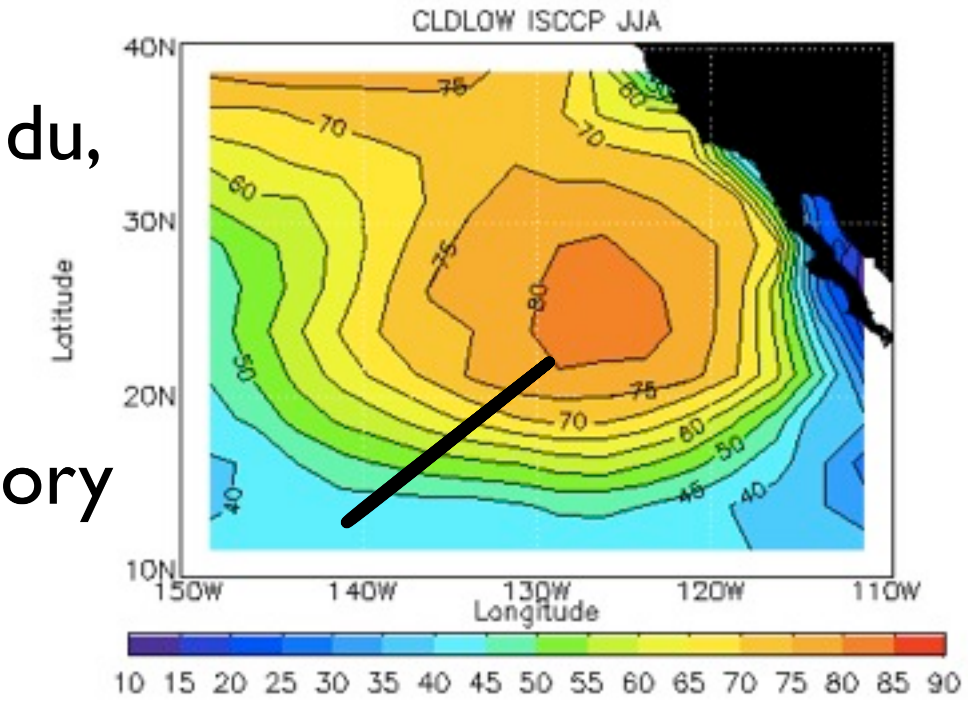


# LES Study of Nd Sensitivity in Sc

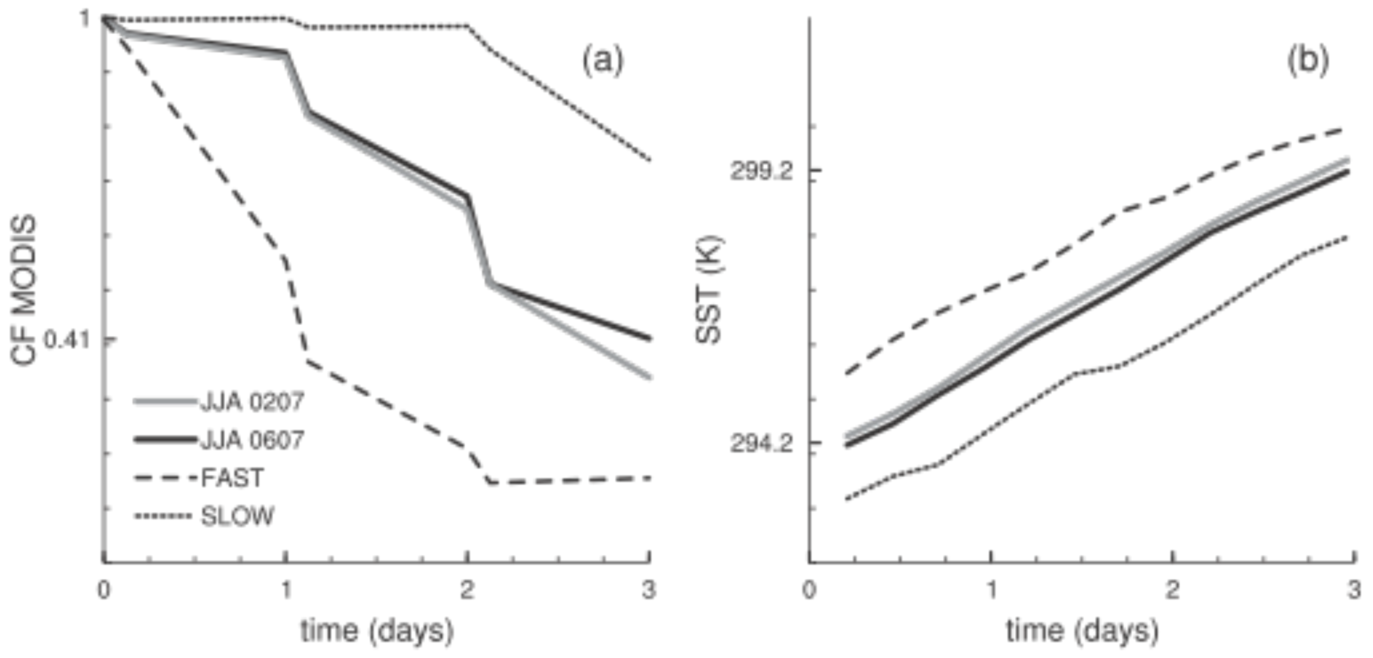
- In large eddy simulations (LES), Sandu et al (2008) found that daytime LWP changes due to increased aerosols worked against the Twomey effect.
- Shallow boundary layer (based on FIRE), well-mixed at night in Nc=600 case.
- Decouples during day in both cases and on second night in Nc=50 case.



# Our Study: Case Setup



- Stratocumulus to trade cumulus transition: a composite case from the Northeast Pacific (Sandu, Stevens & Pincus, 2010; Sandu & Stevens, 2011). Summertime conditions (JJA2006-7).
- Simulation follows composite Lagrangian trajectory over warmer SSTs with fixed subsidence.
- Finish after 3 days before breakup of capping Sc.



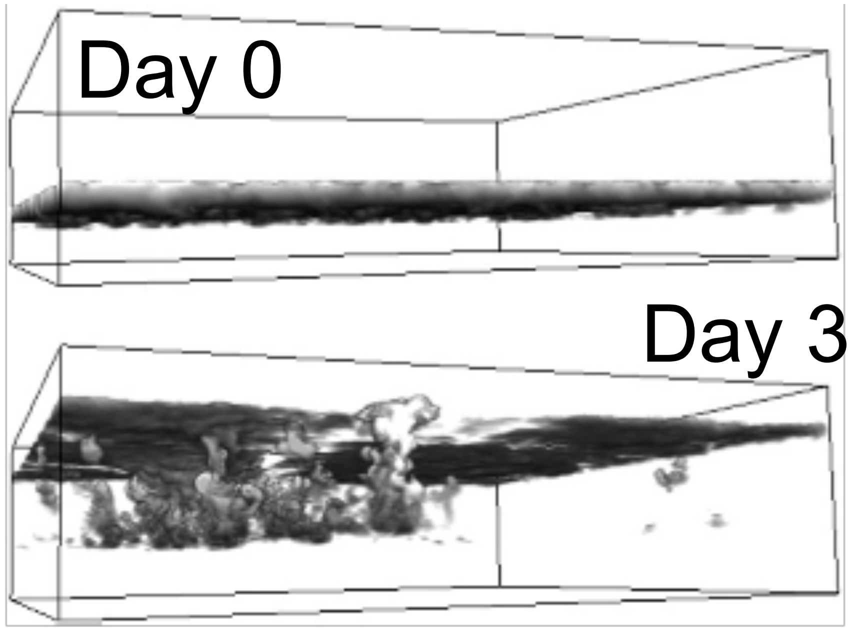


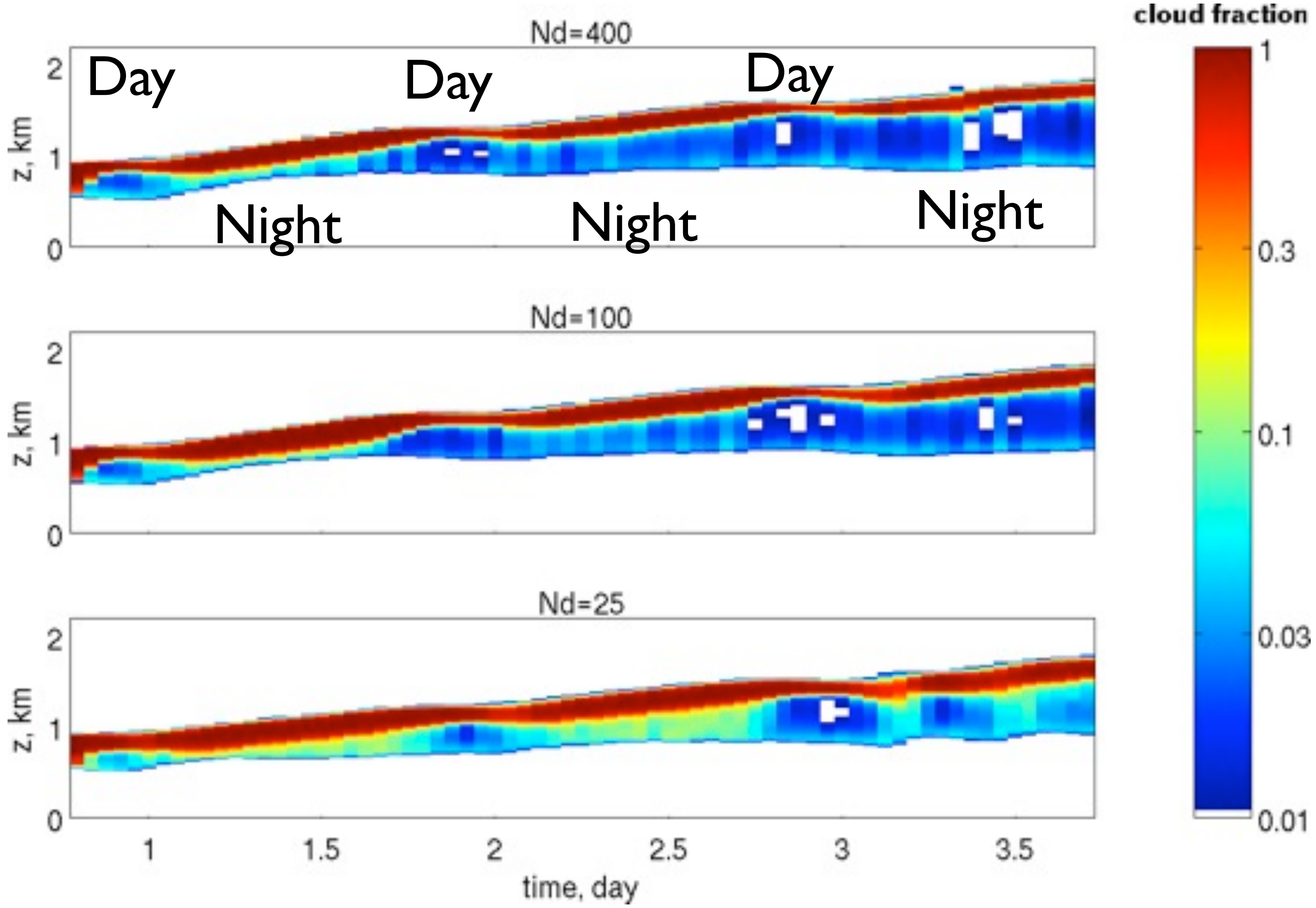
FIG. 3. An image of the cloud field simulated in the REF case, at (top) the beginning and (bottom) the end of the simulation.

# LES results

- Large eddy simulation model: System for Atmospheric Modeling, v. 6.8 (SAM, Khairoutdinov & Randall, 2003). $Lx=Ly\sim4.5$km. $\Delta x=\Delta y=35$m, $\Delta z=5$m from ~0.5-2.5km.

- Microphysics: Khairoutdinov & Kogan (2000), fixed $N_d=25, 100, 400\ cm^{-3}$.

- Radiation: RRTMG w/cloud droplet effective radius computed from LWC and $N_d$, assuming $\sigma_g=1.2$. Includes diurnal cycle.

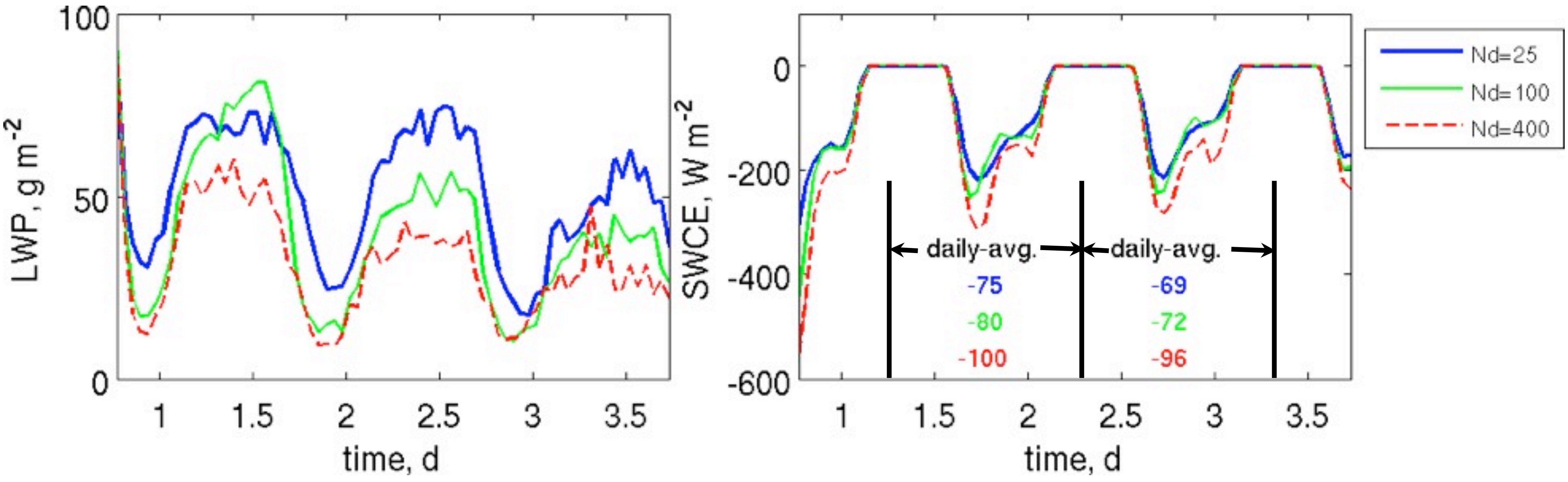


$N_d = 400\ cm^{-3}$

$N_d = 100\ cm^{-3}$

$N_d = 25\ cm^{-3}$

# Cloud thickness and albedo response to $N_d$

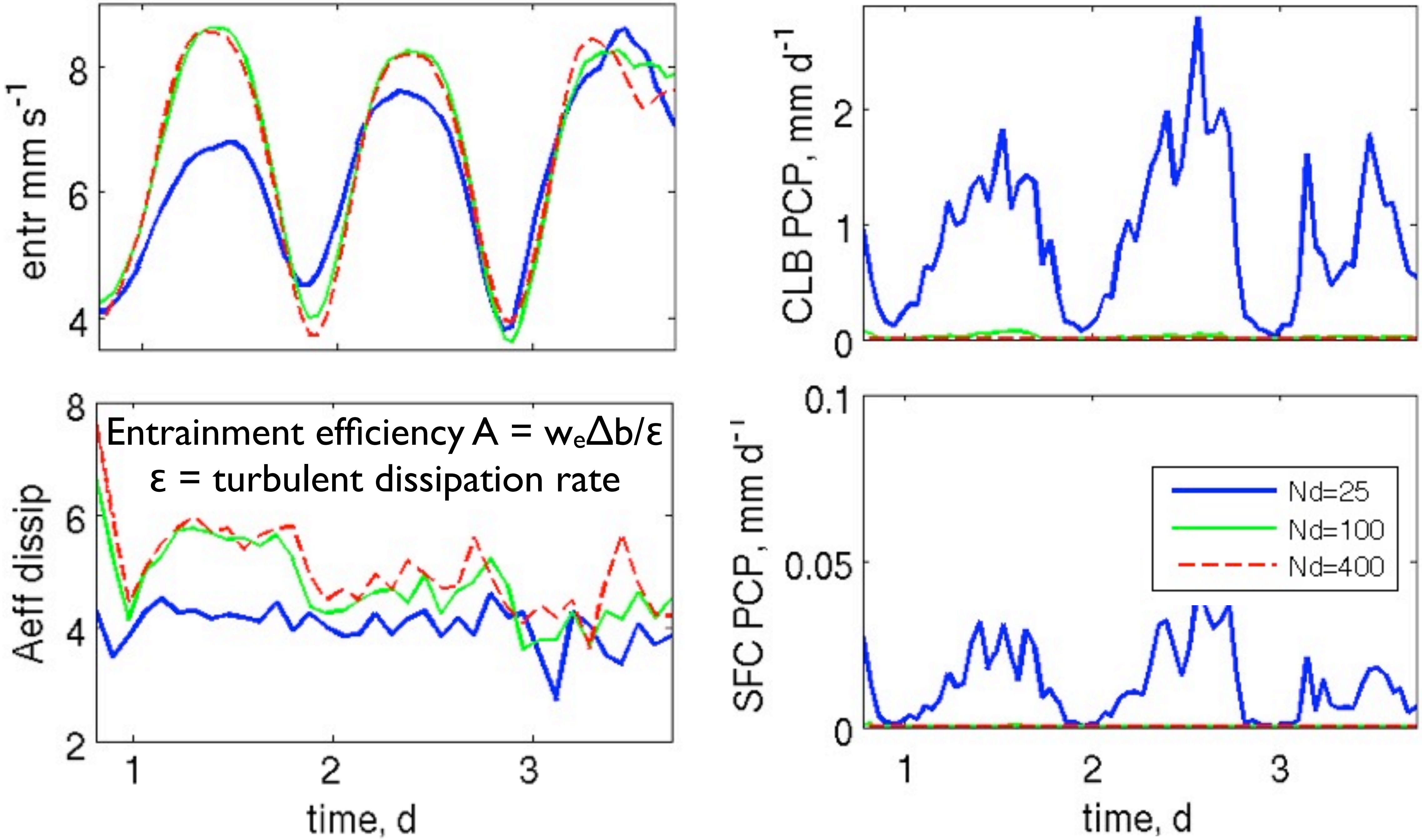


- Optical depth of an Sc layer $\tau \sim LWP^{5/6} N_d^{1/3}$.

  40% decrease in LWP ←→ 4x$N_d$.

- $N_d$ 25 → 100 cm$^{-3}$: 35% daytime LWP decrease, little albedo increase.
- $N_d$ 100 → 400 cm$^{-3}$: little daytime LWP decrease, Twomey effect reigns.

# Entrainment and Drizzle



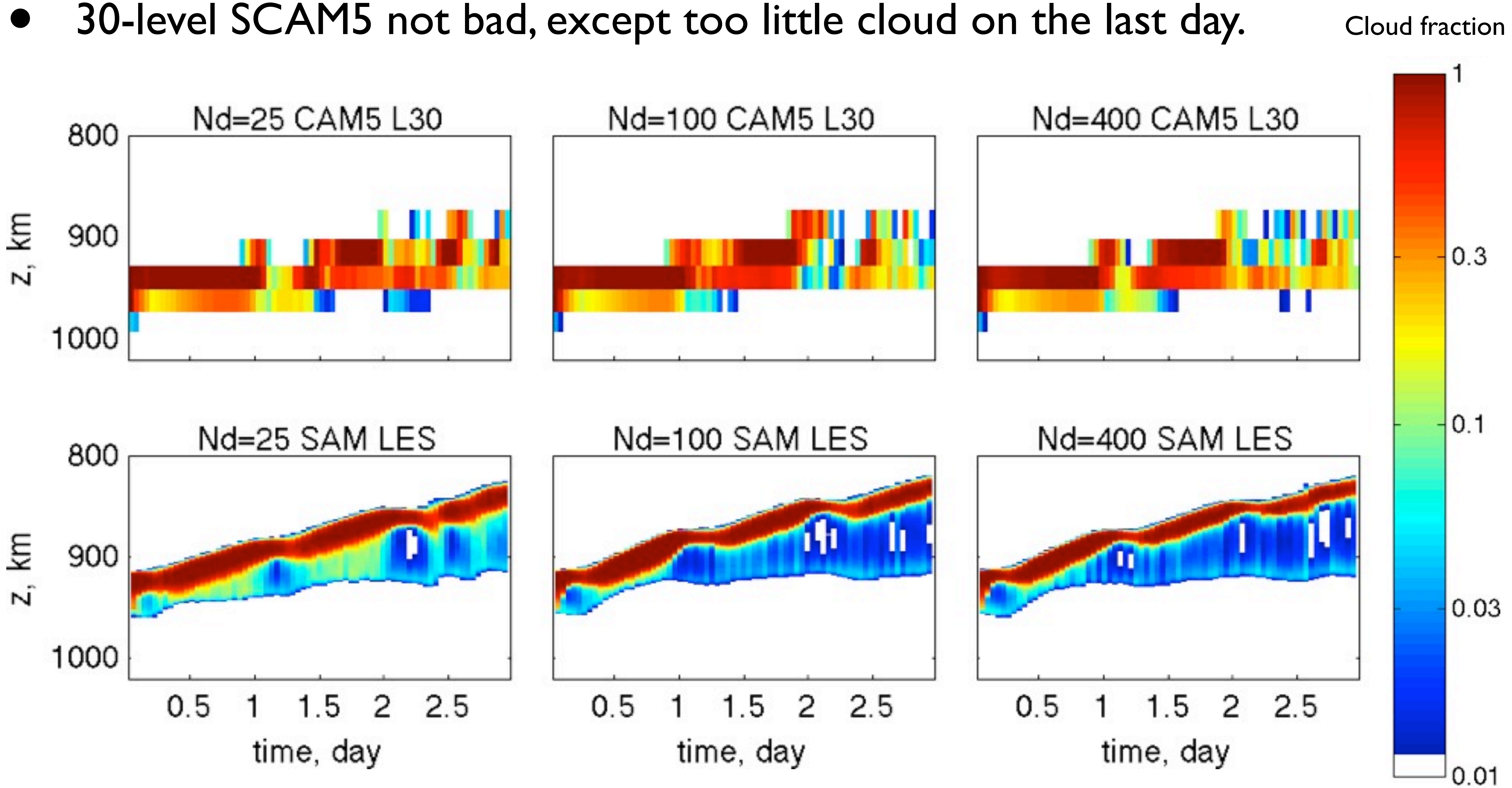
Entrainment efficiency $A = w_e \Delta b / \varepsilon$

$\varepsilon$ = turbulent dissipation rate

- Entrainment efficiency increases with $N_d$ (Bretherton et al. 2007).
- Drizzle evaporating below cloud base is significant for $N_d = 25$ cm$^{-3}$.
- Note that Sandu & Stevens (2011) found that a simulation w/$N_d = 33$ cm$^{-3}$ had surface precip (~0.3 mm d$^{-1}$) and had smaller LWP than $N_d = 100$ cm$^{-3}$.
- Uncertainty in microphysical representations may be large enough to support both results. We will look into this.

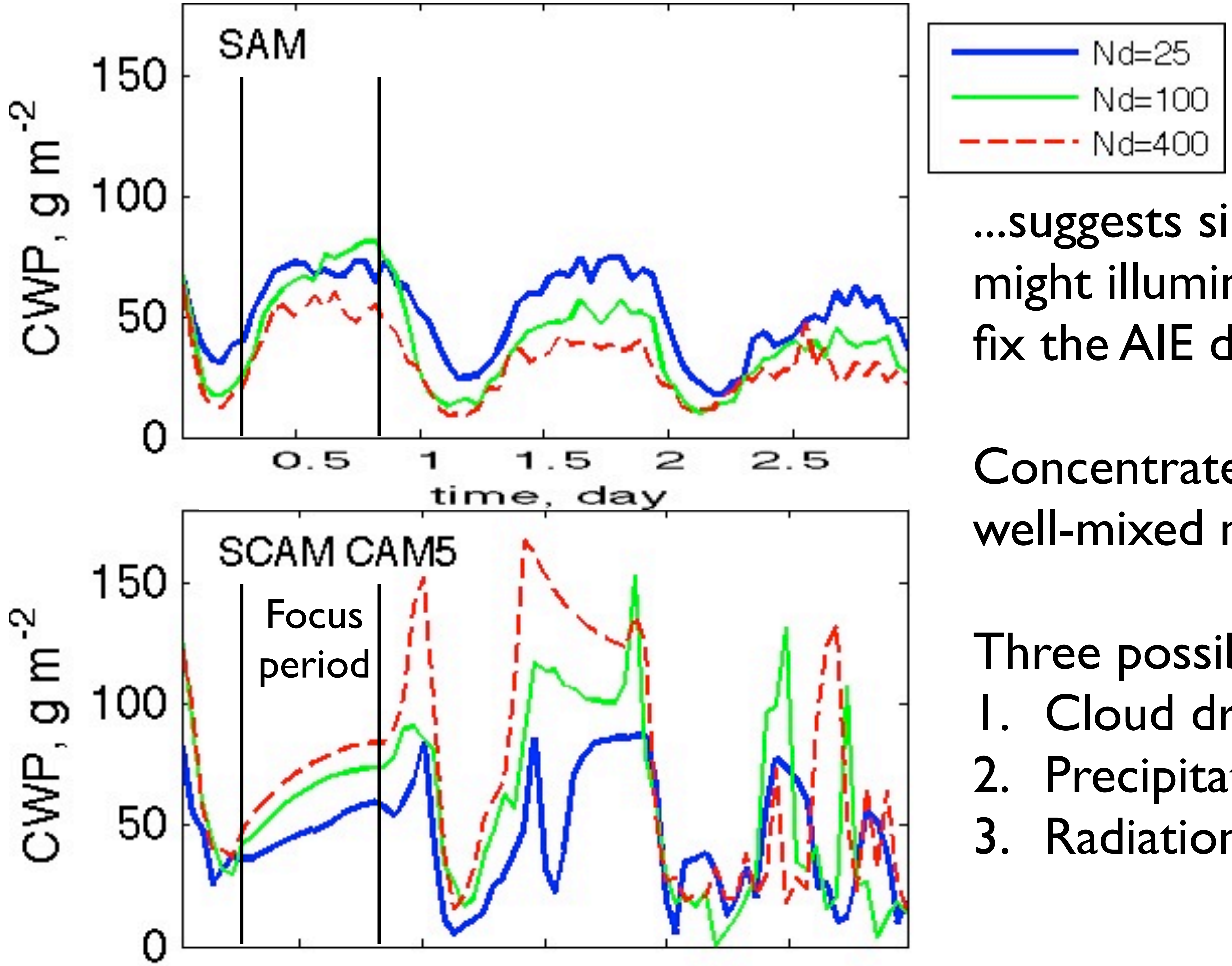
# Can SCAM5 reproduce this behavior?

- SCAM5 is the single-column version of the CAM5 atmospheric GCM.
- 30-level SCAM5 not bad, except too little cloud on the last day.



# But 2nd indirect effect opposite to LES!

- SCAM5 has **thicker** cloud with increasing $N_d$ (i. e. more positive $dLWP/dN_d$ than LES; similar to CAM5-MACM difference that led stronger aerosol indirect effect in CAM5 (Wang et al. 2011).



...suggests single-column modeling might illuminate and maybe help fix the AIE difference.

Concentrate on focus period: well-mixed nocturnal Sc layer

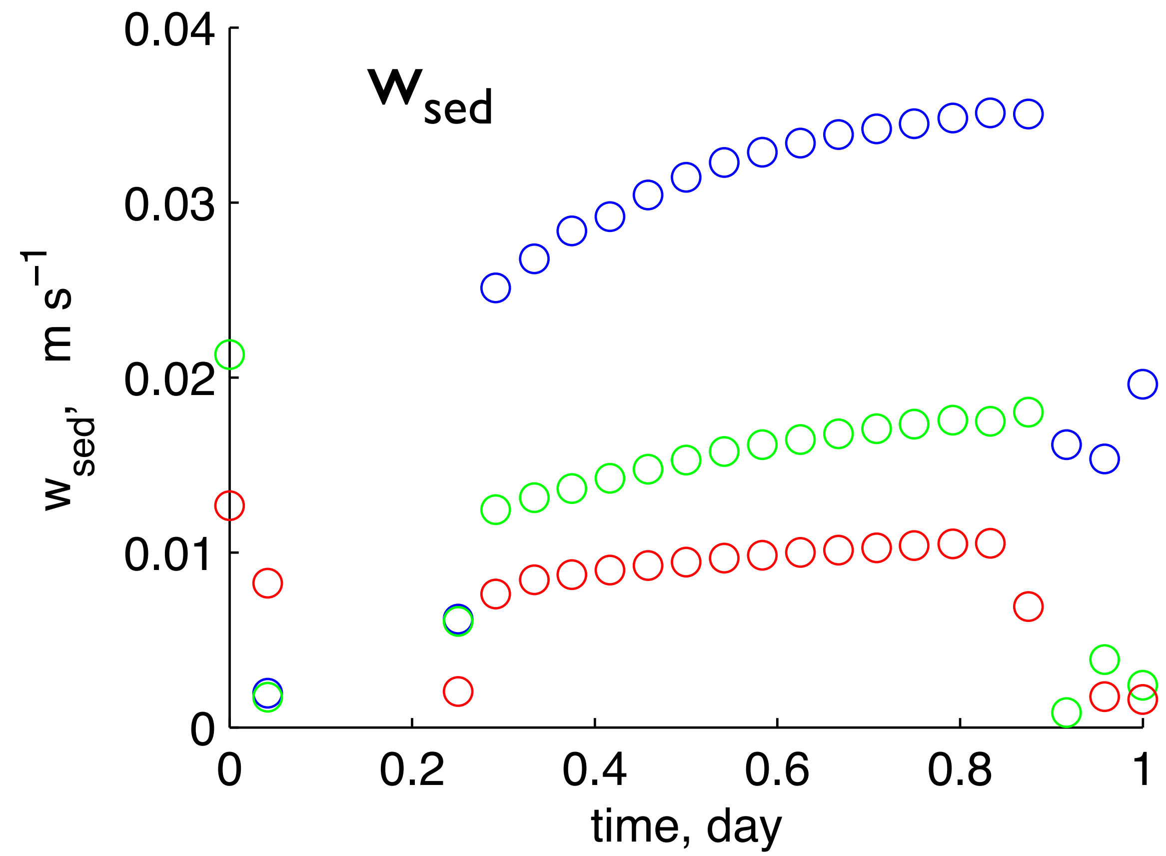
Three possible effects:

1. Cloud droplet sedimentation
2. Precipitation
3. Radiation sensitivity to $N_d$

# SCAM5 sensitivity studies

- Default CAM5 has cloud droplet sedimentation at a predicted rate $w_{sed}$ in stratiform microphysics, but no other entrainment-sedimentation feedback
- NoSed: Cloud droplet sedimentation off in stratiform microphysics.
- EntrSed: Add ‘missing’ entrainment-sedimentation feedback by decreasing cloud enhancement to entrainment rate by LES-tuned factor (Bretherton et al 2007)

$\exp(-a_{sed} w_{sed}/w_*)$, $a_{sed} = 9$ (LES-tuned), $w_*$ = convective velocity ~ $1\ \mathrm{m\ s^{-1}}$

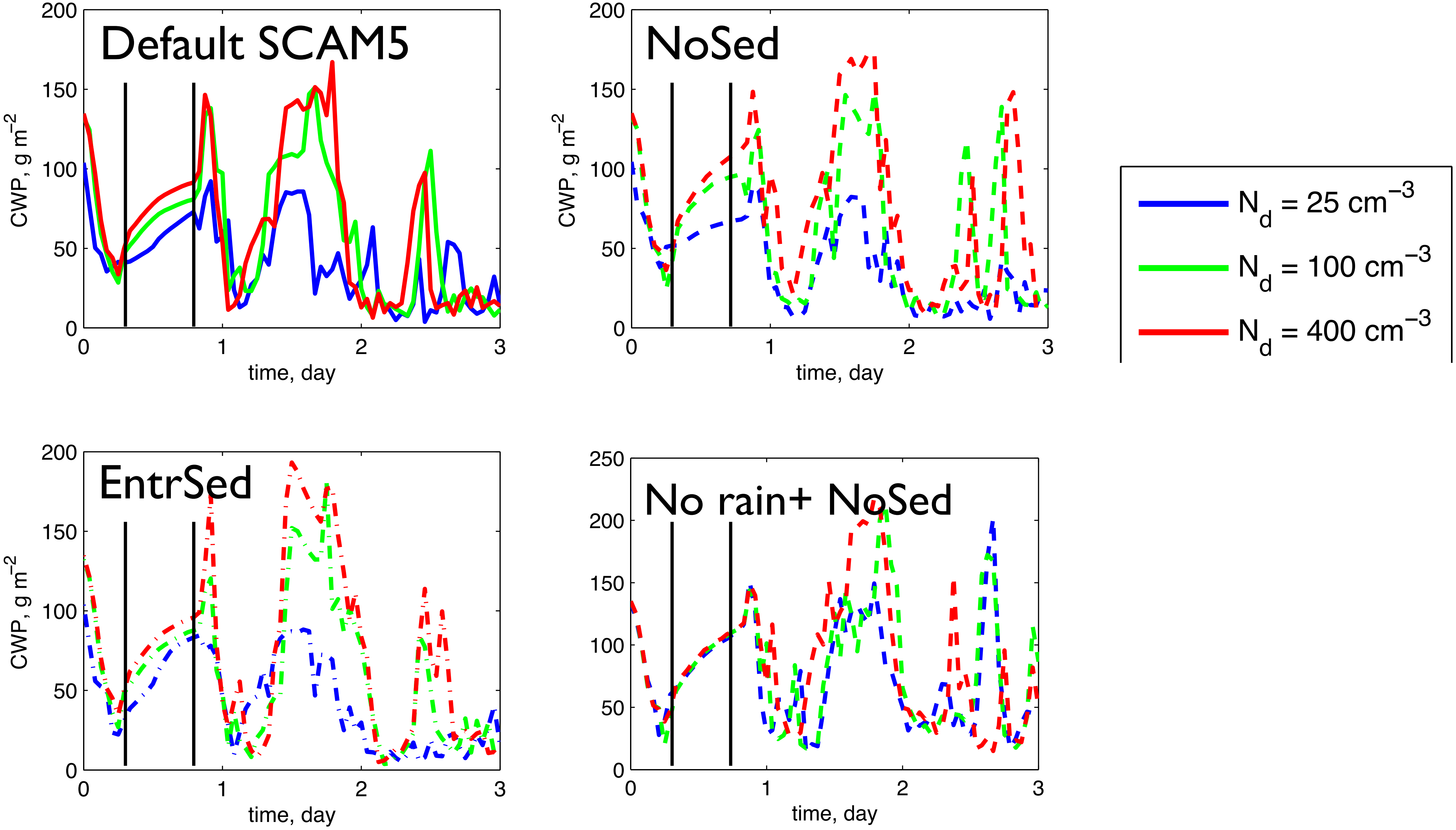


$\exp(-a_{sed} w_{sed}/w_*) = 0.75$

$\exp(-a_{sed} w_{sed}/w_*) = 0.88$

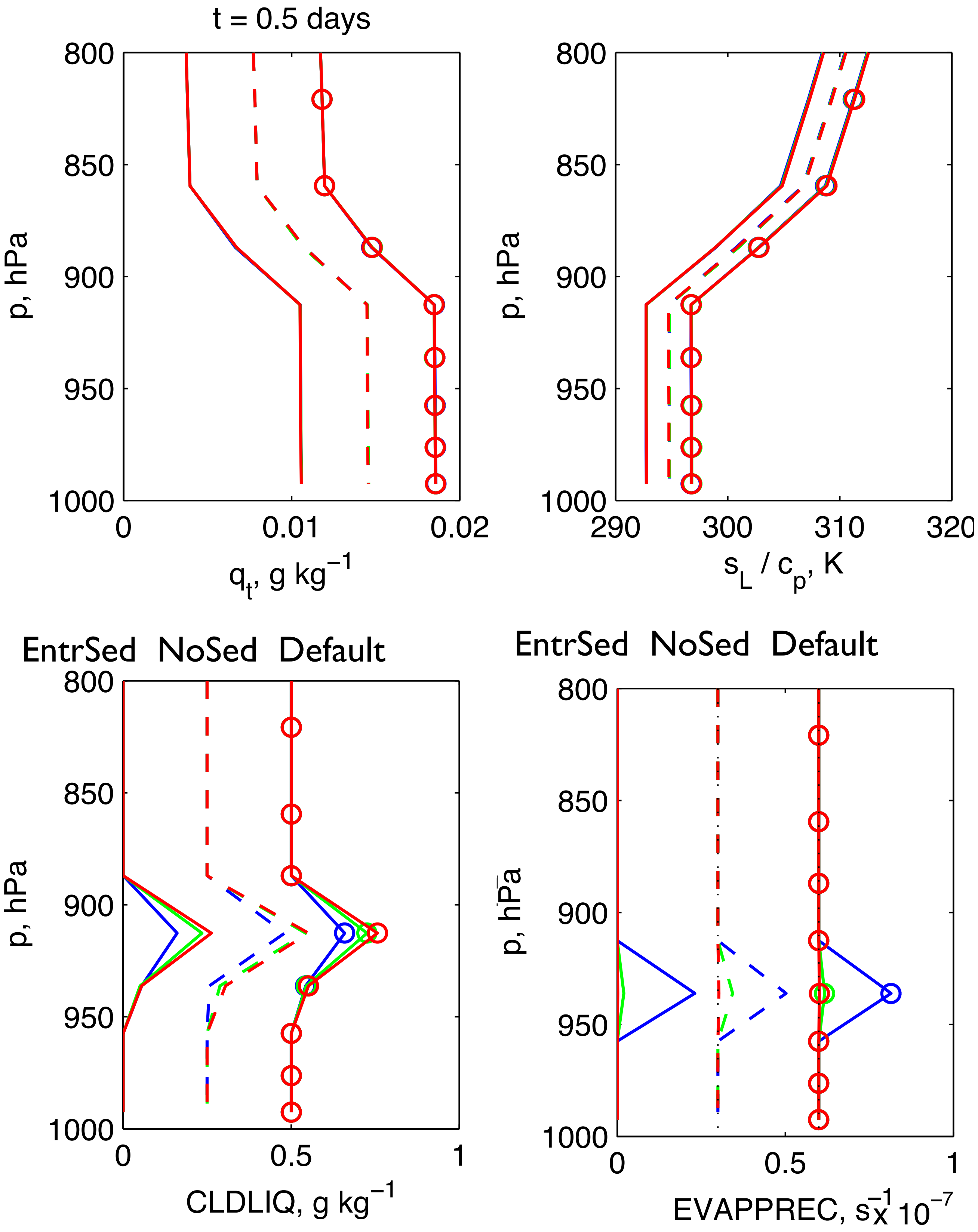
$\exp(-a_{sed} w_{sed}/w_*) = 0.92$

# Sedimentation not the issue



- Differences apparent in first night, when simulated PBL is well-mixed.
- Addition of stratiform sedimentation reduces LWP in all cases
- Addition of entrainment-sedimentation feedback brings a little LWP back
- But $N_d$ = 25 vs. 400 LWP difference as large with no sedimentation.
- They **are** removed when we also suppress stratiform precipitation.

# So evaporating drizzle is a likely culprit



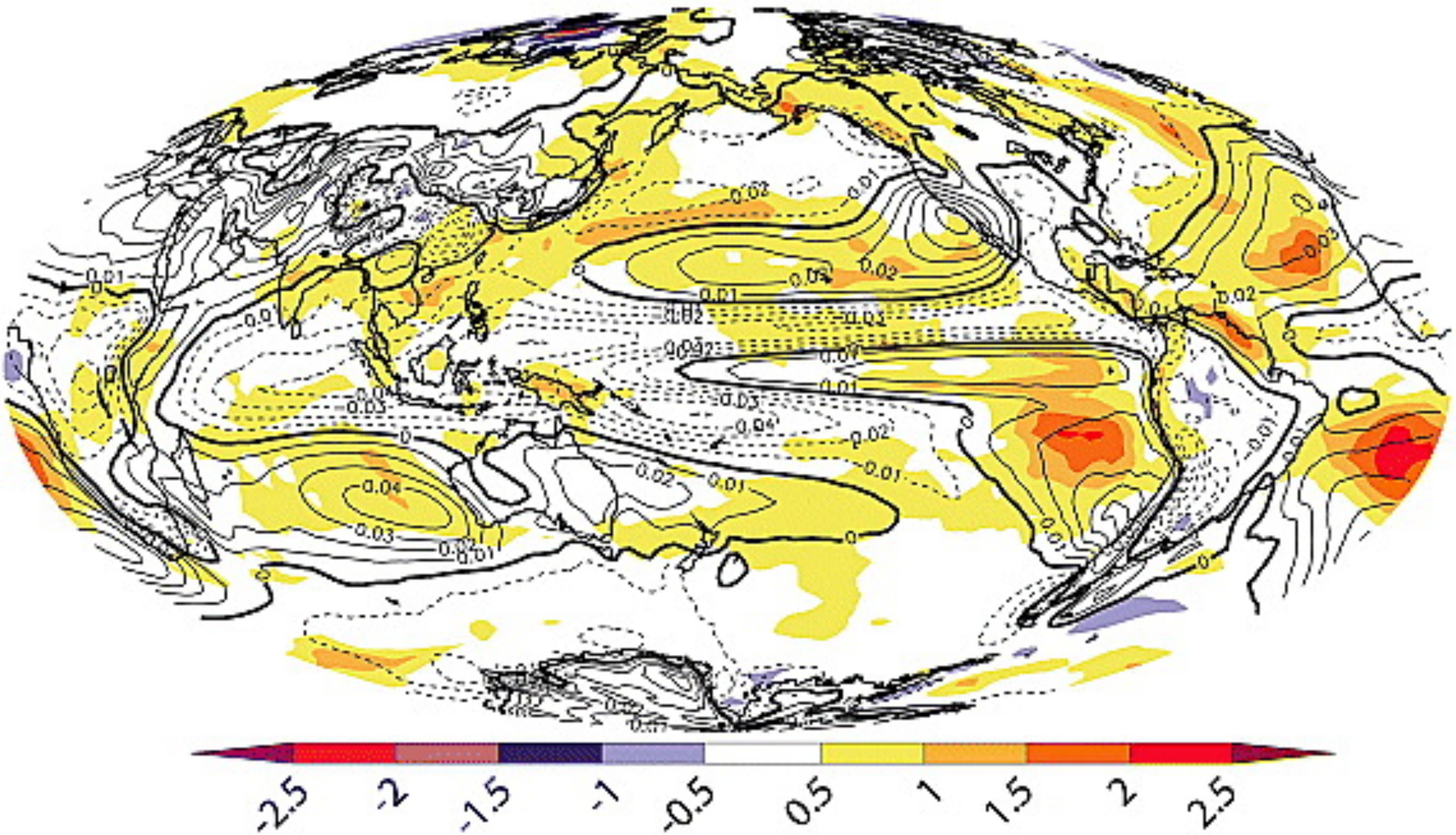
No surface precip at this time

- Look at t = 0.5 day (first night). Significant evaporating drizzle for Nd = 25.
- Loss of $q_l$ during each timestep comparable to 400-25 $\Delta q_l$ .
- Liquid water rained out of cloud in a timestep reduces LWP? Seems not, because results are changed little by halving timestep from 1200 to 600 s.
- So we've isolated the problem, and issures related to precipitation in SCAM, but these do not explain the different Nd sensitivity.

# Conclusions of Nd Sensitivity Study

- LES of marine low cloud transition show interesting sensitivity to cloud droplet number concentration (Nd), with thicker cloud for smaller Nd.
- This seems to be related to the effects of both sedimentation and drizzle on entrainment.
- SCAM5 shows the opposite sensitivity to Nd, with thicker cloud at higher Nd.
- Another LES model (Sandu & Stevens, 2011) shows a similar sensitivity to SCAM5, but that model dries the boundary layer through surface precipitation, while SCAM5 doesn't precipitate at the surface.
- We're still working to understand this sensitivity.
- Note that AM3-CLUBB (Guo et al, 2011) does a good job of reproducing Nd sensitivity of Sc clouds from Ackerman et al (2004).

# 2. Sensitivity to Climate Perturbations



Shade: Regression of Local Cloud Feedback to Global-mean Cloud Feedback $(W \cdot m^{-2} \cdot K^{-1})$
Contour: Background 500hPa Pressure Velocity $(Pa \cdot s^{-1})$

Soden & Vecchi (2011):

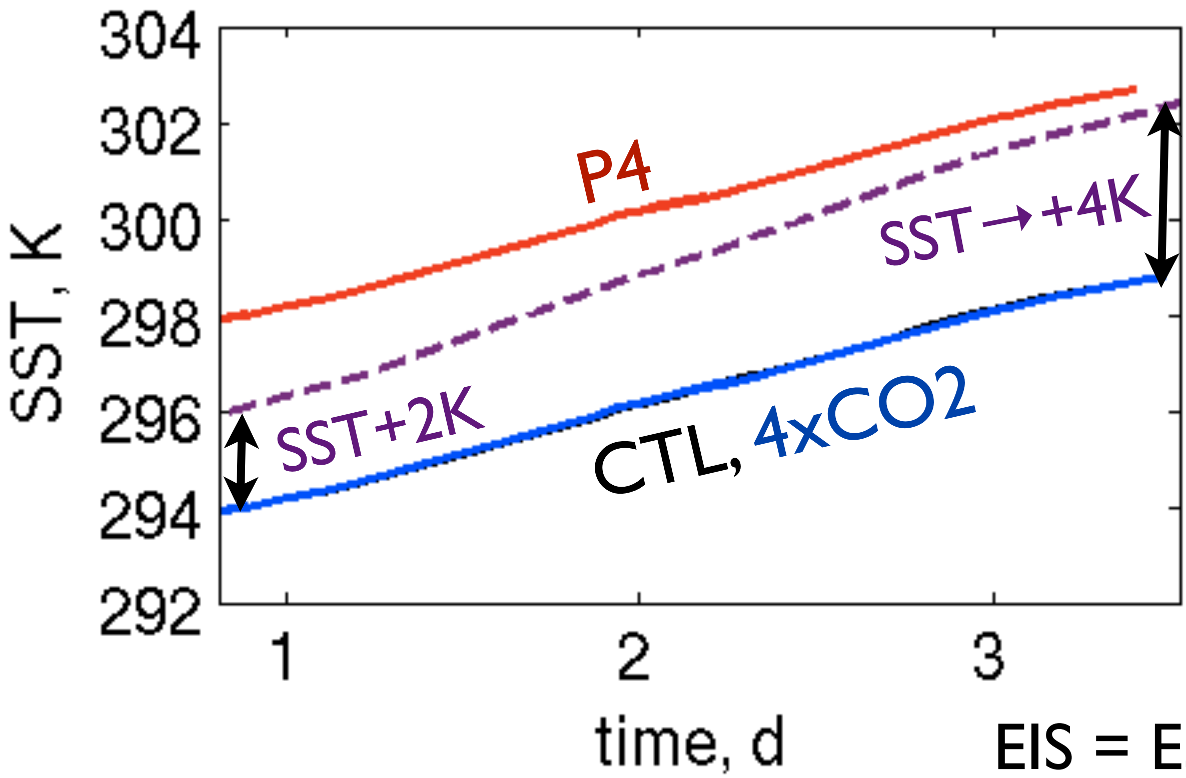
- Scatter in total cloud feedback dominated by low cloud.
- Cloud feedbacks in low cloud transition regions are well-correlated to global mean.

# Background

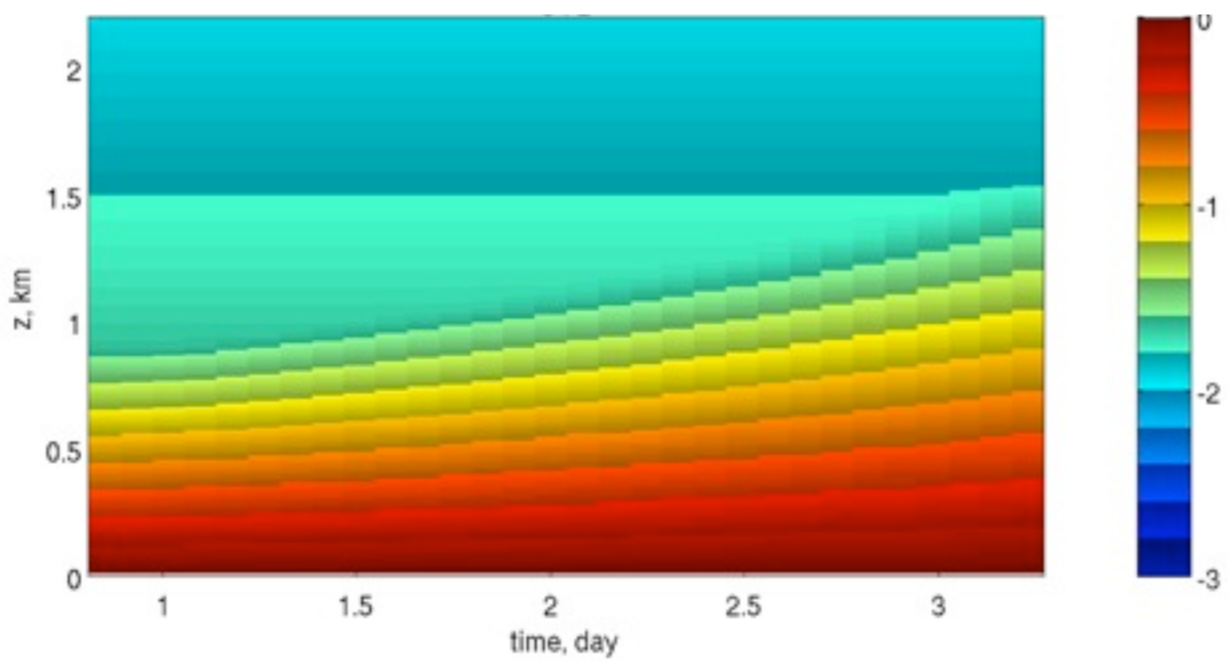
- Bony & Dufresne (2006): differences in tropical cloud response came mainly from shortwave in subsiding regions.
- Many modeling studies of low cloud feedbacks in a single-column setting :
  - MLM: Caldwell & Bretherton (2009), Caldwell et al (2012)
  - LES/CRM: Xu et al (2010), Blossey et al (2009), Rieck et al (2012)
  - SCM: Zhang & Bretherton (2009), Brient & Bony (2012).
- Some modeling studies have suggested mechanisms for low cloud response:
  - Caldwell & Bretherton: subsidence/lapse rate feedback leads to thicker cloud in Sc regions when SST change is uniform in tropics.
  - Rieck et al: Warming leads to a drier, less cloudy cloud layer in trades.
  - Brient & Bony: Increase in lower tropospheric moist static energy gradient leads to reduced cloudiness in trades.

# Case Setup

- Modify Sandu & Stevens (2011) Lagrangian transition case.
- Subsidence fixed aloft, but near-surface divergence decreases with time over a layer of increasing depth.
- Four Climate Perturbations (no changes to wind speed, FT RELH):
  - P4 (warming): SST+4K, moist adiabatic warming aloft,
  - 4xCO2,
  - dEIS (stability↑): SST+2K locally, SST+4K in deep tropics. Stronger than expected changes based on CMIP3 models (ΔEIS<~1K),
  - P4 4x (combined warming and 4xCO2).
- Adapt subsidence aloft in each case so that free tropospheric energy budget is in approximate balance (P4 subsidence ~ 0.9 CTL subsidence).

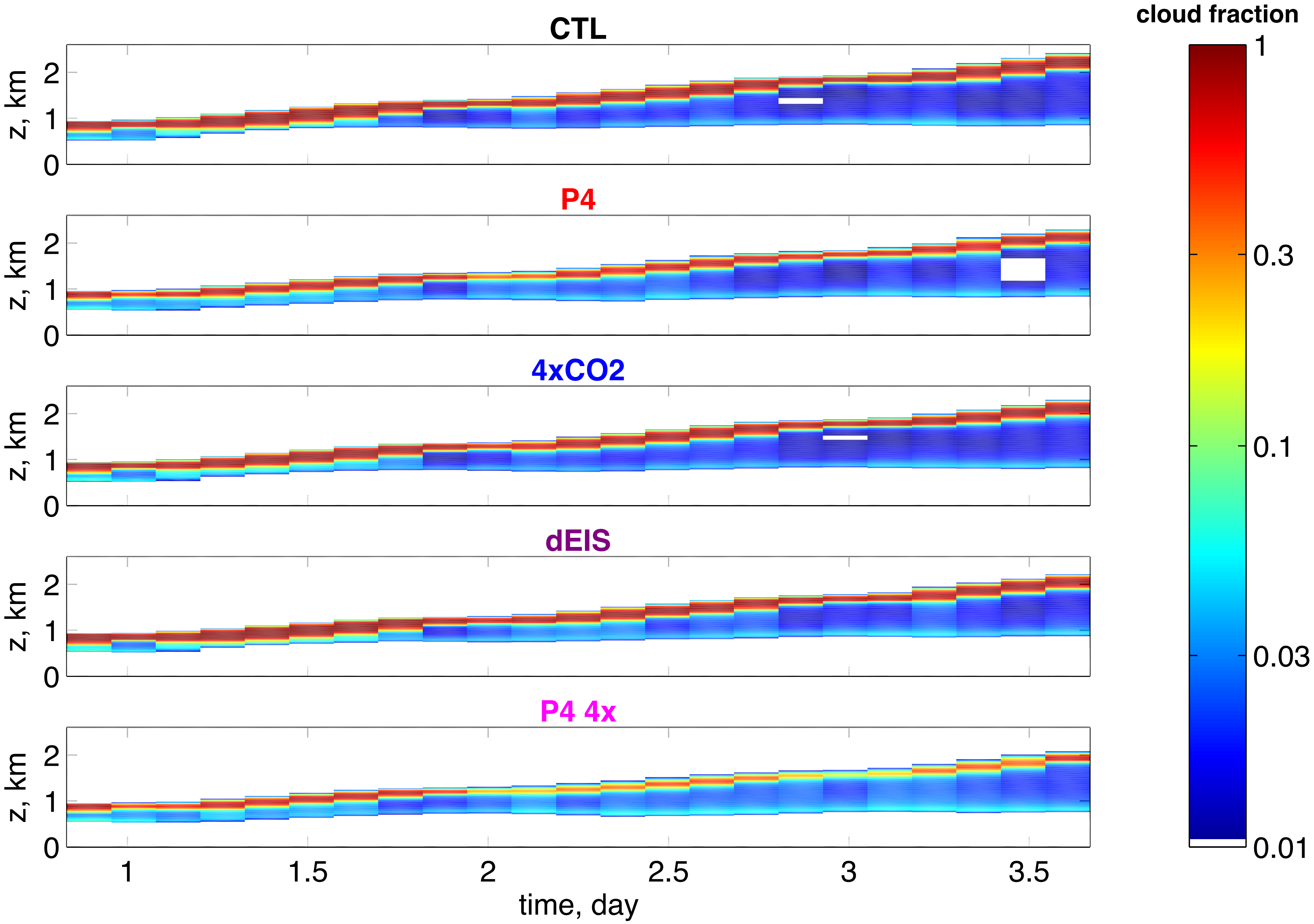


CTL Subsidence, mm $s^{-1}$



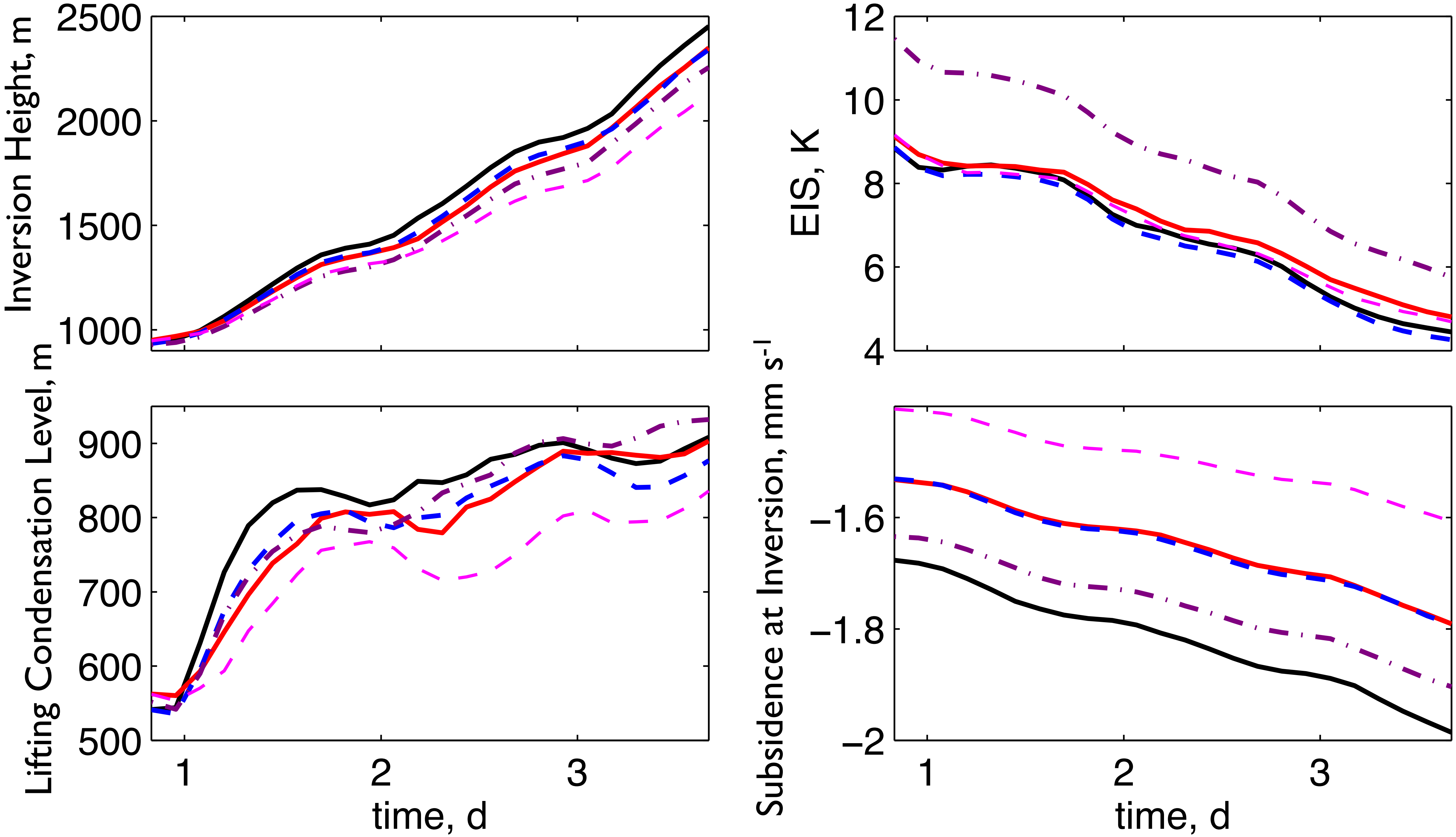
EIS = Estimated Inversion Strength (Wood & Breth, 2006)

# Results: Cloud Fraction



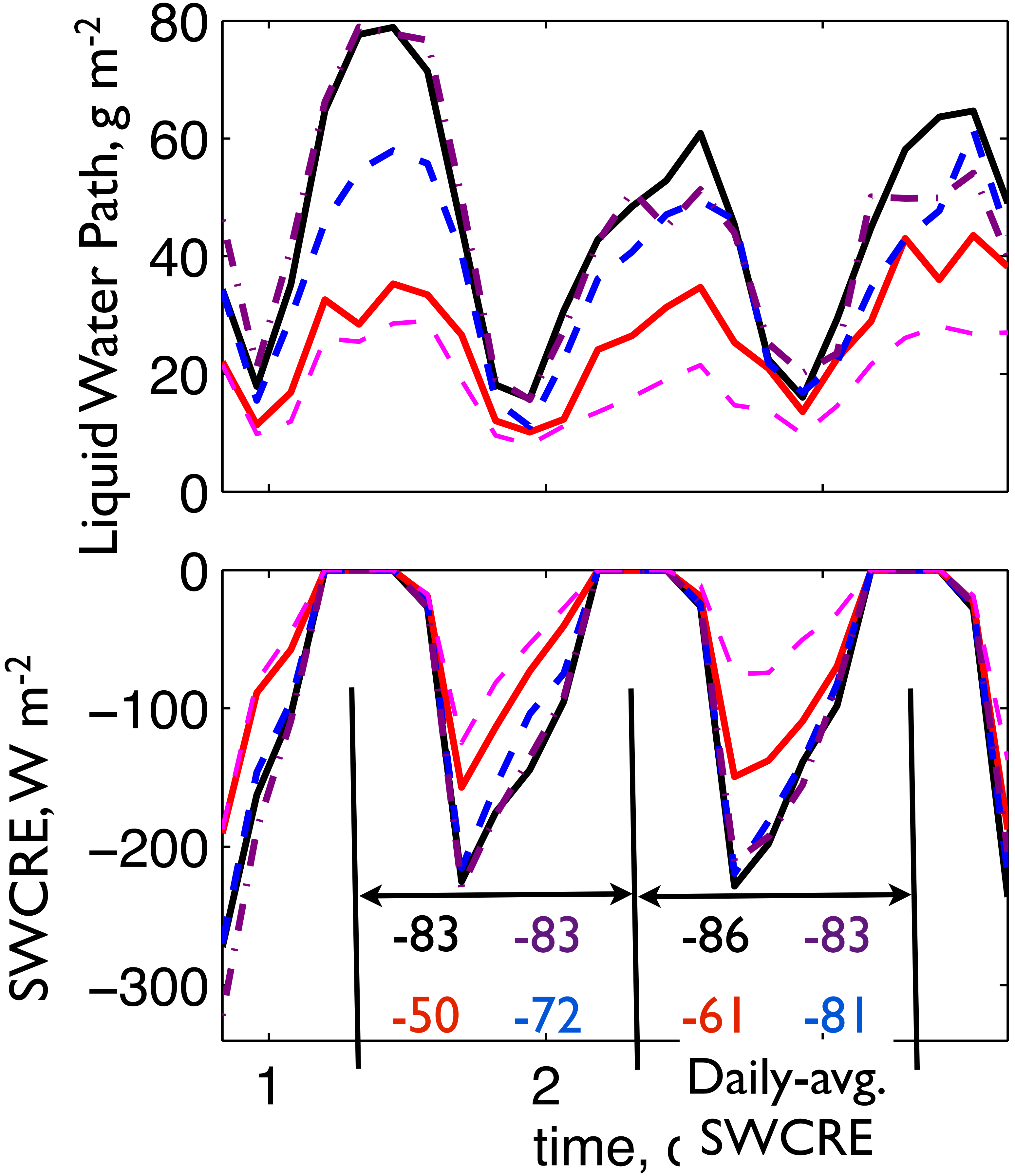
- CTL simulation is broadly similar to previous simulation.
- Cloud thins in P4 simulation relative to CTL. More thinning in P4 4x.
- P4, 4xCO2 runs more decoupled on first night than CTL, dEIS.

# Results: BL depth, stability, subsidence



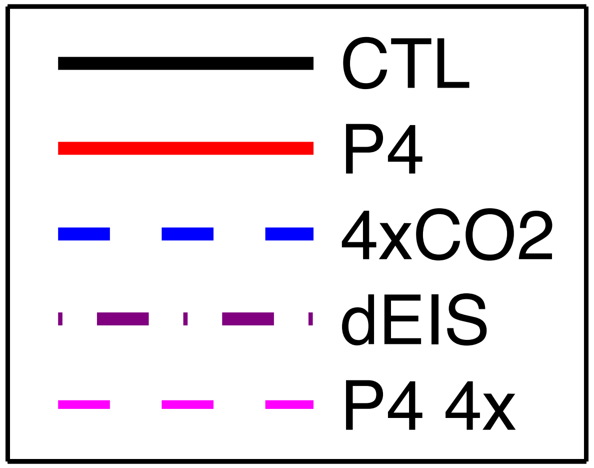
- CTL deepens more despite stronger subsidence.
- Increased stability restrains deepening of dEIS.
- During first night, P4 & 4xCO2 have thinner cloud layer than CTL.

# Results: LWP, SWCRE

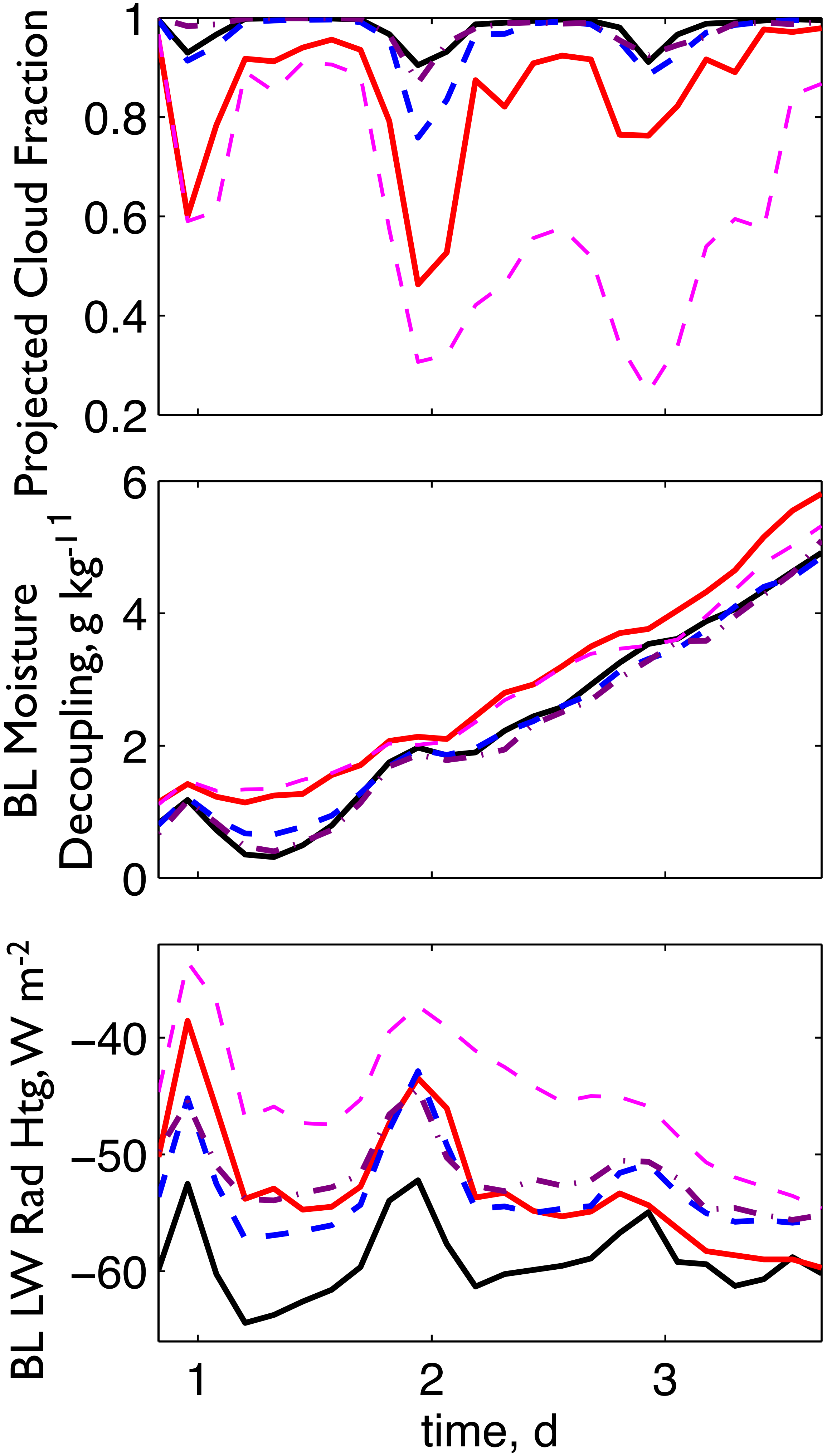


- Warming (P4) leads to thinner cloud.
- Large ΔSWCRE (CTL→ P4) due in part to partial cloud cover (~80-85%), stronger decoupling.
- With increased CO2 (4xCO2), cloud thiner on first full day but mostly recovers on second.
- Increase stability seems to offset warming in dEIS simulation.
- More thinning in combined P4 4x run than in the other runs.

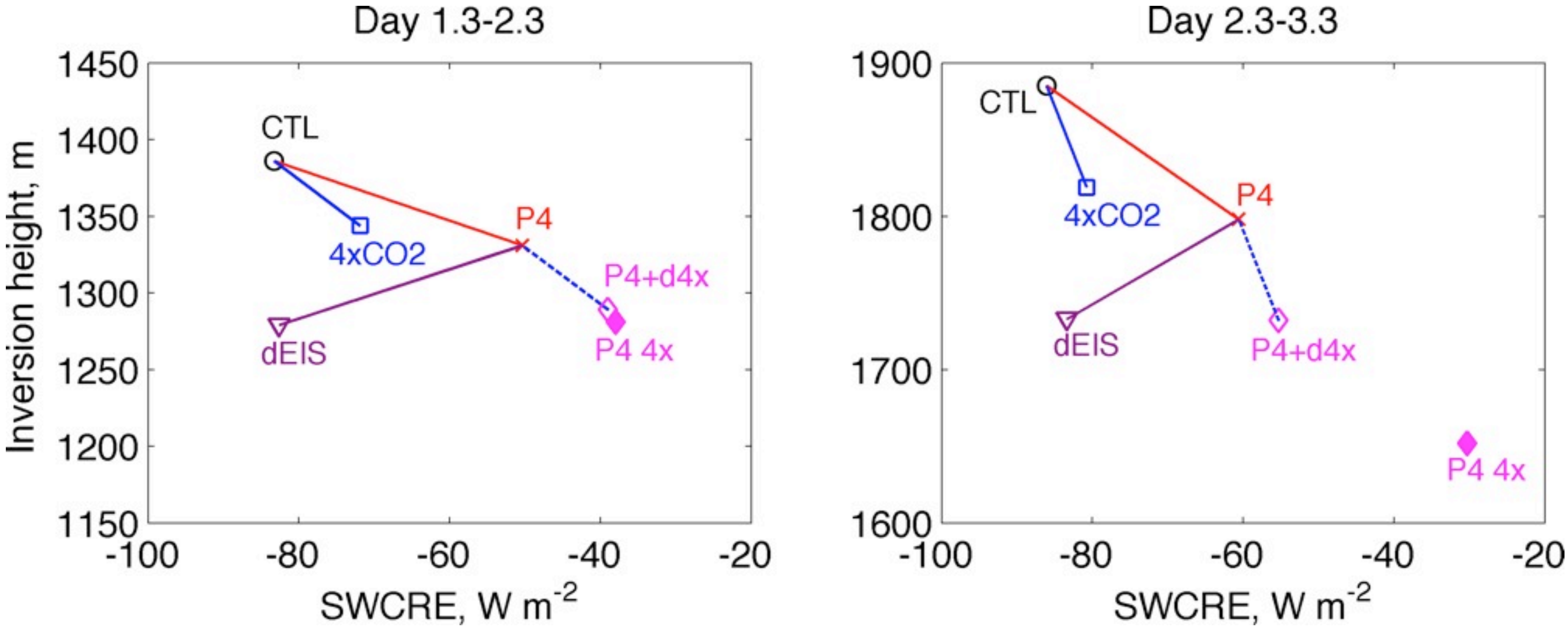
# Driving factors in cloud changes



- Full cloud cover breaks down in P4 run, especially during daytime. Moreso in P4 4x.
- Stronger decoupling in P4 run leads to drier cloud layer, thinner cloud.
- More emissive free troposphere leads to weaker BL-integrated radiative cooling in P4, 4xCO2, dEIS → weaker BL turbulence, less entrainment, thinner cloud (for 1st night).
- Cloud changes are weaker on second night, despite persistent difference in rad cooling. In CGILS, cloud response was weaker when all runs were decoupled -- something similar might be at work here.



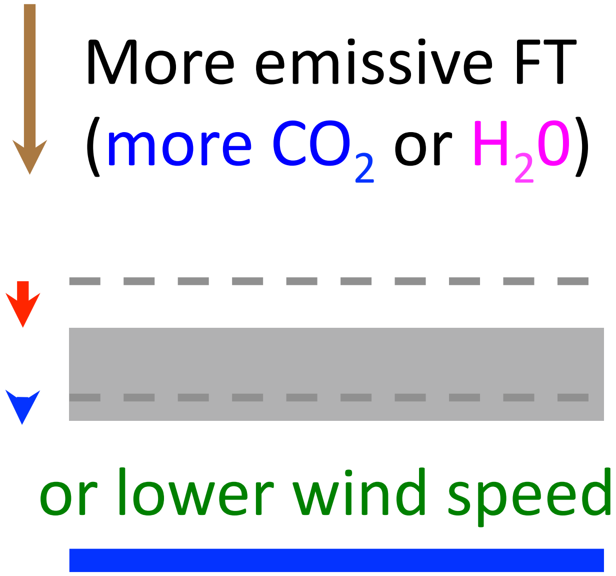
# Cloud changes w/CGILS comparison



- Results are qualitatively consistent with those from CGILS. The surprises are in:
  - the strength of the cloud response in P4 (larger than expected),
  - that changes in radiative cooling have stronger impact on BL height than subsidence changes (e.g., 4xCO2).
  - Similar increases in stability (dEIS) had weaker effect on ΔSWCRE in CGILS.
- Combined effects of P4 and 4xCO2 changes predict P4 4x results on first full day. Linearity assumption not as good next day when P4 4x has much smaller cloud cover.
- In a warmer climate, the BL might decouple more readily through deepening-decoupling mechanism of Bretherton & Wyant (1997).

# Mechanisms of Sc Cloud Response

**Turbulence driving**

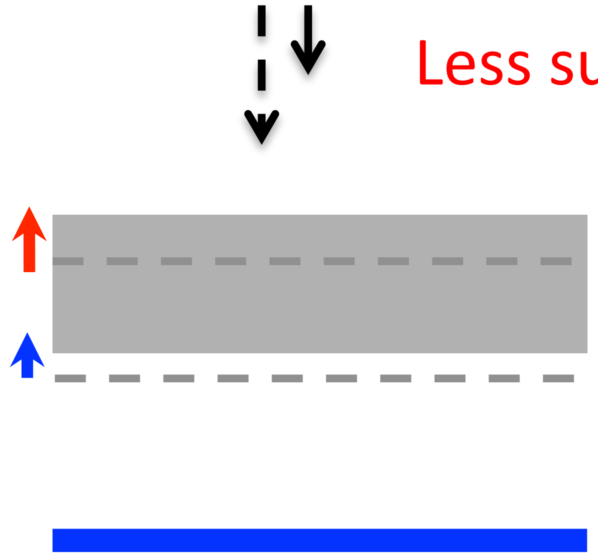


More emissive FT (more $CO_2$ or $H_20$)

or lower wind speed

Less turbulence production by top cooling or sfc flux. Less entrainment. Sc lowers, thins.

**Dynamic**

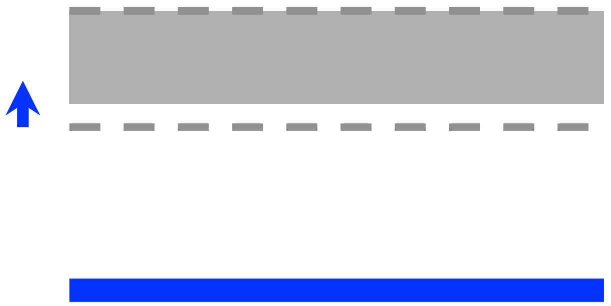


Less subsidence

Sc top rises. More entrainment lifts cloud base. Sc may thicken (S12).

**Moisture gradient**

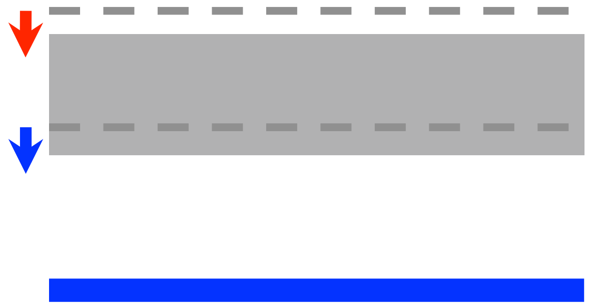
Drier RH or warmer SST



Larger surface – FT moisture difference allows thinner cloud to sustain same entrainment. Sc thins.

**Inversion strength**

FT warms more than SST



Stronger inversion reduces entrainment. Sc top and base lower. Sc may thicken (S11).

- Changes from CTL → P4 and CTL → 4xCO2 are similar in turbulence driving, subsidence and inversion strength.
- Suggests that increased moisture gradient is responsible for larger cloud response in P4 simulation.

# Conclusions

- Preliminary exploration of climate sensitivity of marine low cloud transitions indicates positive low cloud feedbacks for the conditions studied here.
- Warming and direct effect of $CO_2$ act to thin cloud, consistent with results seen in CGILS.
- Stability increases offset cloud thinning, though expected EIS changes in subtropics are smaller than simulated here (0.5-1 K).

# Future Plans

- These transition simulations don't actually simulate the full breakup of inversion cloud.
- We are constructing a six-day Lagrangian transition case based on the median trajectory of Sandu, Stevens & Pincus (2010).
- We will explore effects of warming, CO2, stability and subsidence changes both separately and together, as in Bretherton et al (2012).
- Simulate case in both LES and single-column models. Will they agree better for perturbations to climate than they do for aerosols?