Are subtropical stratocumulus to cumulus transitions driven by dynamics or microphysics?

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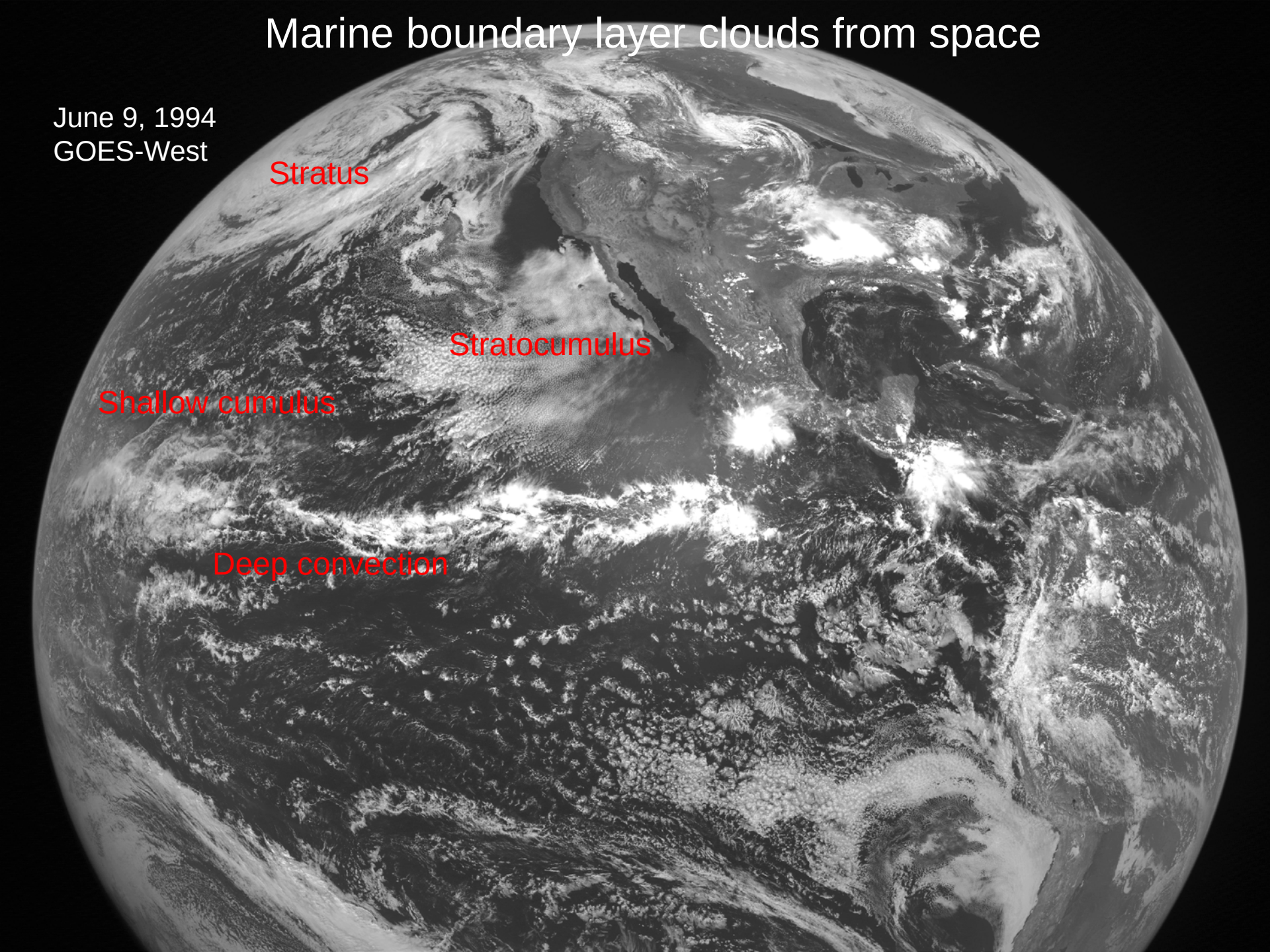
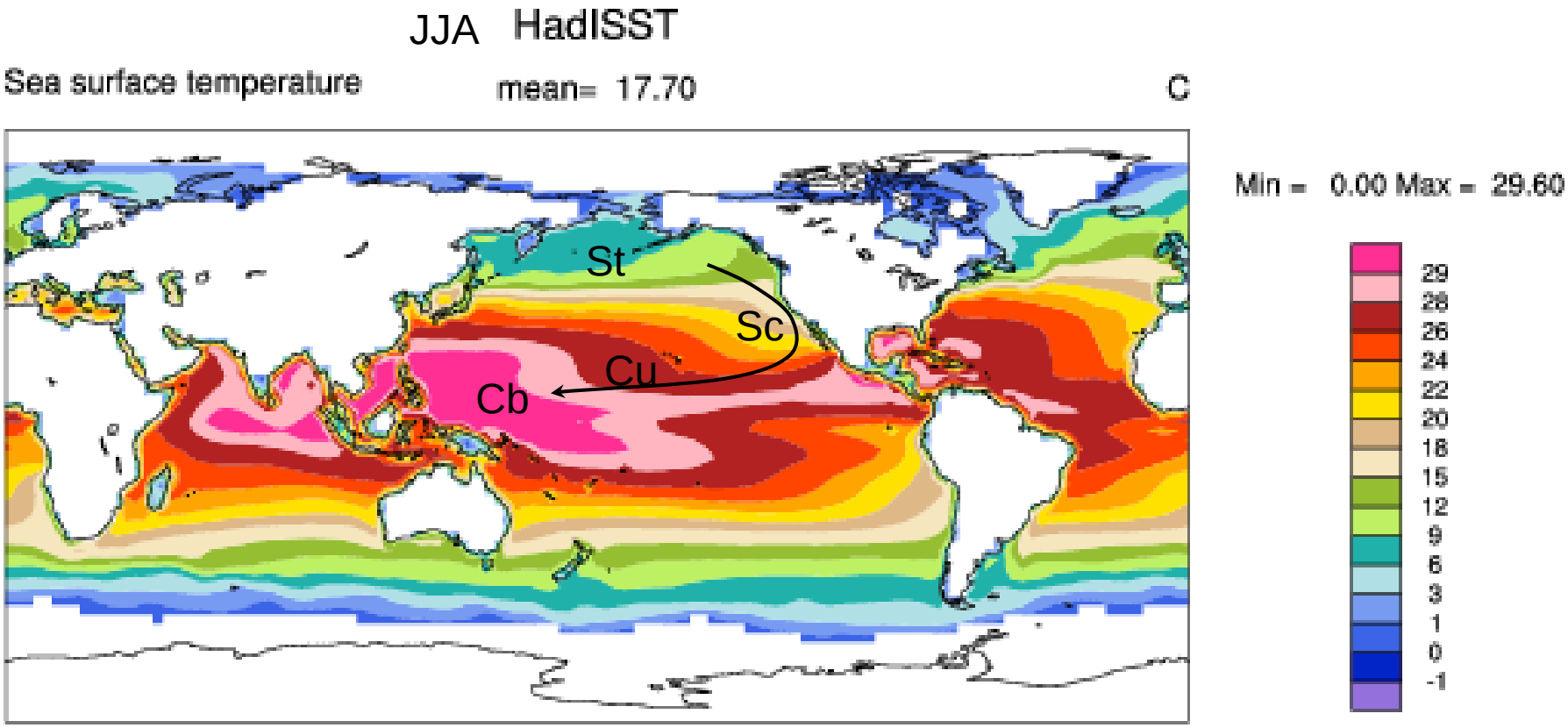
Thanks: Rob Wood, Peter Blossey, many colleagues and students

Marine boundary layer clouds from space

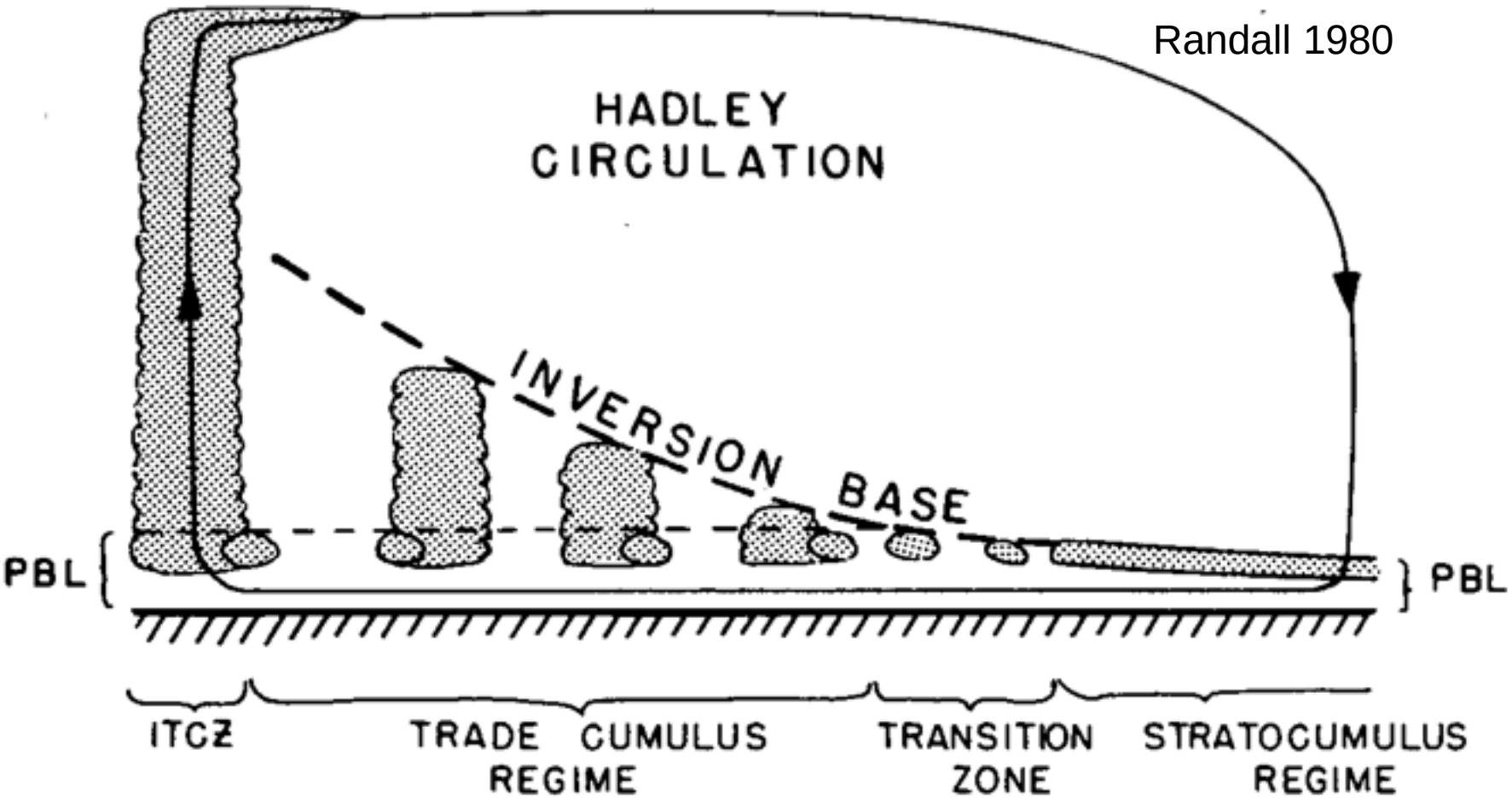


Low cloud regimes and SST

- Transition from Sc - shallow Cu - deep Cu as temperature of sea-surface rises compared to that of mid-troposphere.



1980 view of the Sc-Cu transition

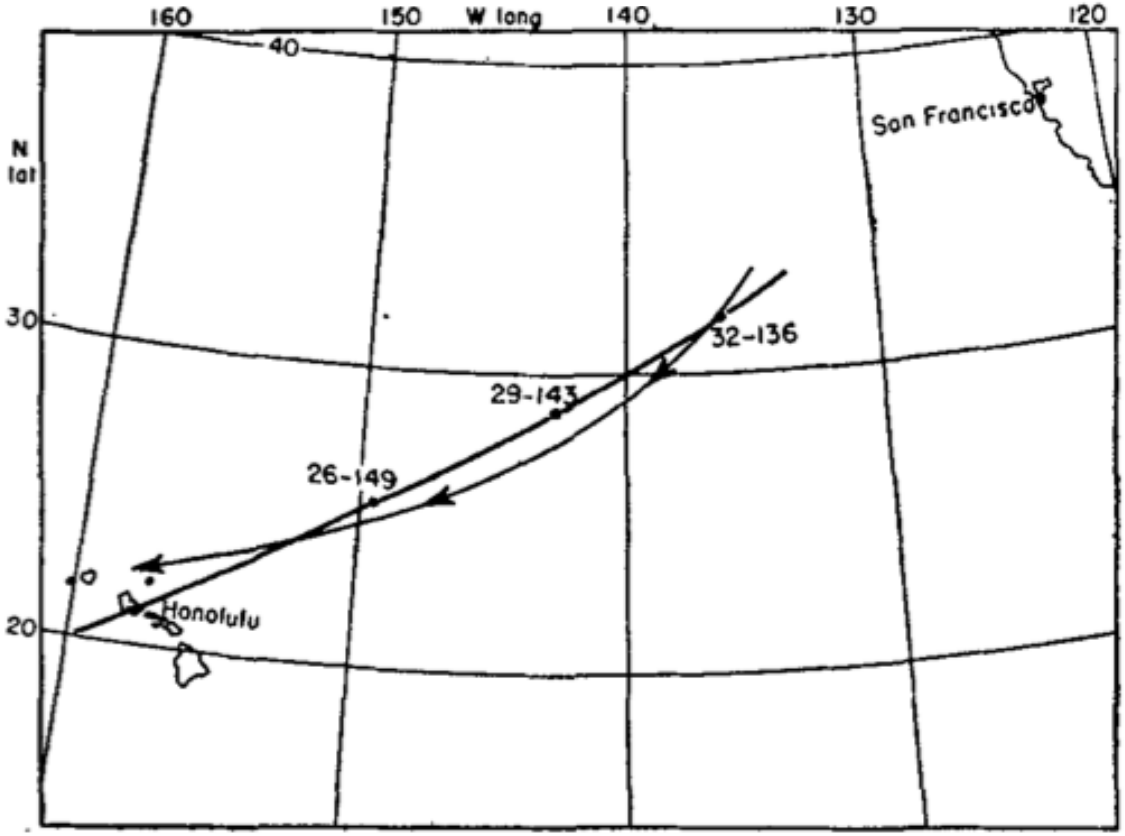


Why do the Sc break up in the transition zone?

The north-east trade of the Pacific Ocean

By H. RIEHL, T. C. YEH, J. S. MALKUS* and N. E. LA SEUR
University of Chicago

(Manuscript received 26 October 1950, in revised form 7 May 1951)



Courtesy of WWII:
3 weatherships
2/day sondes
Pibals to 3 km
Hourly sfc obs

Figure 1. Location of weather ships July-October 1945, and mean surface air trajectory for period.

Riehl: Entrainment of air must deepen the inversion

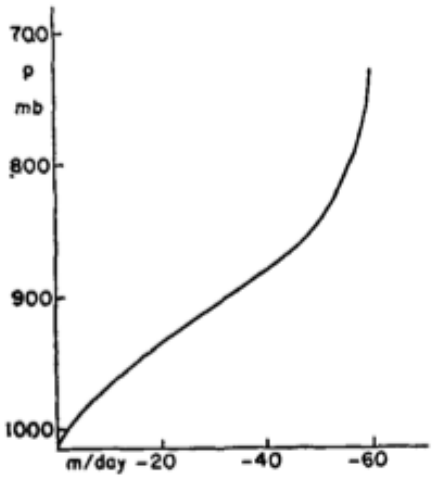


Figure 7. Vertical distribution of vertical motion (m day^{-1}).

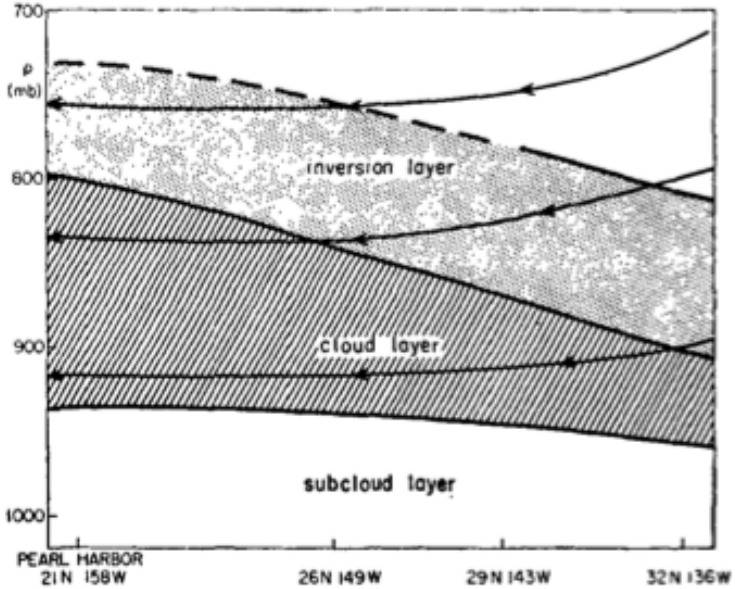


Figure 8. Illustrating the four layers of the trade-wind zone in relation to sample air trajectories.

The foregoing (*cf.* also Riehl and Yeh 1950) brings out clearly that it is necessary to re-examine previous descriptions of the rise of the trade inversion. *Whereas the inversion ascends downstream, individual columns descend, shrink vertically and spread horizontally* (*Fig.* 8). *Trajectories cross both inversion top and base. Large masses of air, located above the inversion at* 32°*N.*, 136°*W., have become a part of the cloud layer when they reach Honolulu.* If we consider the previous history of the air passing the Hawaiian islands, we can distinguish the following divisions (Fig. 9) :

Stratocumulus-capped mixed layer from DYCOMS-II

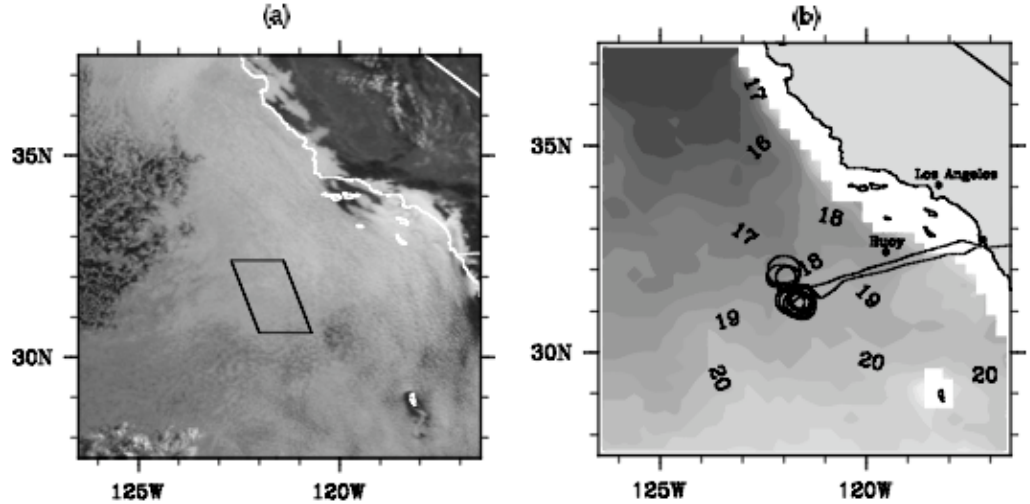
'Well-mixed' : Moist-conserved variables

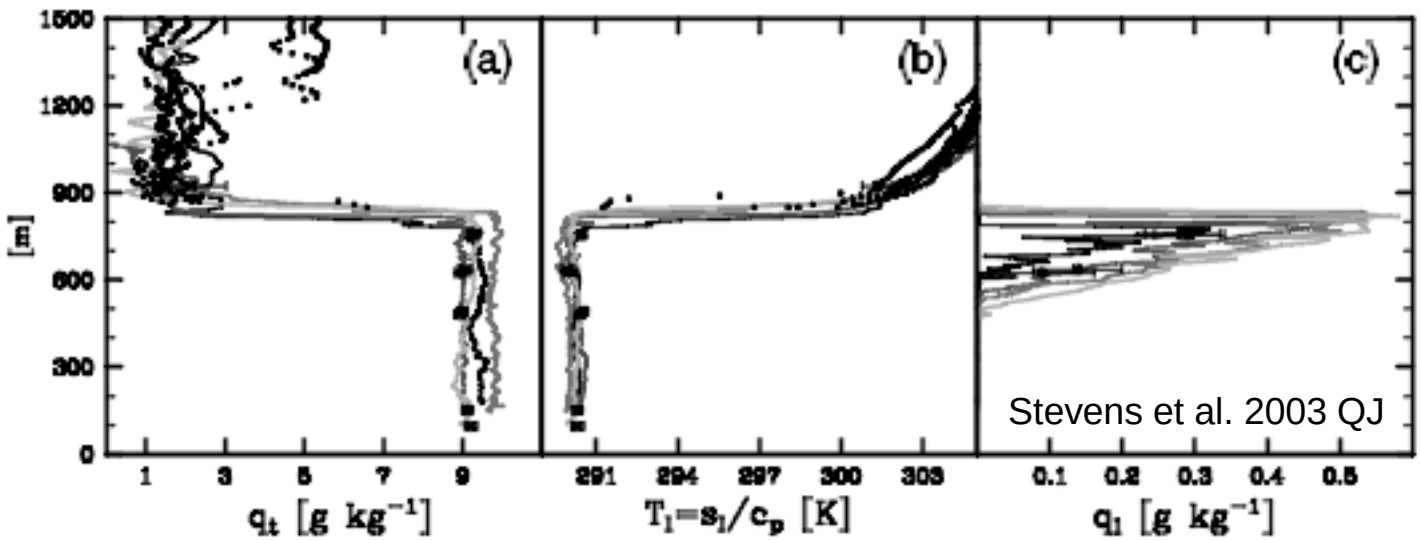
$s_l = c_pT + gz - Lq_l$,

$q_t = q_v + q_l$

$h = c_pT + gz + Lq_t$

are nearly uniform with height within the MBL.



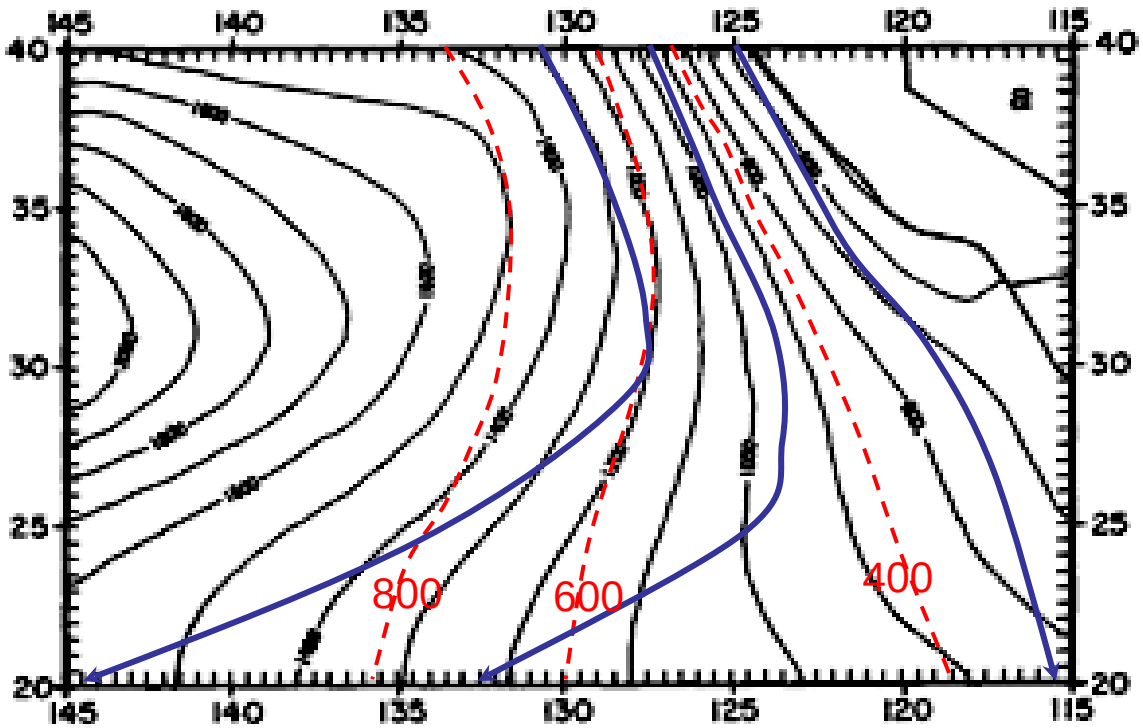


q_l increases linearly with z above cloud base

Figure 1. Cloud-layer state as observed during RF01: (a) total-water specific humidity q_t, (b) liquid-water static energy temperature s_l/c_p, and (c) liquid-water specific humidity q_l. Lines are from soundings, darker indicating earlier, filled circles and bars denote level-leg means and standard deviations, and dots denote dropsonde data from the above-cloud portion of the descent.

Issue: Mixed-layer models don't dissipate Sc downwind

MLM run with July-mean SST and atmospheric conditions



Wakefield and Schubert (1981)

z_i

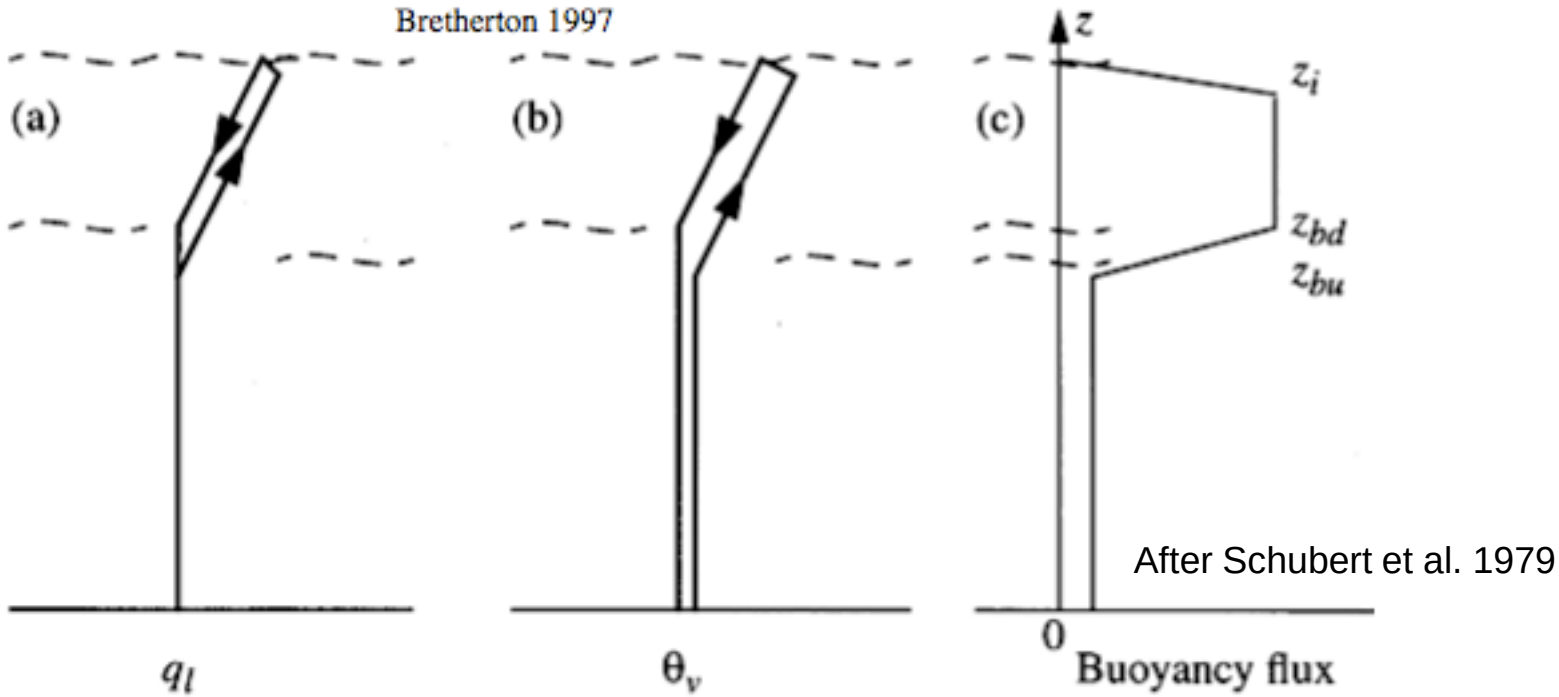
cloud thickness

July-mean trajectory

Sc thickens downstream since inversion rises faster than cloud base

Transition to Cu must result from breakdown of MLM

Parcel circuits in a Sc-capped mixed layer



- Upward moisture flux implies discontinuous increase in liquid water and buoyancy fluxes at cloud base ➔ turbulence driven from cloud, unlike dry CBL.
- Convective velocity $w_* \sim 1$ m s^{-1}:

$$w_*^3 = 2.5\int_0^{z_i} \overline{w'b'}dz$$

ASTEX (June 1992)

- Azores, just upstream from typical Sc-Cu transition
- Decoupled boundary layers were the norm
- Lagrangian multiaircraft, multiship sampling strategy
- Suggested decoupling might be a key part of transition

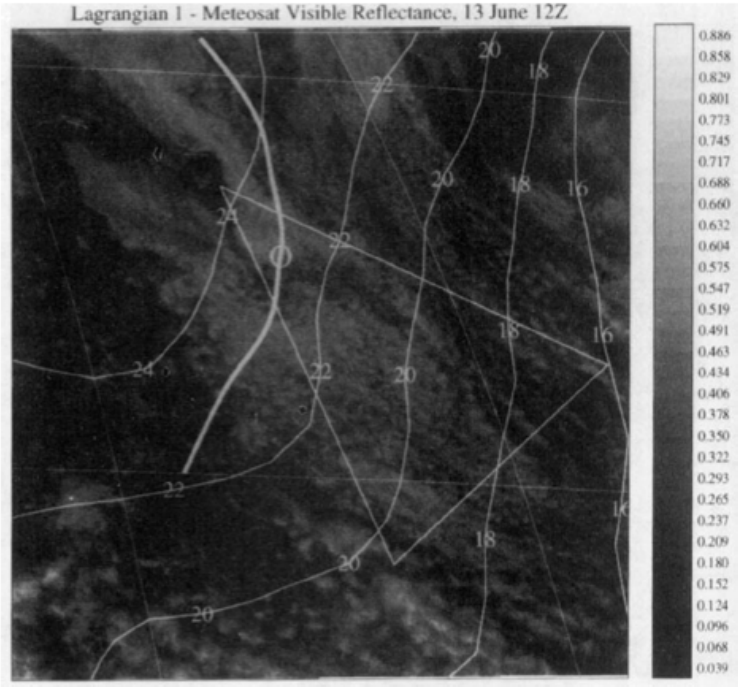


FIG. 6. Meteosat visible satellite imagery at 1200 UTC on 13 June, midway through L1. Contours indicate the ECMWF-analyzed 1000-mb geopotential height field (m); the thick gray line shows the best-guess trajectory. An O denotes the approximate air column position at the time of the image.

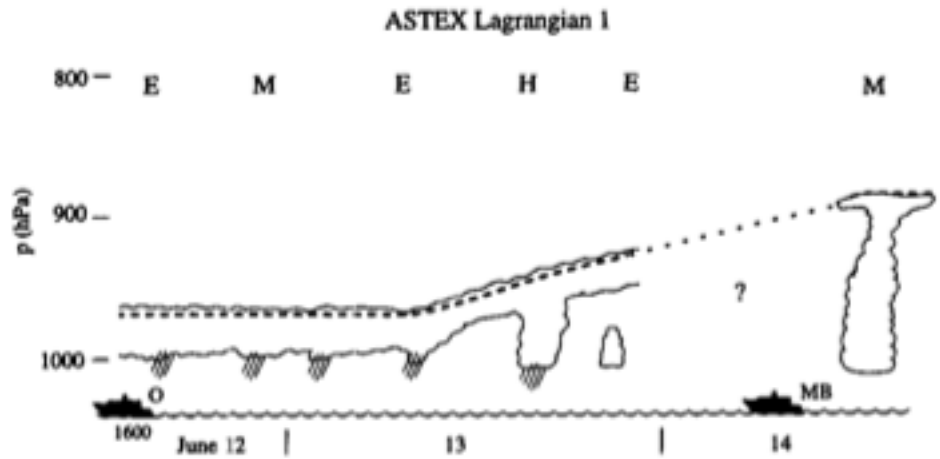
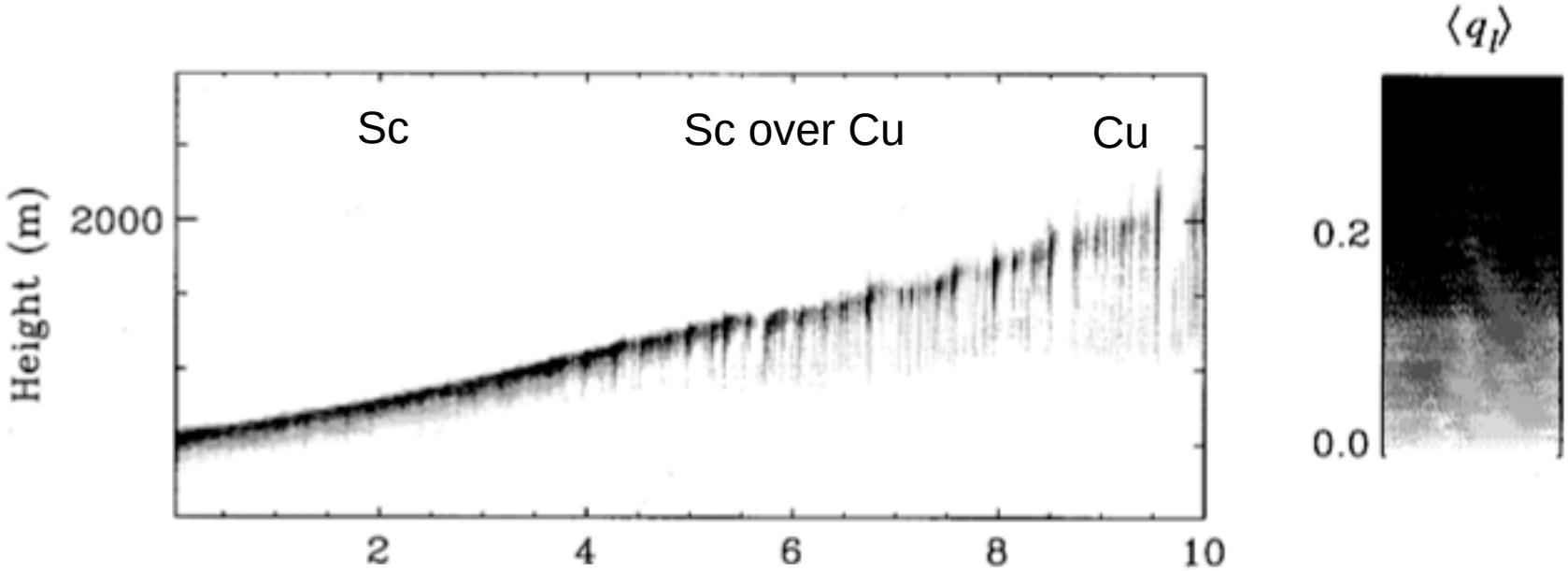


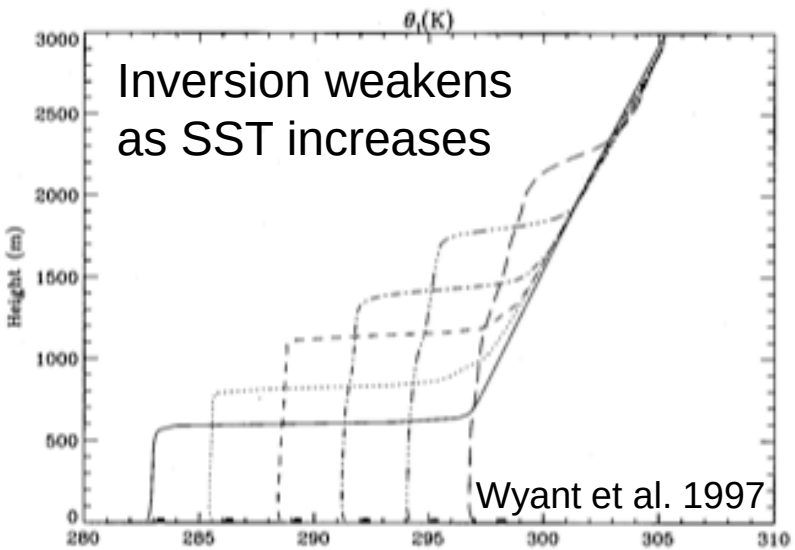
FIG. 1. Schematic of MBL evolution and platform deployment in L1. The air column was followed starting at the R/V *Oceanus* (O at left) until it passed near to the R/V *Malcolm Baldridge* (MB at right) and moved out of aircraft range. Symbols E (Electra), M (C130), and H (C131a) are placed at the midpoint time of each flight. The dashed line traces the approximate inversion pressure, and cloud is stippled. The "?" indicates a 14-hour data gap.

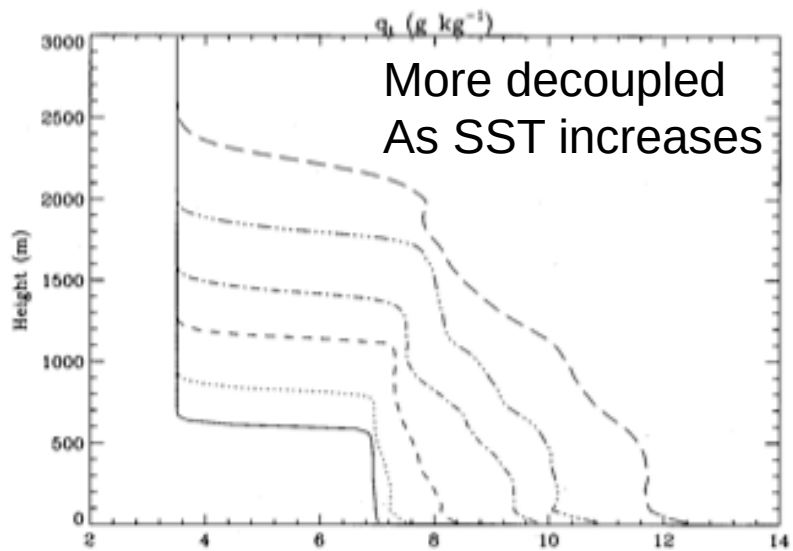
But how does decoupling lead to Sc breakup?

2D Lagrangian cloud resolving model of Sc-Cu transition

8 days, SST = 285 + 1.5 K d^{-1}, 4x3 km, ⊗x = 50 m, ⊗z = 25 m, no diurnal cycle







Sc breakup, decoupling and penetrative entrainment

DIDECUPE = Deepening-Induced Decoupling and Cumulus Penetrative Entrainment (Wyant et al. 1997)

1. Deeper Sc-capped boundary layers with weaker inversions over warmer water favor persistent decoupling.
2. Decoupling leads to development of a Cu layer, which takes over the entrainment, mixing in enough dry air to evaporate the Sc below the inversion.

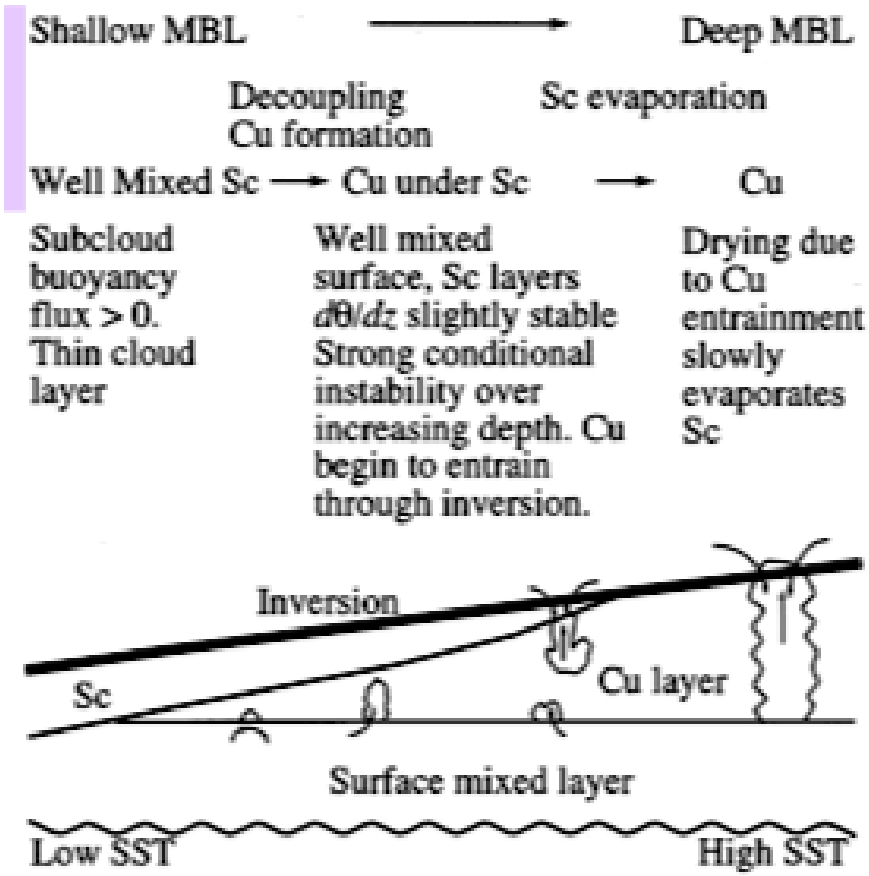


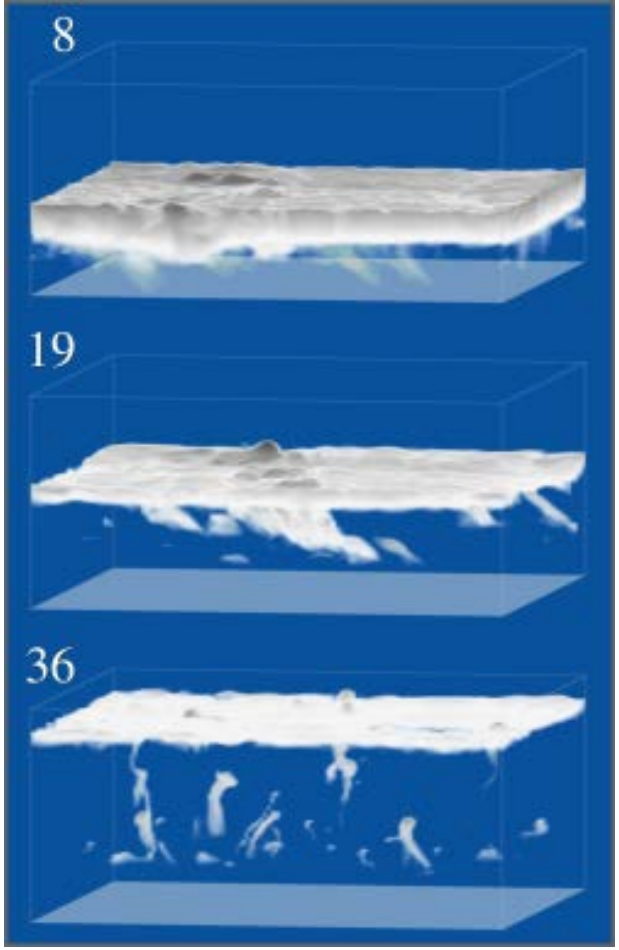
FIG. 10. A conceptual diagram of the STCT.

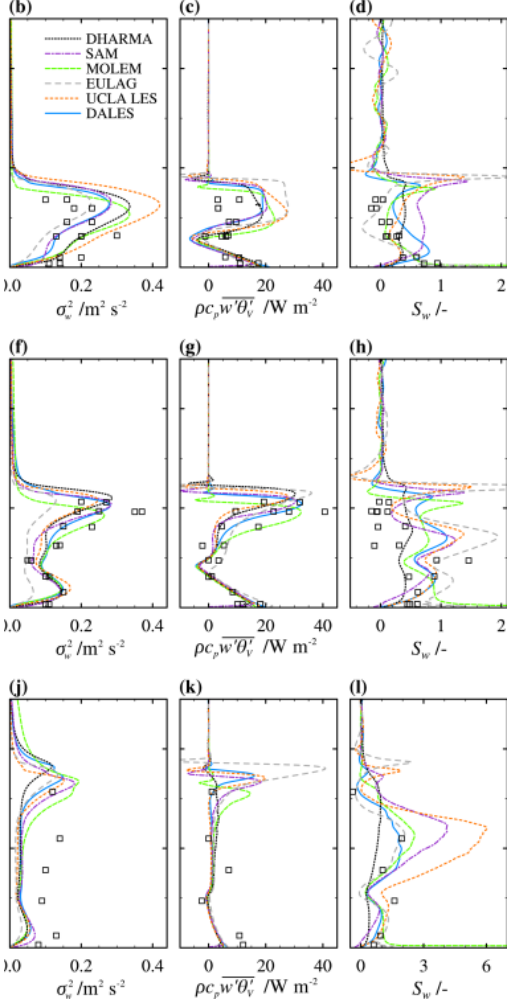
(Wyant et al. 1997)

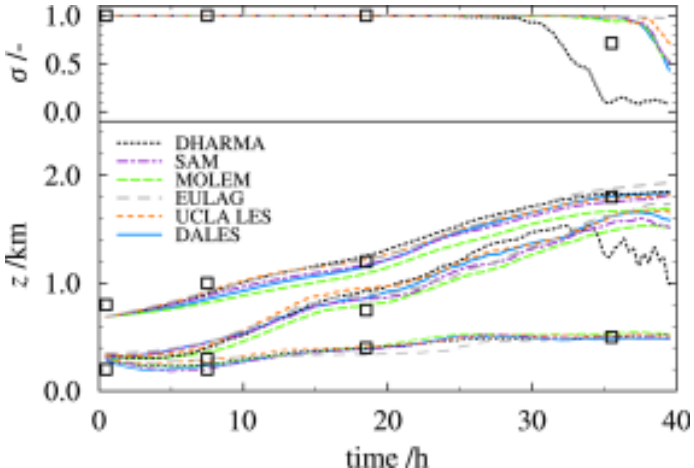
Can LES quantitatively simulate the Sc-Cu transition?

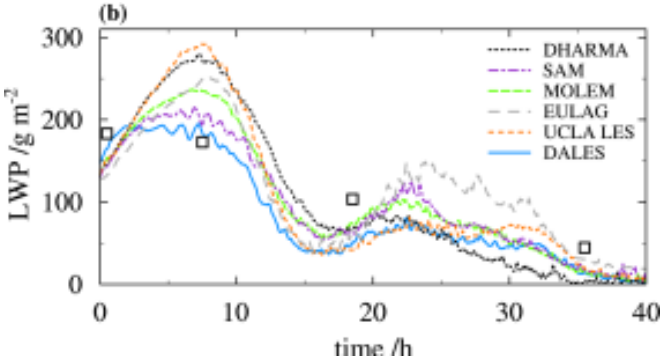
Dussen et al. 2013

- ASTEX Lagr. 1
- 6 LES models
- Cloud-layer dz = 5 m
- $L_x = L_y = 4.45$ km
- $N_c = 100$ cm^{-3}
- Nice agreement w obs w/o aerosol variability









The Seasonal Cycle of Low Stratiform Clouds

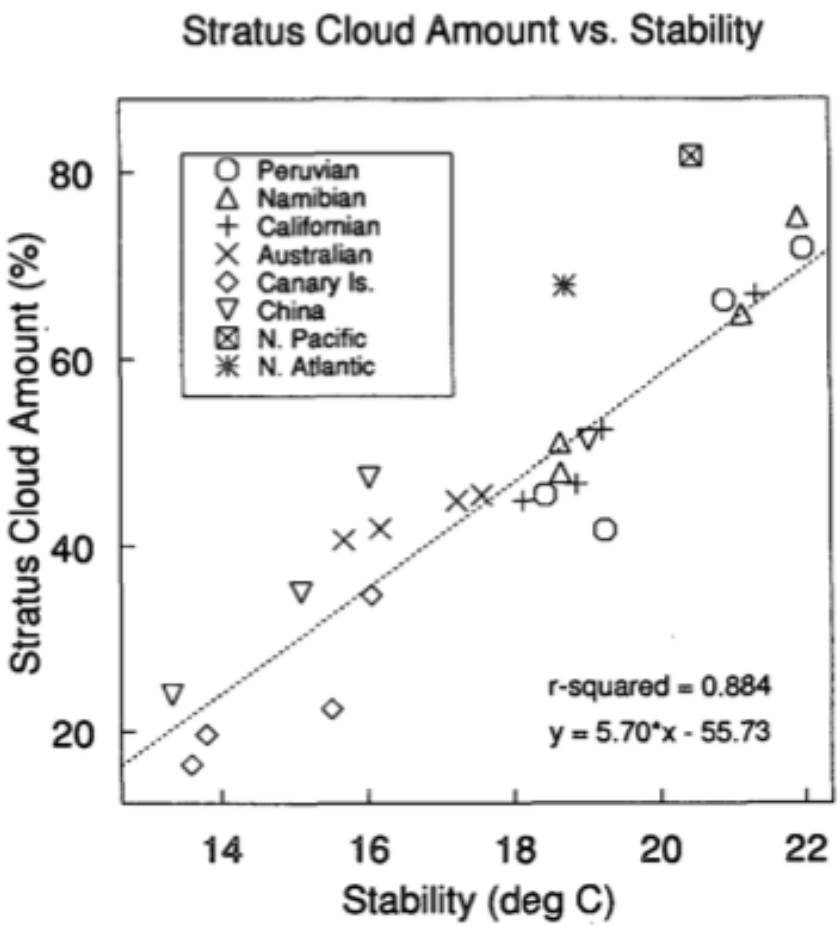
STEPHEN A. KLEIN AND DENNIS L. HARTMANN

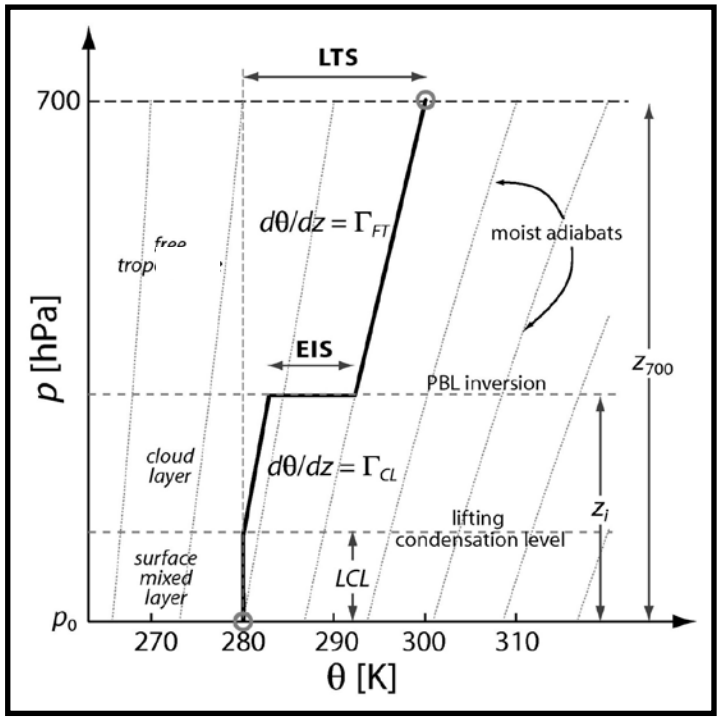
1993, J. Climate

The cloudiness transition in all five subtropical Sc regions is similarly related to lower tropospheric stability ➔ NEP representative of other Sc-Cu transitions

$$LTS = \theta_{700} - \theta_{1000}$$

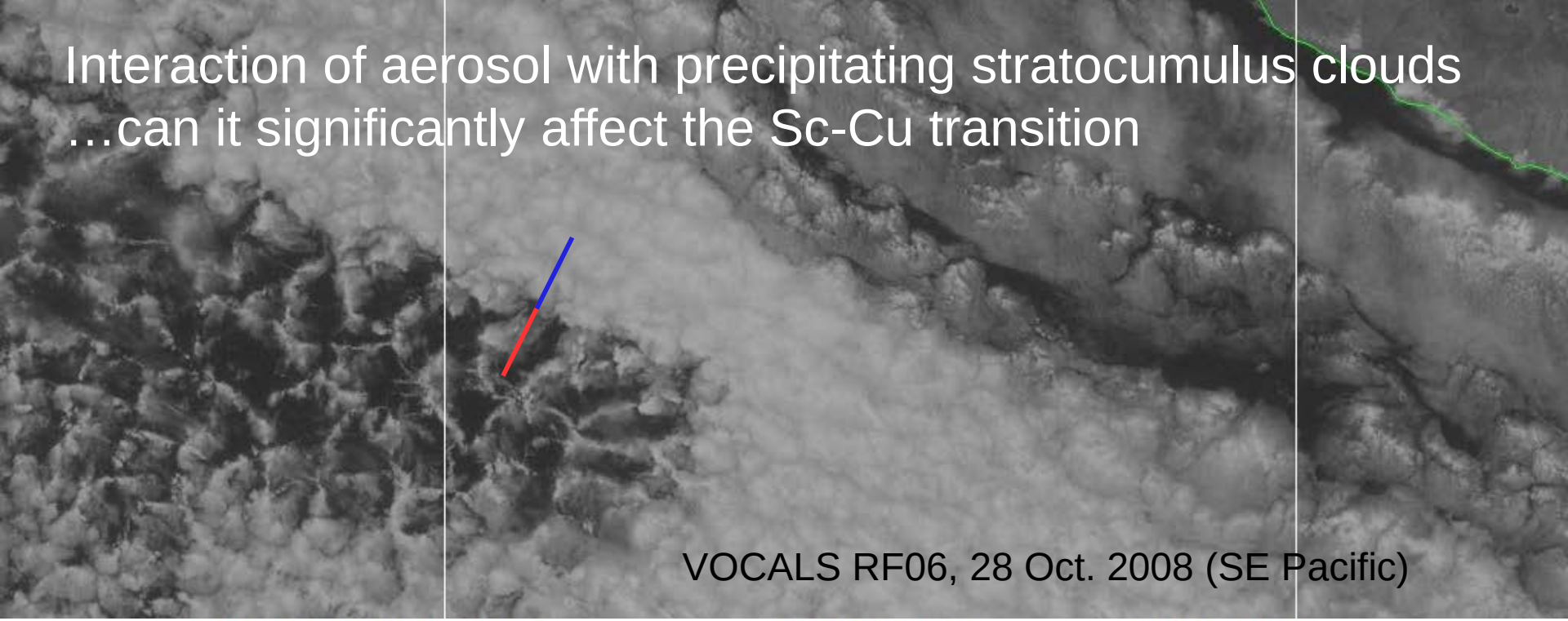
$$EIS = LTS - \Gamma_{850}^{ma}(z_{700} - z_{LCL})$$

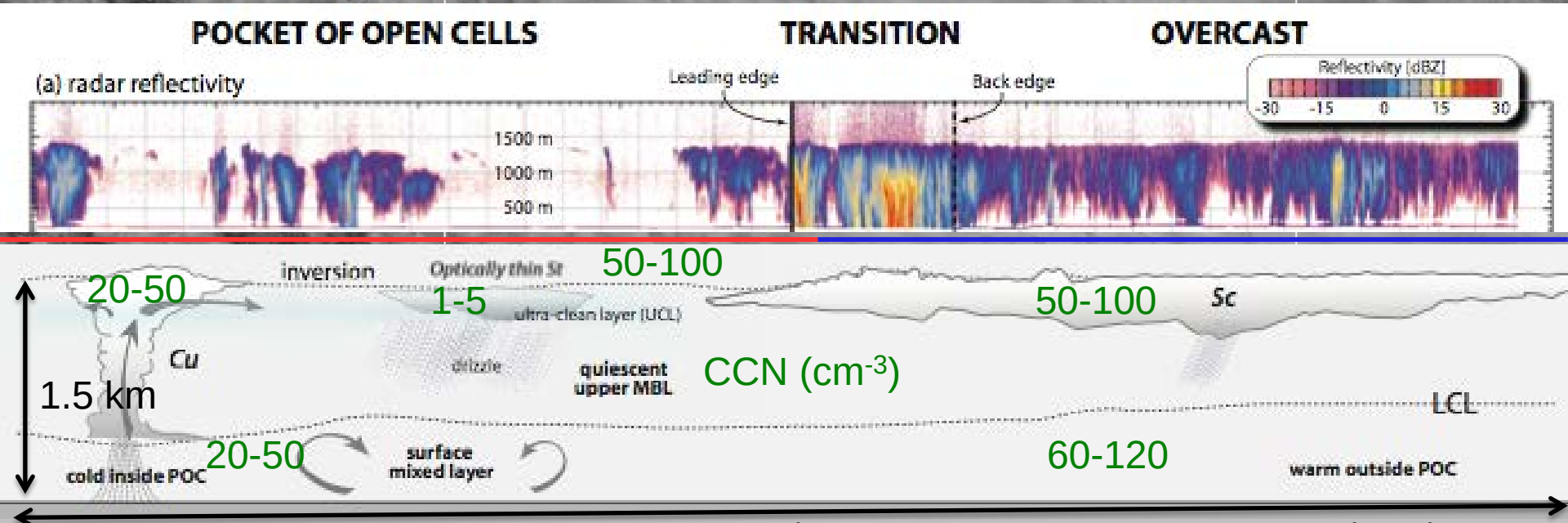




Wood and Bretherton (2006)

Interaction of aerosol with precipitating stratocumulus clouds …can it significantly affect the Sc-Cu transition





Wood et al. 2011

Aerosol effects on Sc-Cu transition

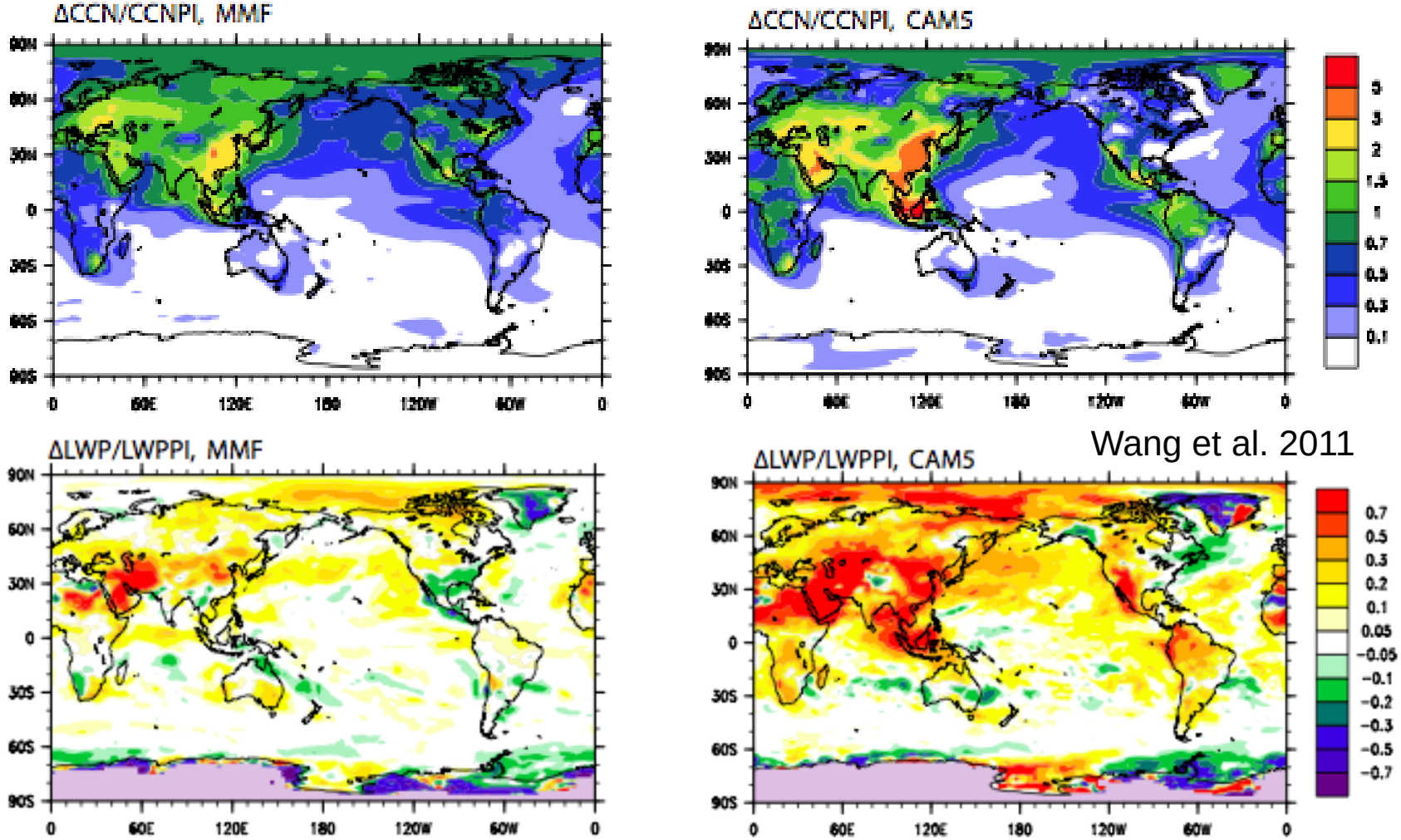
- LES sensitivity studies show that low aerosol favors a long-lasting transition to open cells with broken cloud; however, POCs are the exception not the rule (Wood et al. 2008; 2011).
- The same relation between LTS and cloud cover holds across Sc-Cu transitions, both SH and NH, despite aerosol differences (KH 1993; Sandu et al. 2011).
- My take: aerosol variations are a perturbation on the Sc-Cu transition, not the main driver, which is deepening-warming decoupling and erosion of the upper Sc layer.
- However, even modest anthropogenic aerosol effects on the Sc-Cu transition are relevant to anthropogenic aerosol indirect effects on climate change.

Hence reasonable climate models choose to differ

2000 – 1850 Aerosol Direct+Indirect Radiative Forcing ($ERF_{ari+aci}$)

MACM: -1.0 W m^{-2}

CAM5: -1.7 W m^{-2}

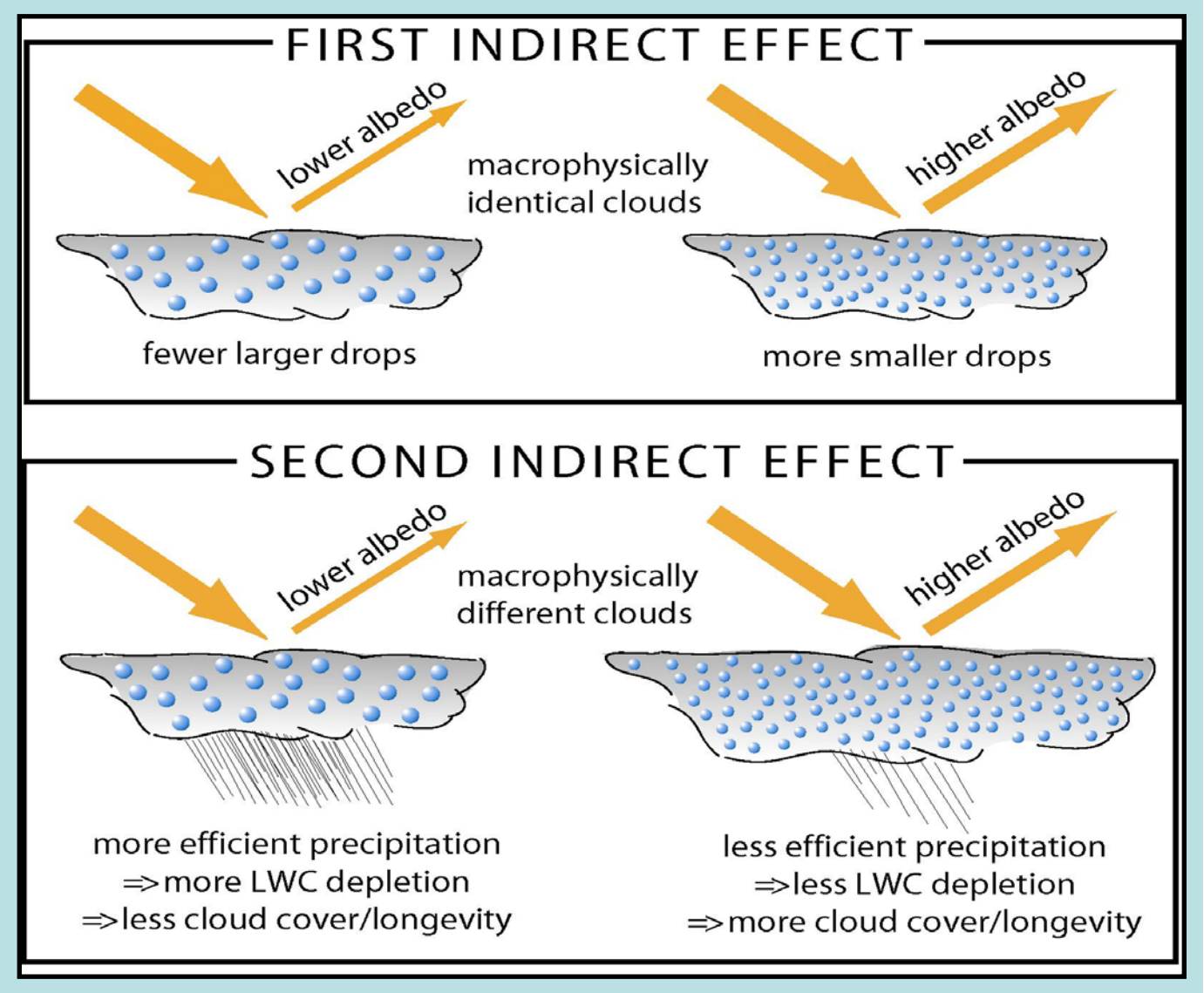


Wang et al. 2011

Same aerosol enhancement makes CAM5 clouds brighten more due to more liquid water

Getting ERF_{aer} to -0.5 W m^{-2} requires smaller ΔCCN/CCNPI or negative ΔLWP/LWPPI

Aerosol Impacts on (Liquid) Clouds



$A_{cld} = fn(LWP^{5/6}N^{1/3})$

Twomey effect

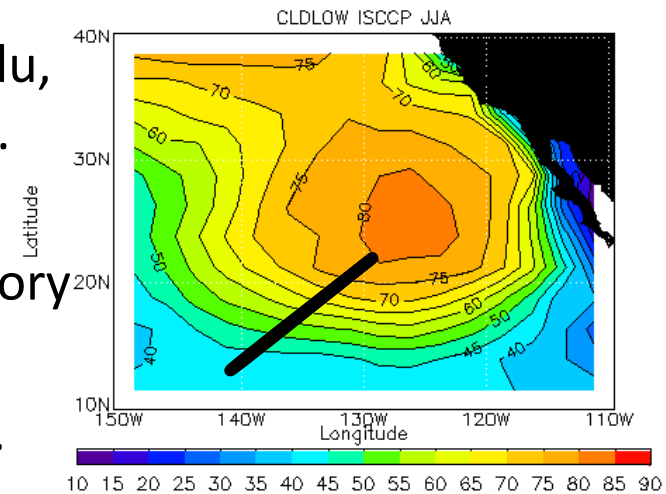
} ERF_{aci}

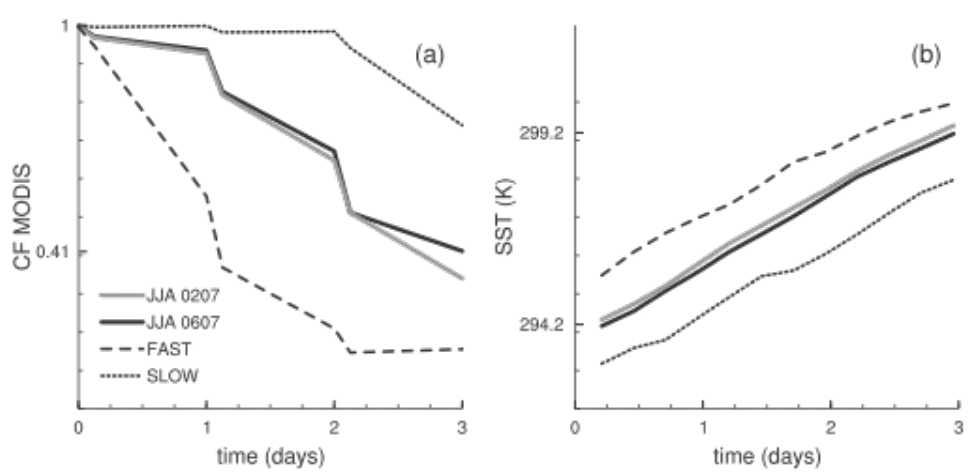
Implicit assumption:
- Smaller droplets➔
- Less rainout➔
- More cloud

Is this always true?
How important?

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.





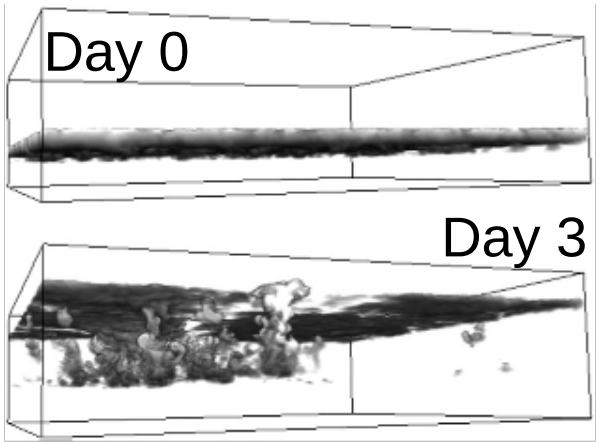


FIG. 3. An image of the cloud field simulated in the REF case, at (top) the beginning and (bottom) the end of the simulation.

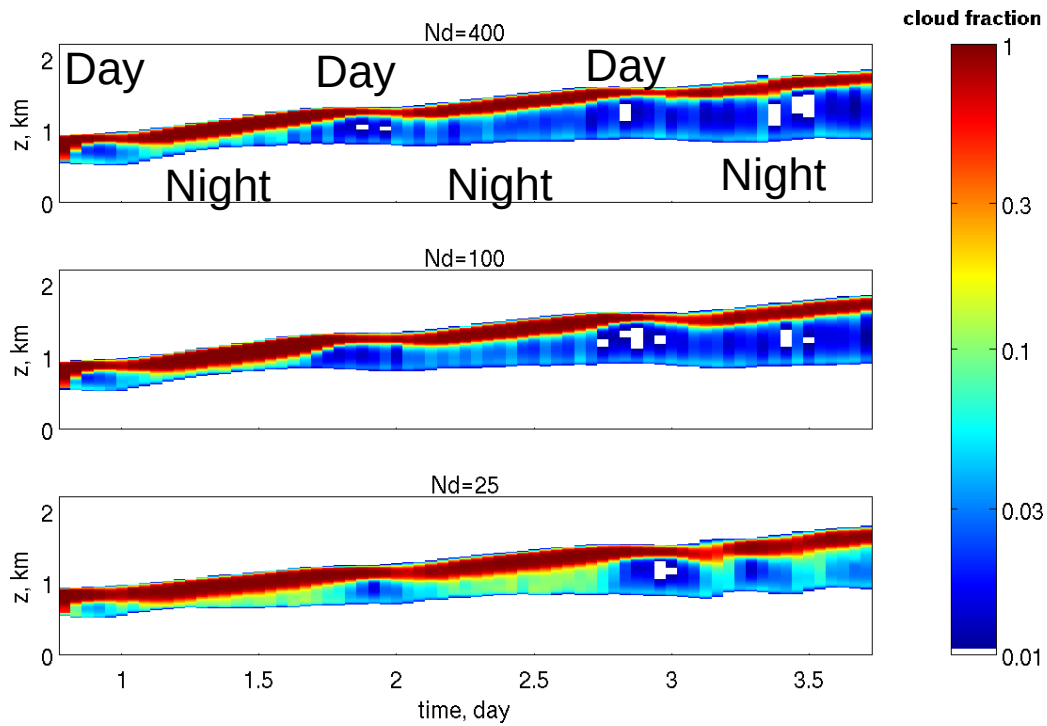
LES results (Blossey)

- System for Atmospheric Modeling, v. 6.8.
- L_x=L_y≈4.5km. Δx=Δy=35m, Δz=5m 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 σ_g=1.2. Includes diurnal cycle.

N_d = 400 cm^{-3}

N_d = 100 cm^{-3}

N_d = 25 cm^{-3}



SWCRE

-98 W m^{-2}

-76 W m^{-2}

-72 W m^{-2}

➔sub-Twomey

More CCN ➔ thinner cloud! (Ackerman et al. 2004, Bretherton et al. 2007)

Conclusions

- The Sc-Cu transition is mainly driven by decoupling/Cu formation well-correlated with lower tropospheric stability and does not require precipitation or aerosol changes.
- POCs are examples of how aerosol-cloud-precipitation feedbacks can locally promote a Sc-Cu transition.
- My take is that aerosol variability perturbs but doesn't control climatological Sc-Cu transitions in the subtropics (and midlat cold air outbreaks?)
- Even small aerosol effects on subtropical and/or midlat Sc-Cu transitions in regions of substantial anthropogenic aerosol enhancement could affect global RF_{aci}.