The subtropical stratocumulus to cumulus transition

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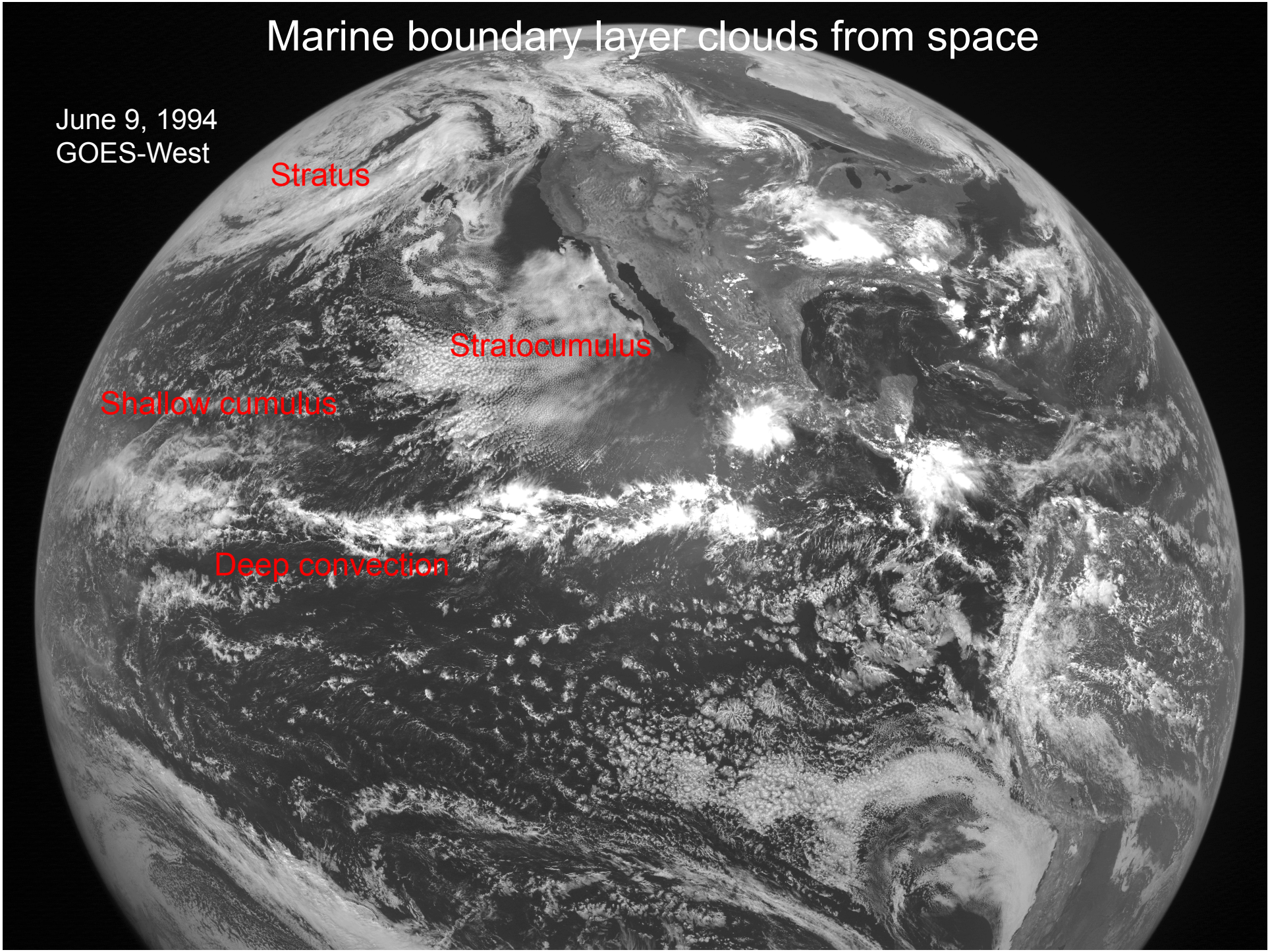
Thanks: Peter Blossey, Rob Wood, many colleagues and students

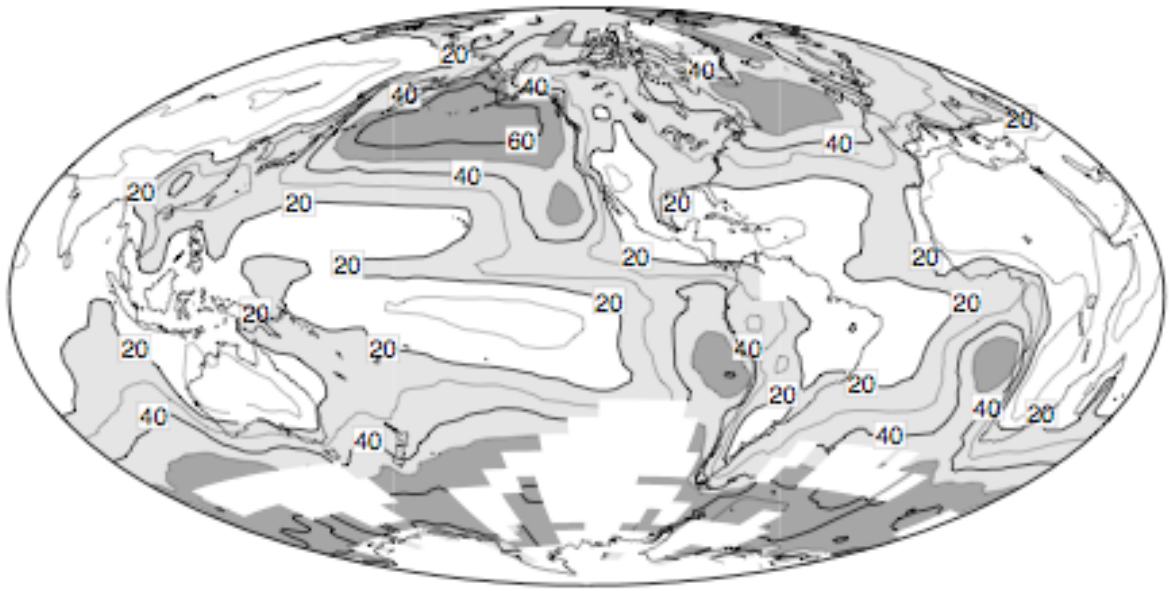
Outline

1. Brief global context
2. Historical development of Sc-Cu transition research…an interplay of concepts, observations and models
3. A modeling frontier: Cloud feedbacks in Sc-Cu transition

Marine boundary layer clouds from space

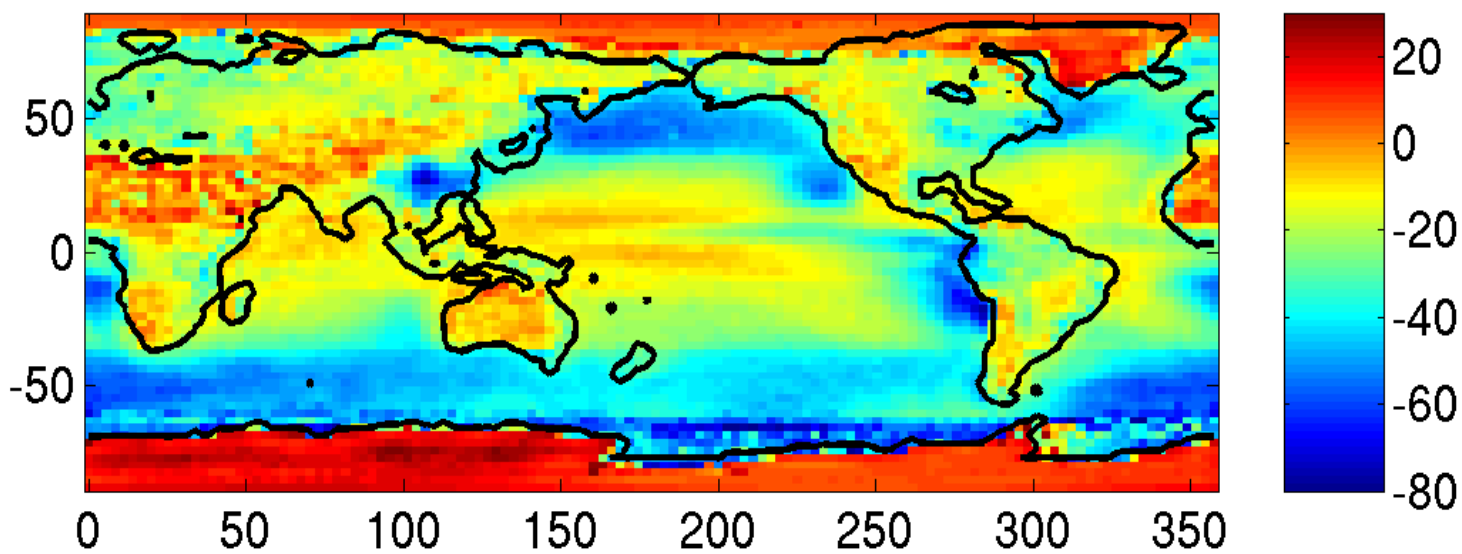


Annual Stratus Cloud Amount



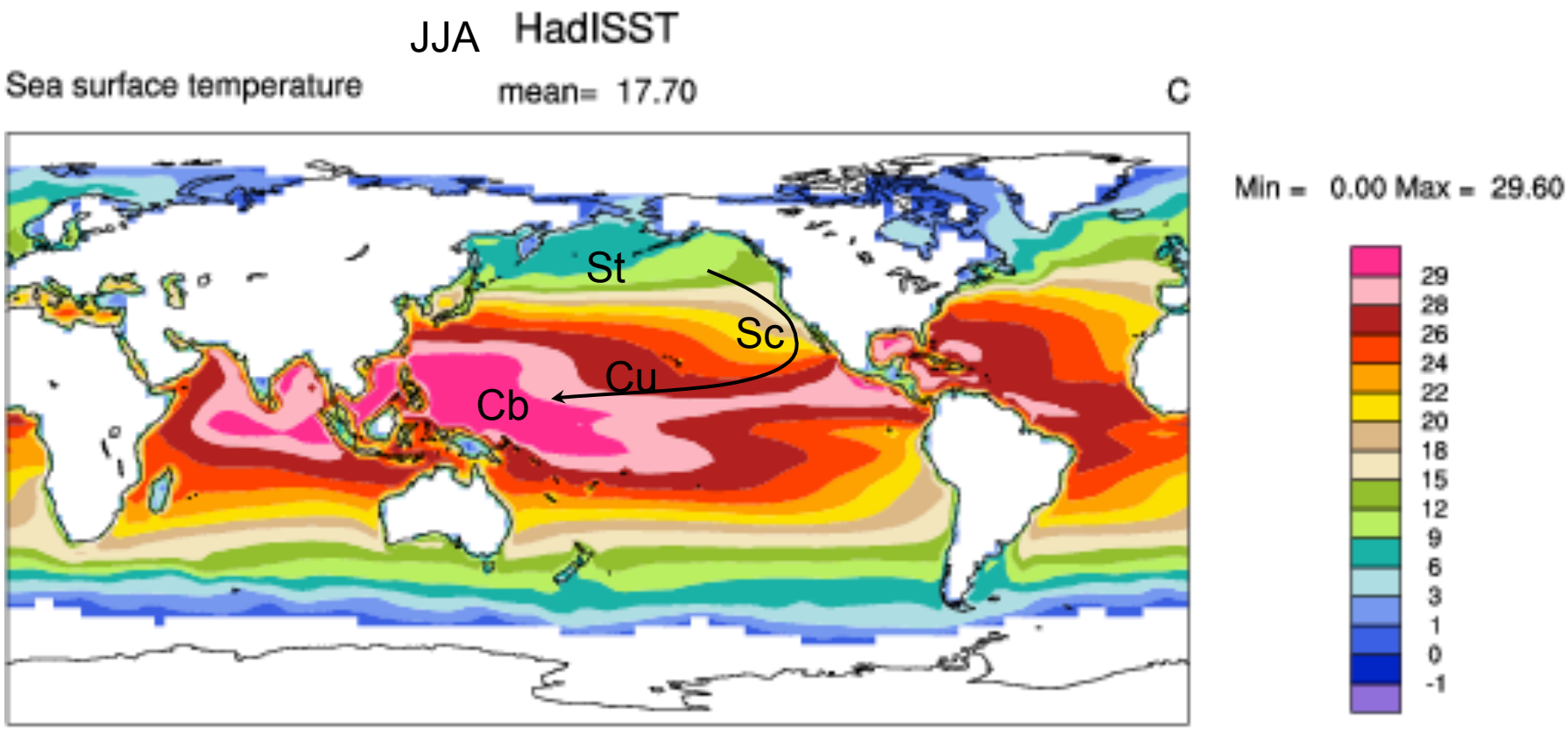
Klein and Hartmann (1993), from surface observations

ERBE Net Cloud Forcing, W/m^2



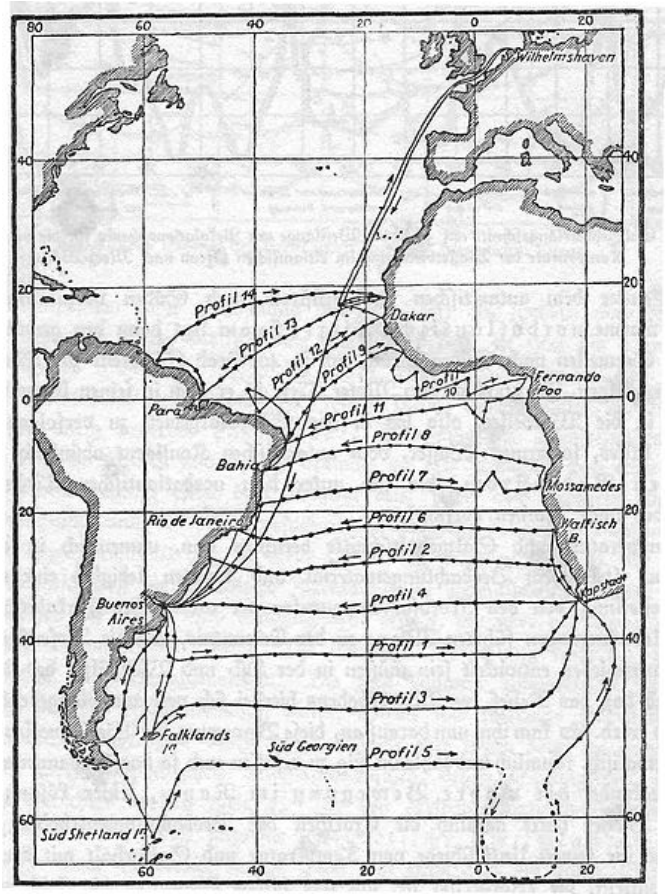
Low cloud regimes and SST

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



Meteor expedition (1925-7) and von Ficker (1936)

- Atlantic balloon/kite soundings: moist layer capped by sharp trade inversion
- Heat balance maintained mainly through the water vapor cycle.
- Latent heat in the form of water vapor is accumulated by the trades. The release of this latent heat through condensation be far removed from the site of accumulation.

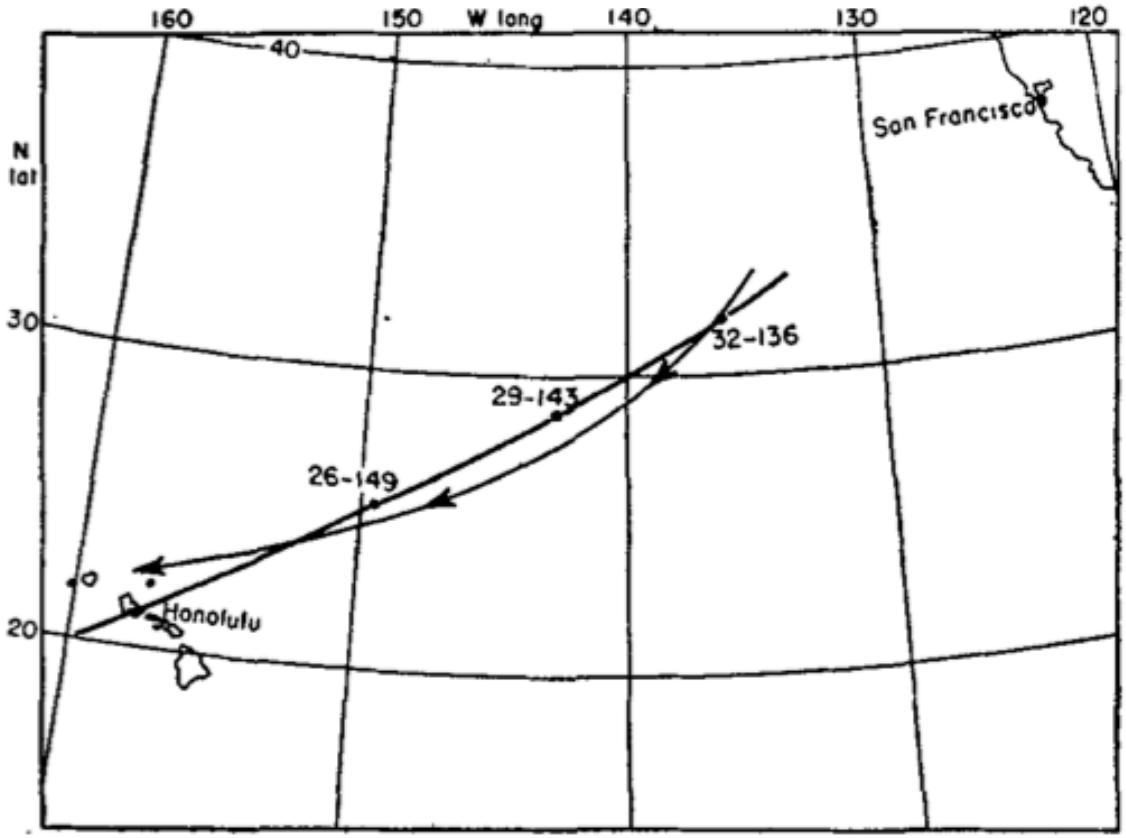


Implicitly, it was often assumed the trade inversion was a material surface separating the moist air mass below from the dry air above.

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

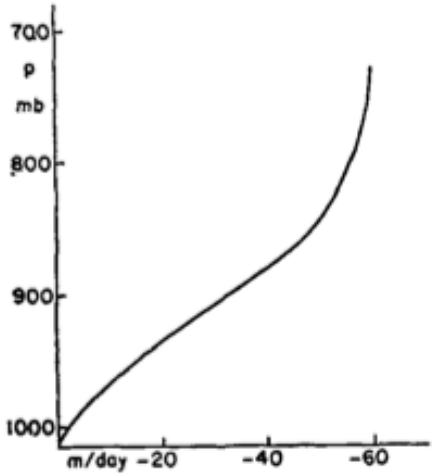


Figure 7. Vertical distribution of vertical motion (m day^{-1}).

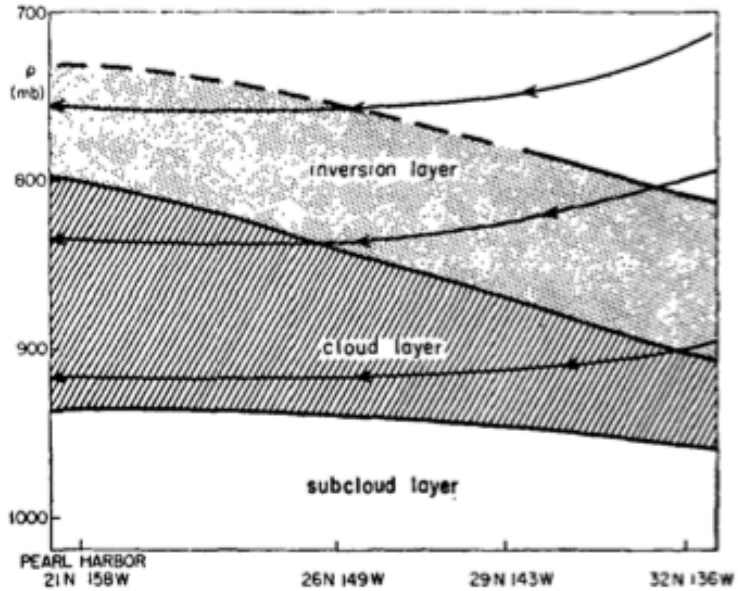


Figure 8. Illustrating the four layers of the trade-wind zone in relation to sample air trajectories.

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) :

Models of cloud-topped mixed layers under a strong inversion

By D. K. LILLY
National Center for Atmospheric Research, Boulder, Colorado

1968, QJRMS

In conditions of …subsidence the potential temperature of the lower troposphere may be substantially higher than that of the ocean surface….a temperature inversion must form somewhere. The turbulence …maintains a sharp…inversion, … radiation from the top of a cloud would exert a cooling effect on the mixed layer. In the present theory we …consider radiation off the cloud tops to be an essential element.

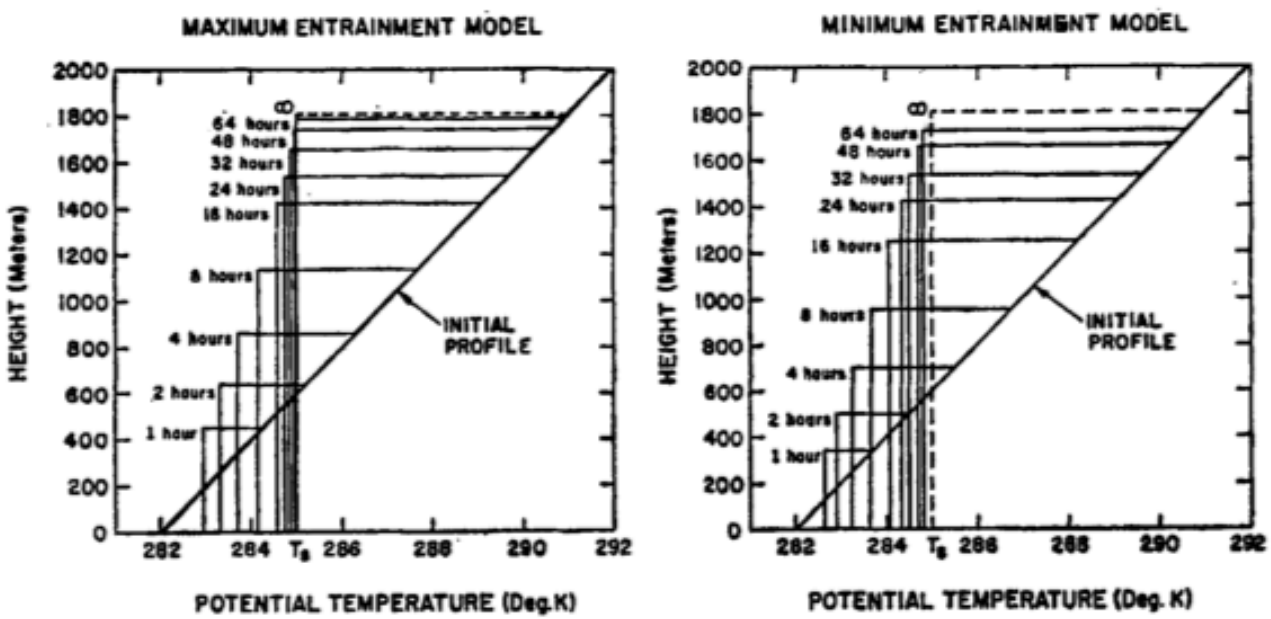


Figure 1. Time-dependent solutions of the dry cloud model for maximum and minimum entrainment hypotheses. The diagonal line is the initial stable sounding, while the successive step functions represent development and ascent of the mixed layer and inversion top. At infinite time both hypotheses lead to the same solution, for which the mixed layer potential temperature equals that of the surface and radiative cooling is balanced by entrainment heating.

Lilly's key realizations:

1. Turbulence mainly driven by cloud radiative cooling
2. This turbulence keeps the PBL well mixed
3. TKE budget makes entrainment adjust to balance this cooling

Stratocumulus-capped mixed layer from DYCOMS-II

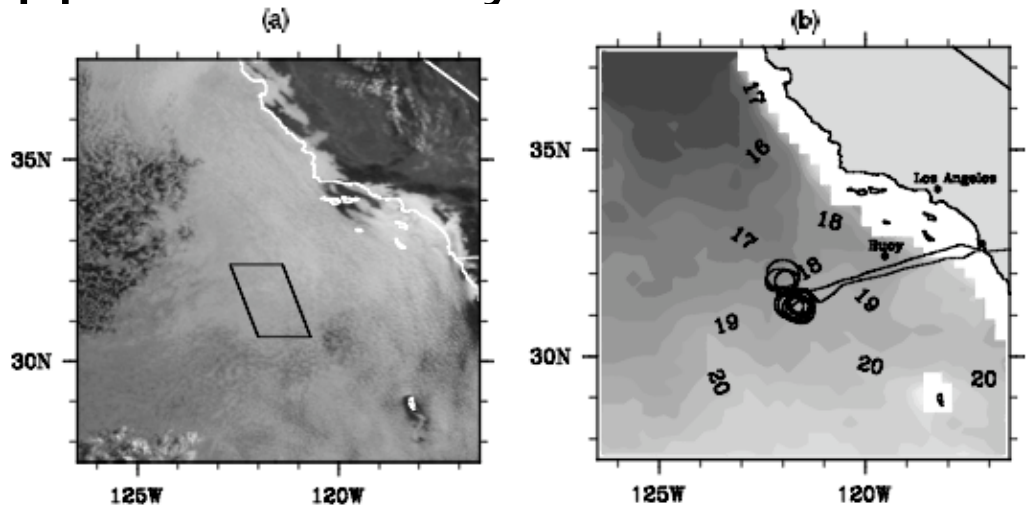
'Well-mixed' : Moist-conserved variables

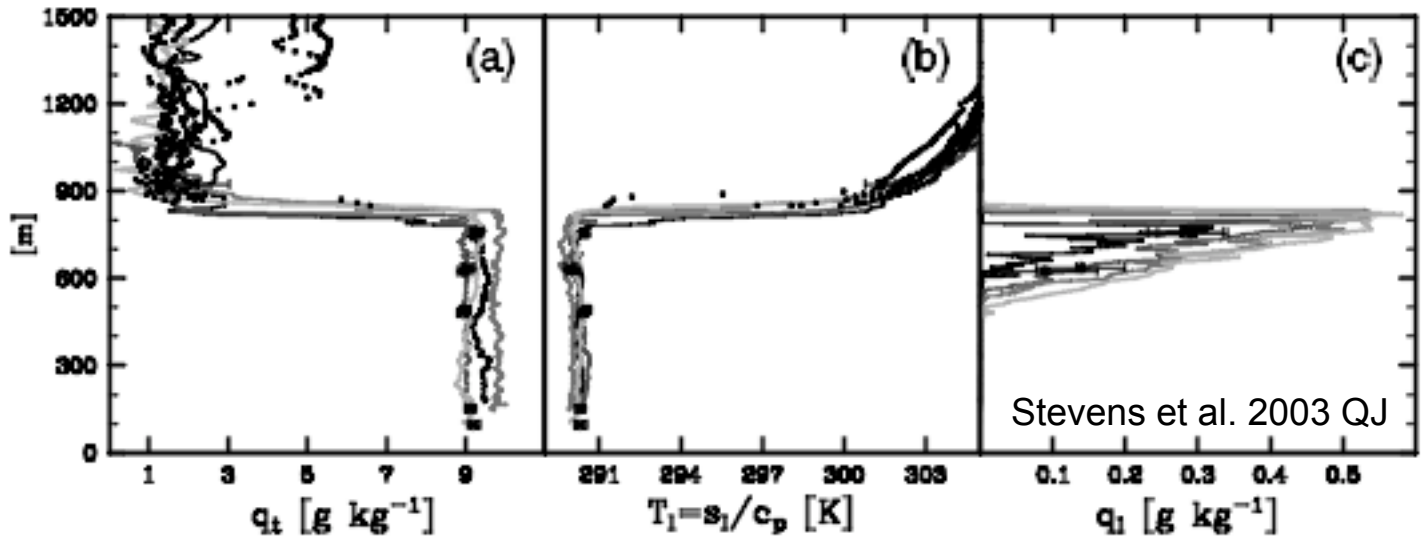
$s_l = c_pT + gz - Lq_l$,

$q_t = q_v + q_l$

$h = c_pT + gz + Lq_t$

are nearly uniform with height within the MBL.



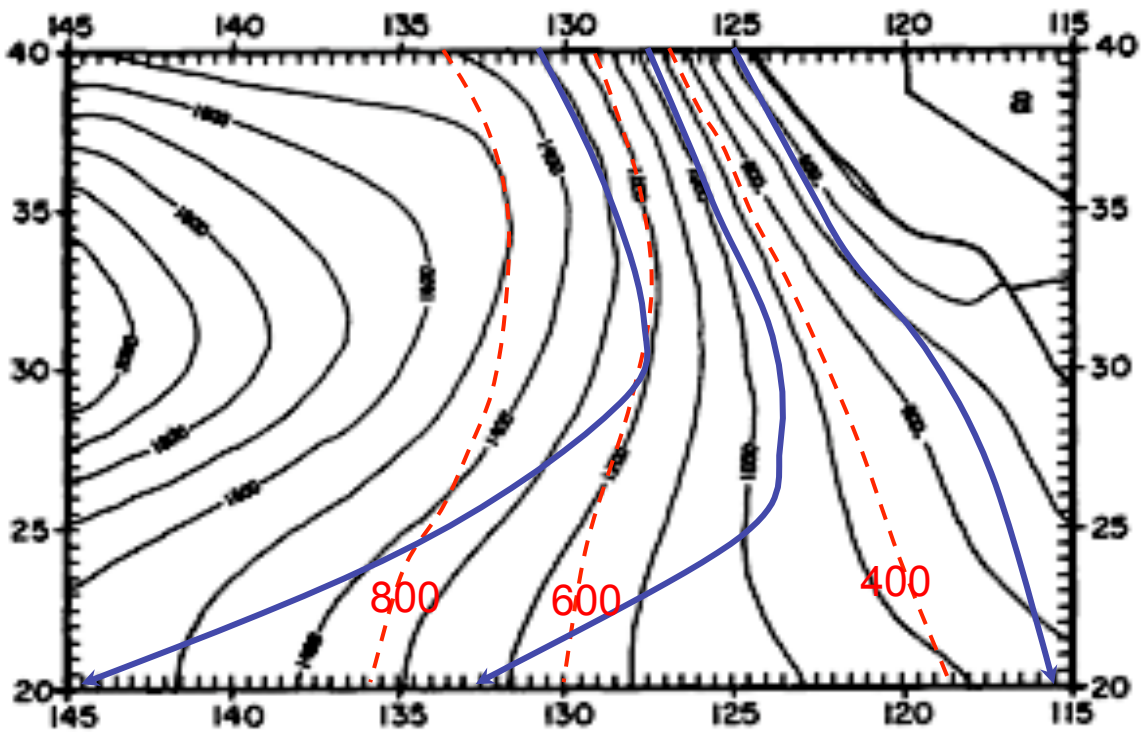


q_l increases linearly with z above cloud base

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

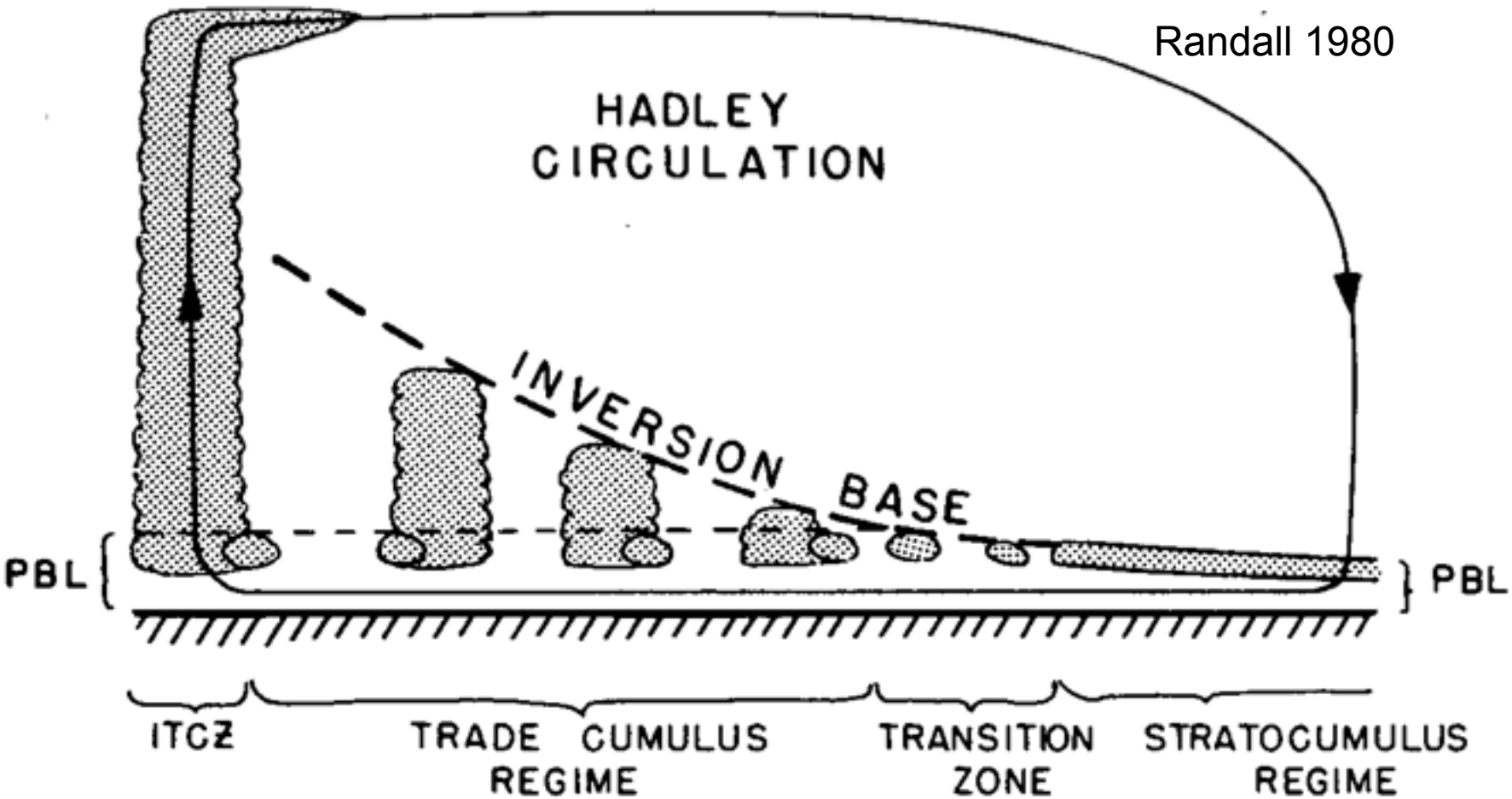
cloud thickness

July-mean trajectory

Sc thickens downstream since inversion rises faster than cloud base

Transition to Cu must result from breakdown of MLM

1980 view of the Sc-Cu transition



Why do the Sc break up in the transition zone?

Cloud-top Entrainment Instability

Randall (1980) and Deardorff (1980) suggested that Sc might be unstable if cloud-top entrainment could create negatively buoyant mixtures ('buoyancy reversal').

Condition: $\Delta_2 = \beta\Delta h - c_p T \Delta q_t < 0$

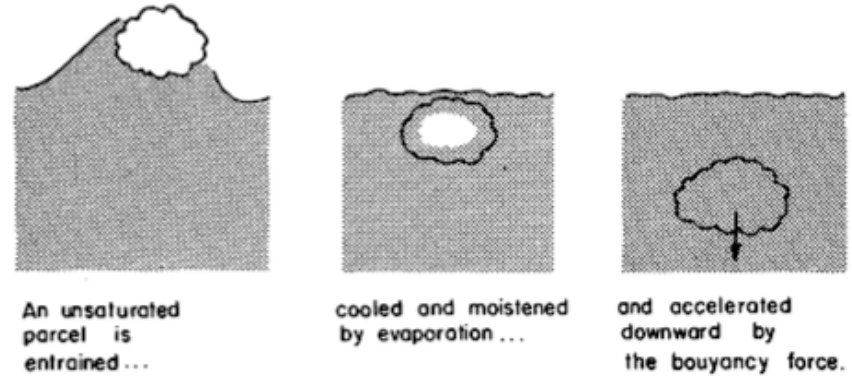
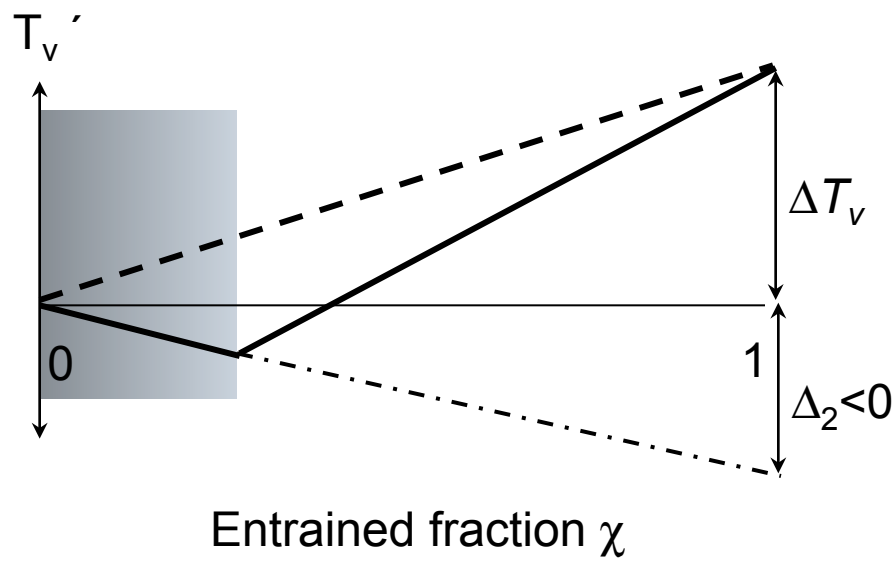


FIG. 4. A schematic illustration of the "parcel" interpretation of CIFKU. The stippled area represents cloudy air.



Randall CTEI hypothesis for Sc to Cu breakup

Further downstream of Sc region, climatological $\Delta_2<0$ ➔ huge entrainment increase, Sc instability and breakup.

Cu then develop in the entrainment-diluted boundary-layer.

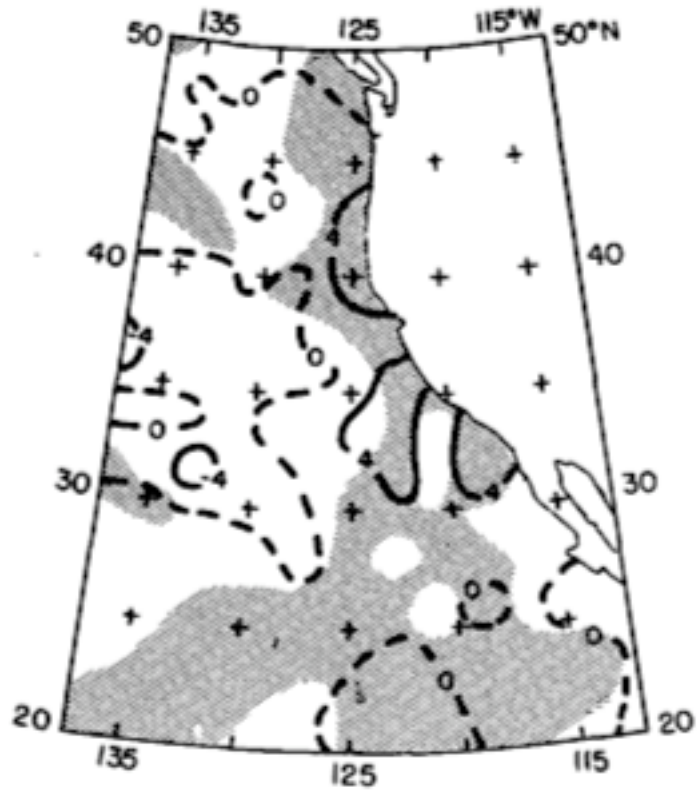


FIG. 6. The distribution of $[\Delta s_e - (\Delta s_e)_{crit}]/c_p$ [K], off the coast of California, from the data of Neiburger (1960). Stippled regions are those in which the relative humidity at the inversion base exceeded 90%.

Problem: Sc persist in presence of buoyancy reversal

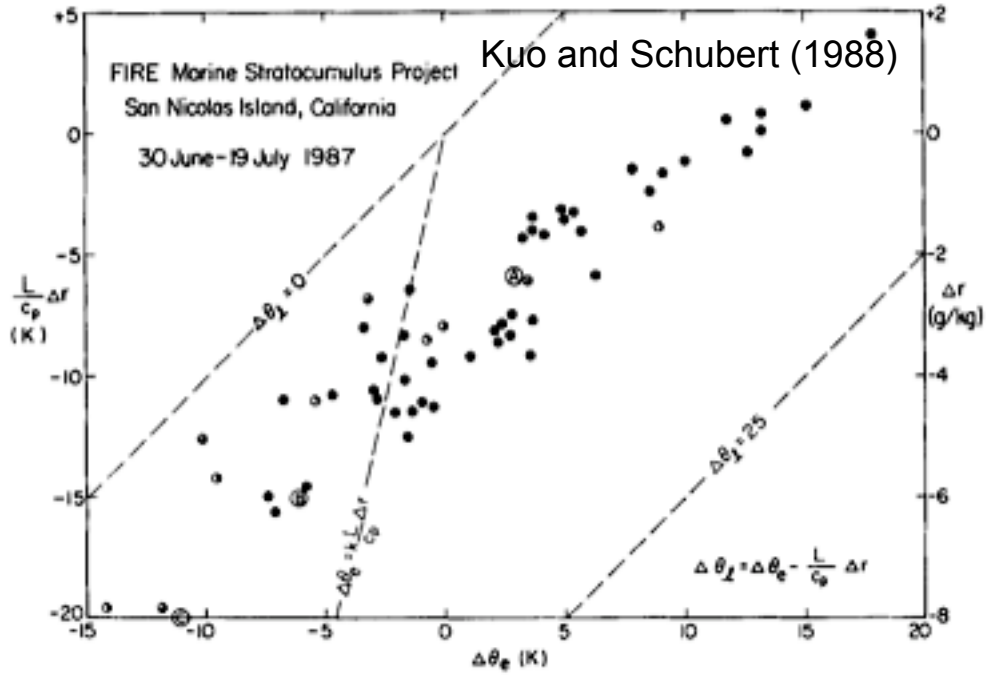


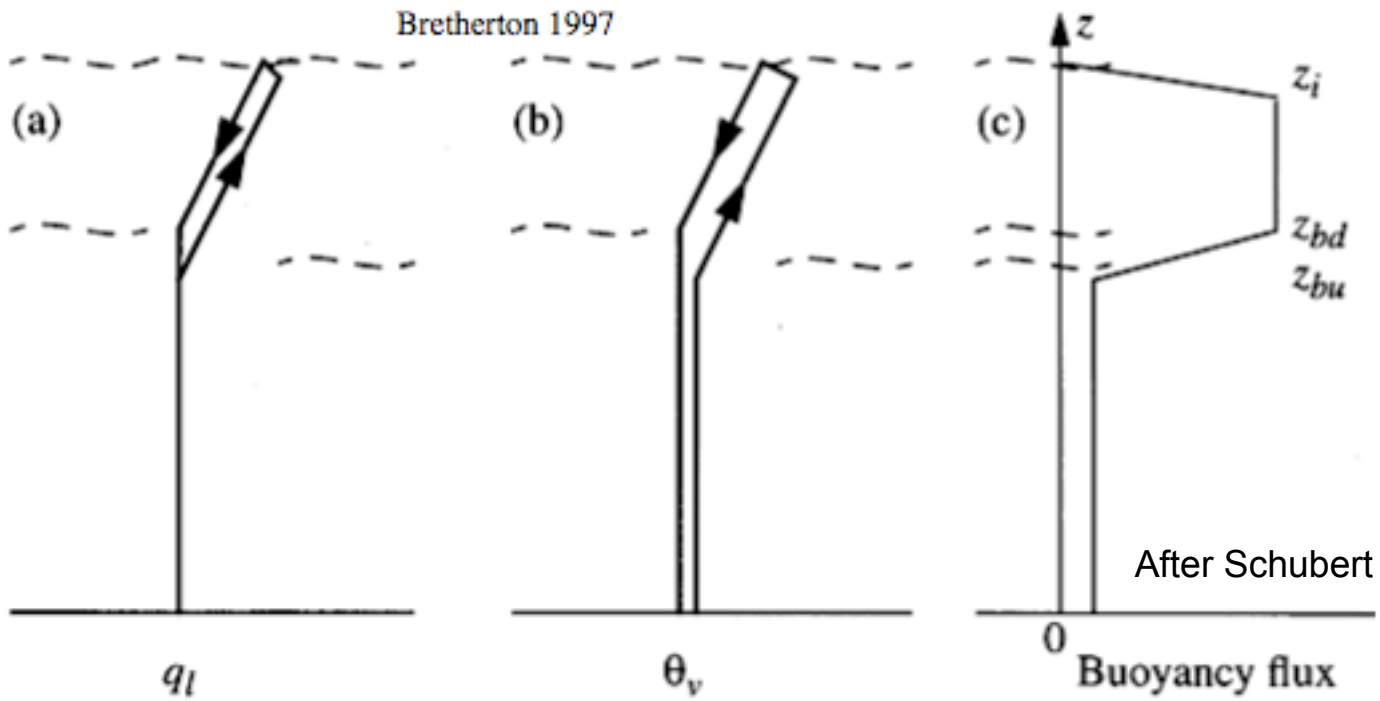
Figure 4. The $(\Delta\theta_e, \Delta r)$ plane, with the critical thermodynamic instability curve $(\Delta\theta_e = k(L/c_p)\Delta r)$. Plotted points have been obtained from fifty-five high vertical resolution soundings taken during stratocumulus conditions on San Nicolas Island, California during the period 30 June to 19 July 1987. The cases exhibiting breakup are indicated by the partially blackened symbols, with the fraction of blackening indicating the fraction of twelve hours before cloud disappearance. Fully blackened symbols indicate that conditions remained cloudy for at least twelve hours. Note the existence of persistent stratocumulus under conditions which are unstable according to the thermodynamic theory of evaporative instability.

Buoyancy reversal if:
$k = 1+c_p\,\Delta\theta_l/L\Delta q_t > 0.23$

Issues:

- Buoyancy reversal can enhance entrainment without runaway instab.
- Other competing processes (e.g. radiative cooling)
- Stricter CTEI criteria (e. g. k > 0.4, Lock 2009) also don't match Sc breakup conditions very well.

Parcel circuits in a Sc-capped mixed layer



After Schubert et al. 1979

- 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}:

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

Nicholls et al. (1984+): diurnal decoupling

The cloud and subcloud layer are found to be decoupled… Potential instability in the lower layer could lead to low-level cumulus that rise into the stratocumulus layer thereby reconnecting the two previously separated regions.

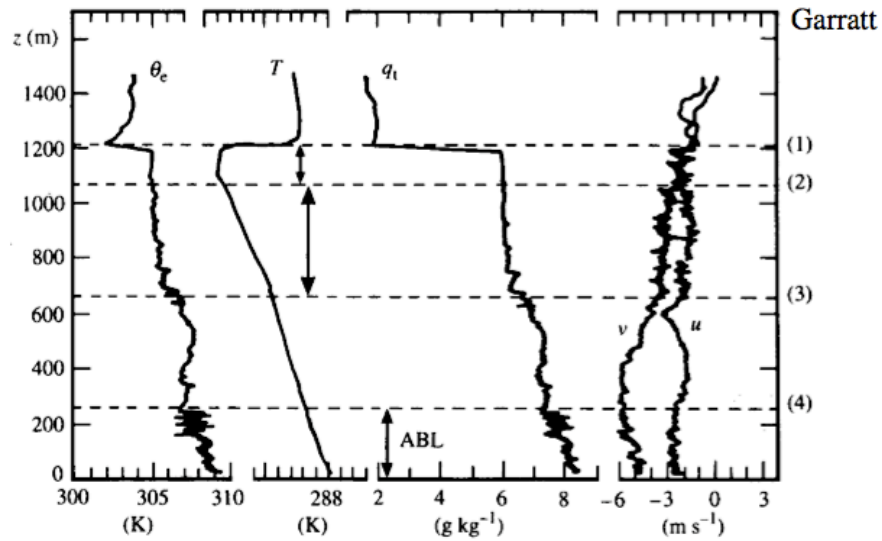
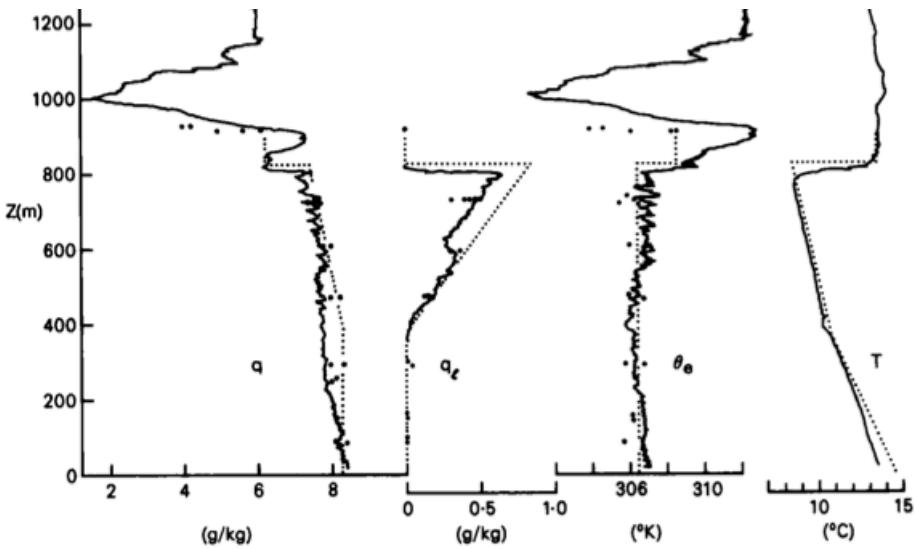
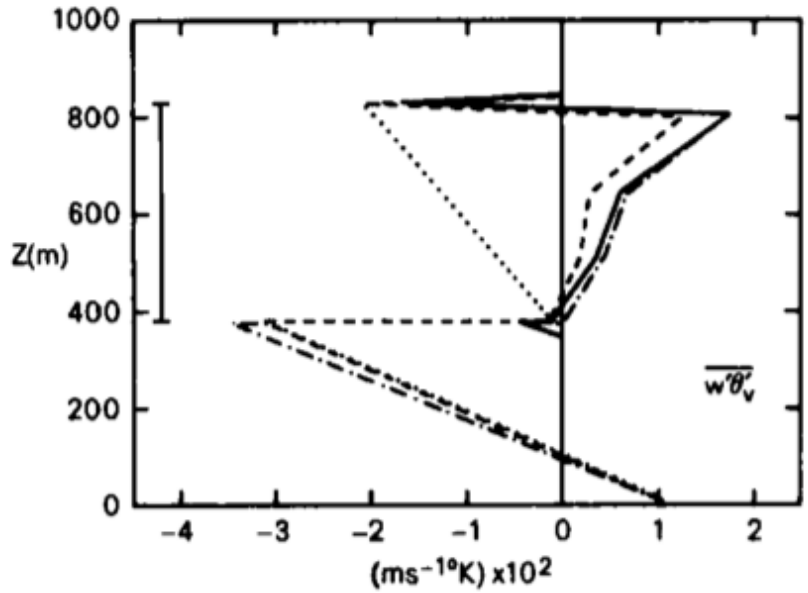


Fig. 7.5 Observed mean profiles of thermodynamic variables and wind components made in the CTBL over the ocean during JASIN, for a decoupled stratocumulus layer. The pecked horizontal lines delineate layer boundaries as follows: (1) cloud top; (2) cloud base; (3) bottom of subcloud layer; (4) top of the surface-related Ekman layer. After Nicholls and Leighton (1986), *Quarterly Journal of the Royal Meteorological Society*.

To keep the PBL below well mixed…

requires negative subcloud buoyancy fluxes too large for turbulence to sustain





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

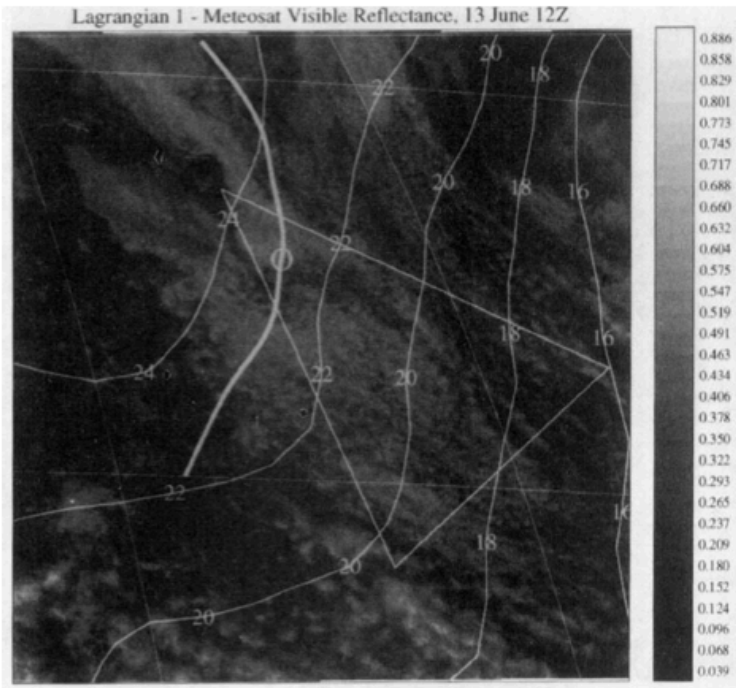


FIG. 6. Meteosat visible satellite imagery at 1200 UTC on 13 June, midway through L1. Contours indicate the ECMWF-analyzed 1000-mb geopotential height field (m); the thick gray line shows the best-guess trajectory. An O denotes the approximate air column position at the time of the image.

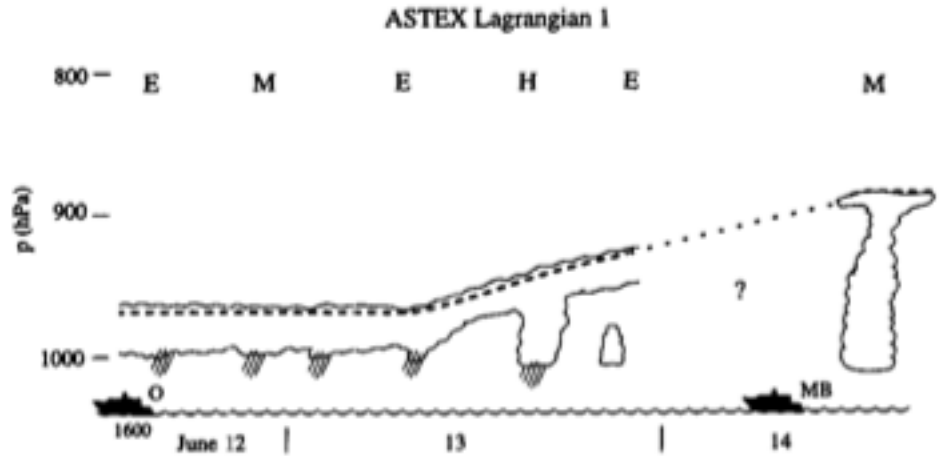
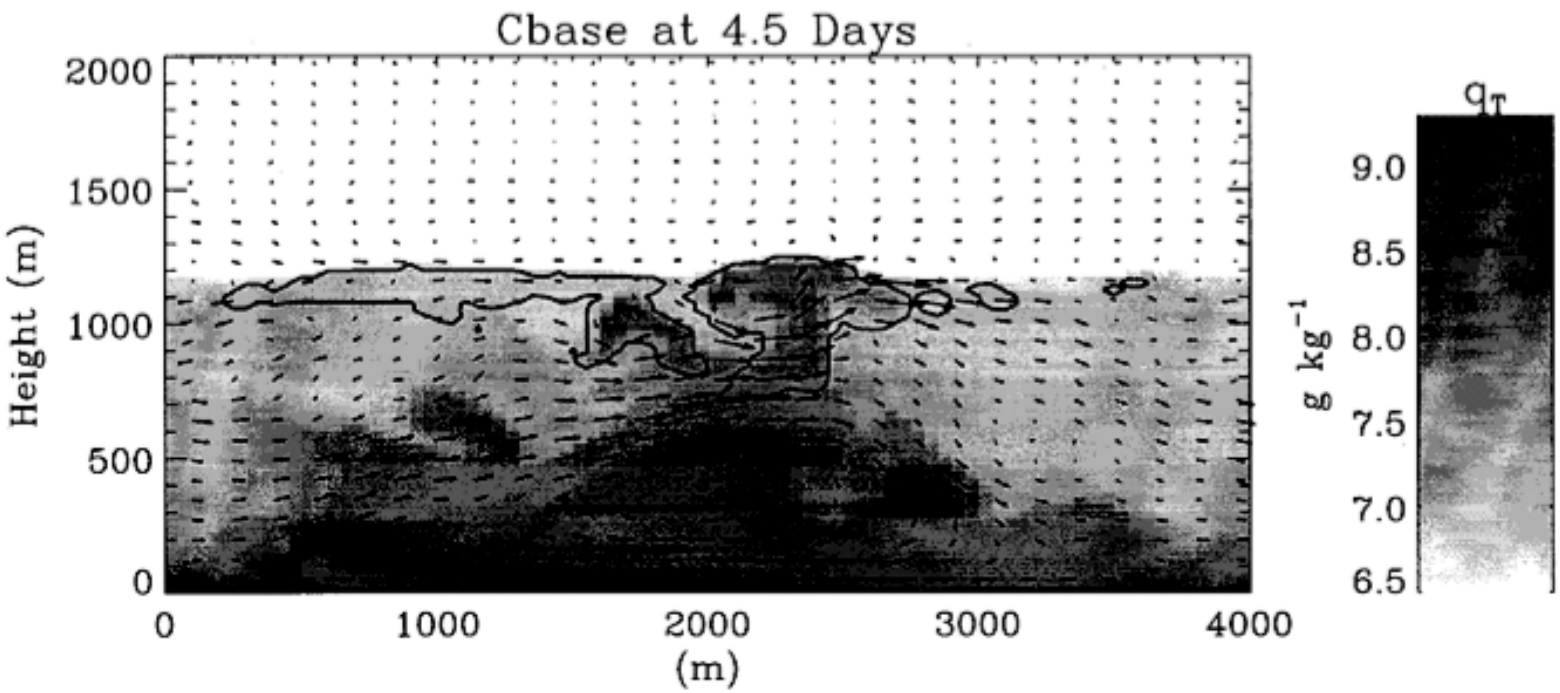


FIG. 1. Schematic of MBL evolution and platform deployment in L1. The air column was followed starting at the R/V *Oceanus* (O at left) until it passed near to the R/V *Malcolm Baldridge* (MB at right) and moved out of aircraft range. Symbols E (Electra), M (C130), and H (C131a) are placed at the midpoint 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

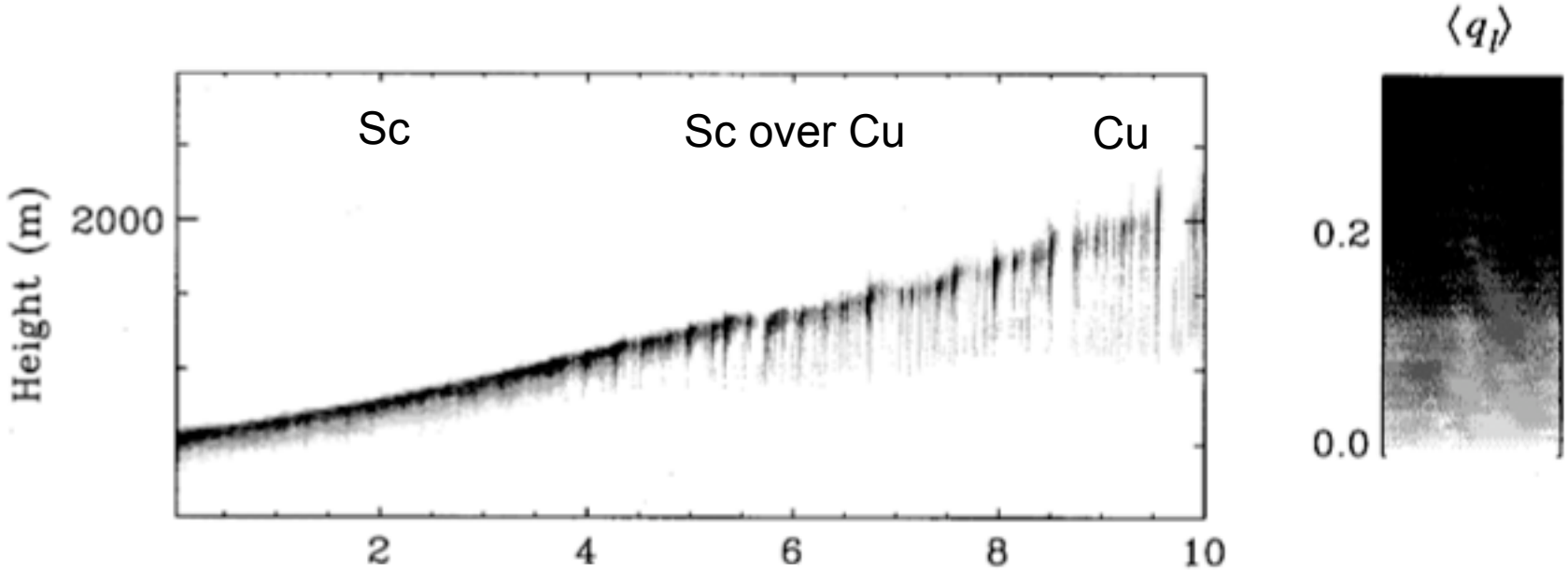
- 2D, 4x3 km, Δx = 50 m, Δz = 25 m, 8 days
- SST = 285 + 1.5 K d^{-1}, D = 3×10^{-6} s^{-1}, V_g = 7.1 m s^{-1}
- Diurnally-averaged insolation for 30 N.

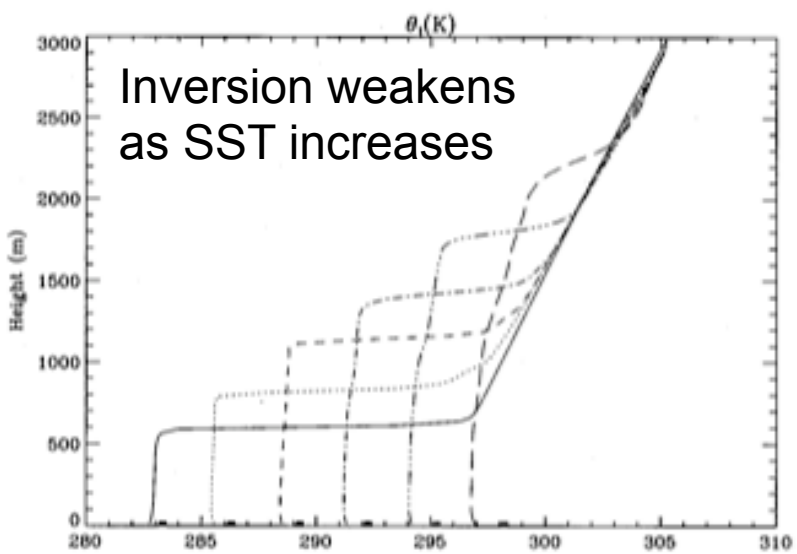


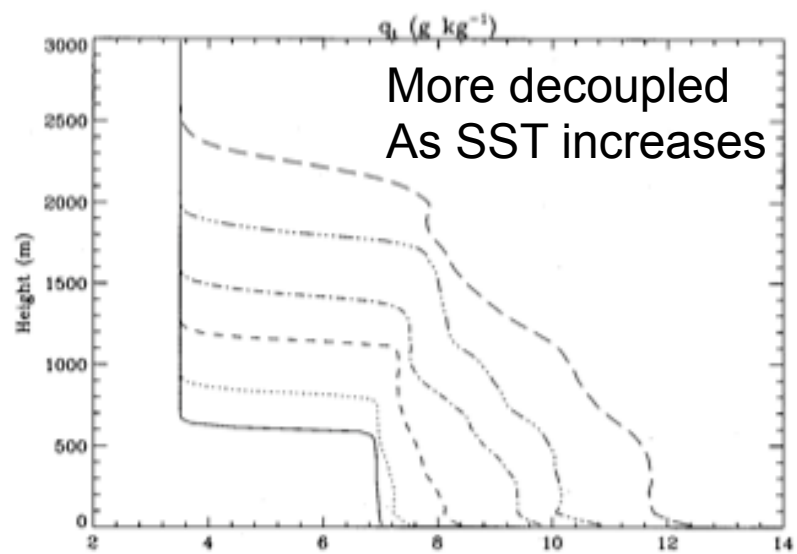
Wyant et al. 1997, see also Krueger et al. 1995

L

Horizontal-mean statistics







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.

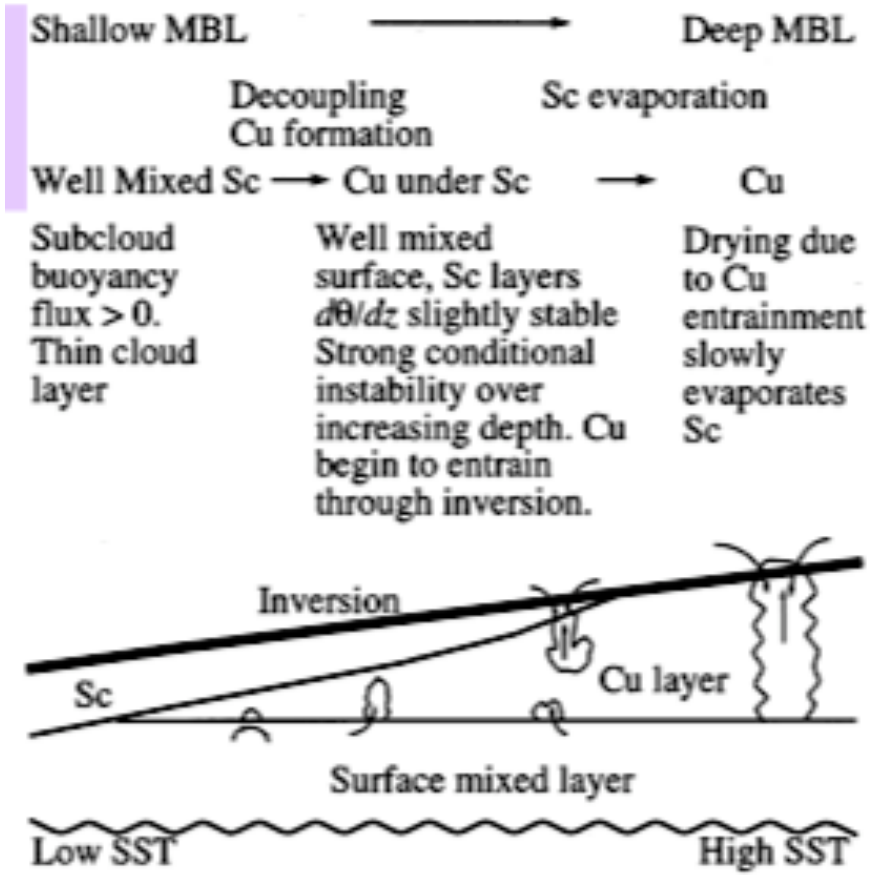


FIG. 10. A conceptual diagram of the STCT.

(Wyant et al. 1997)

The Seasonal Cycle of Low Stratiform Clouds

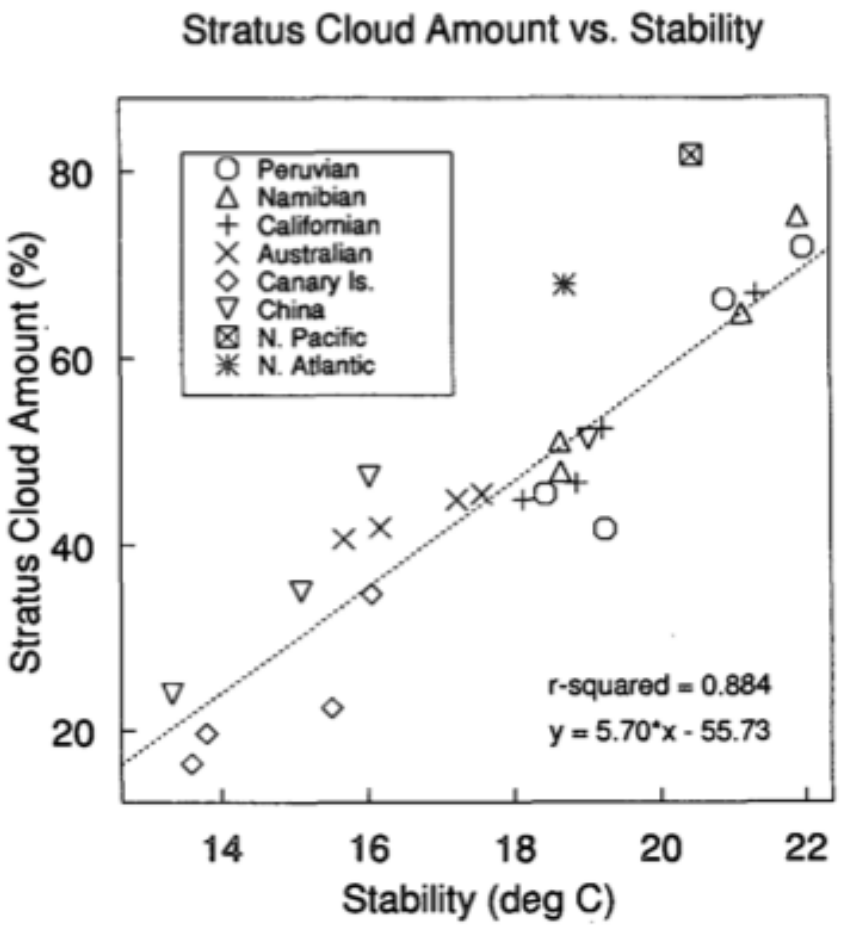
STEPHEN A. KLEIN AND DENNIS L. HARTMANN

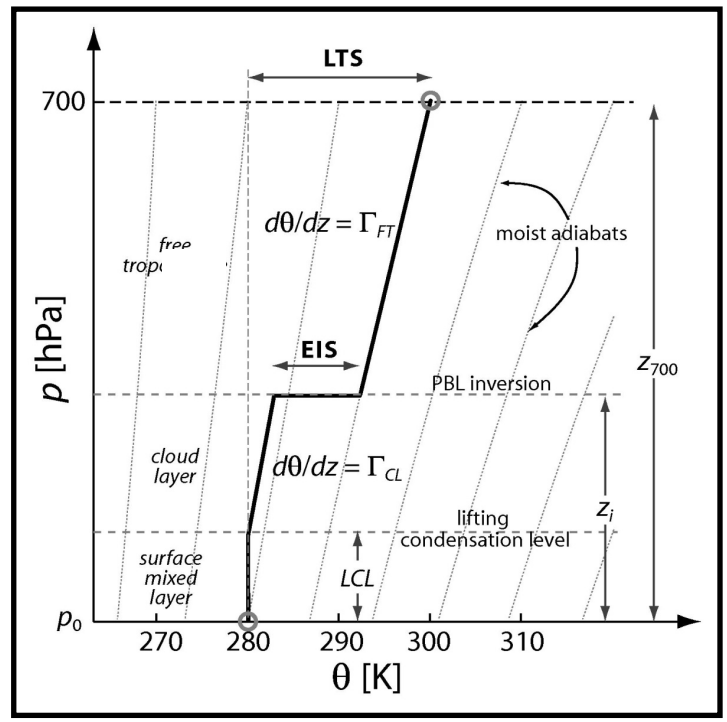
1993, J. Climate

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)

Put this knowledge into climate models

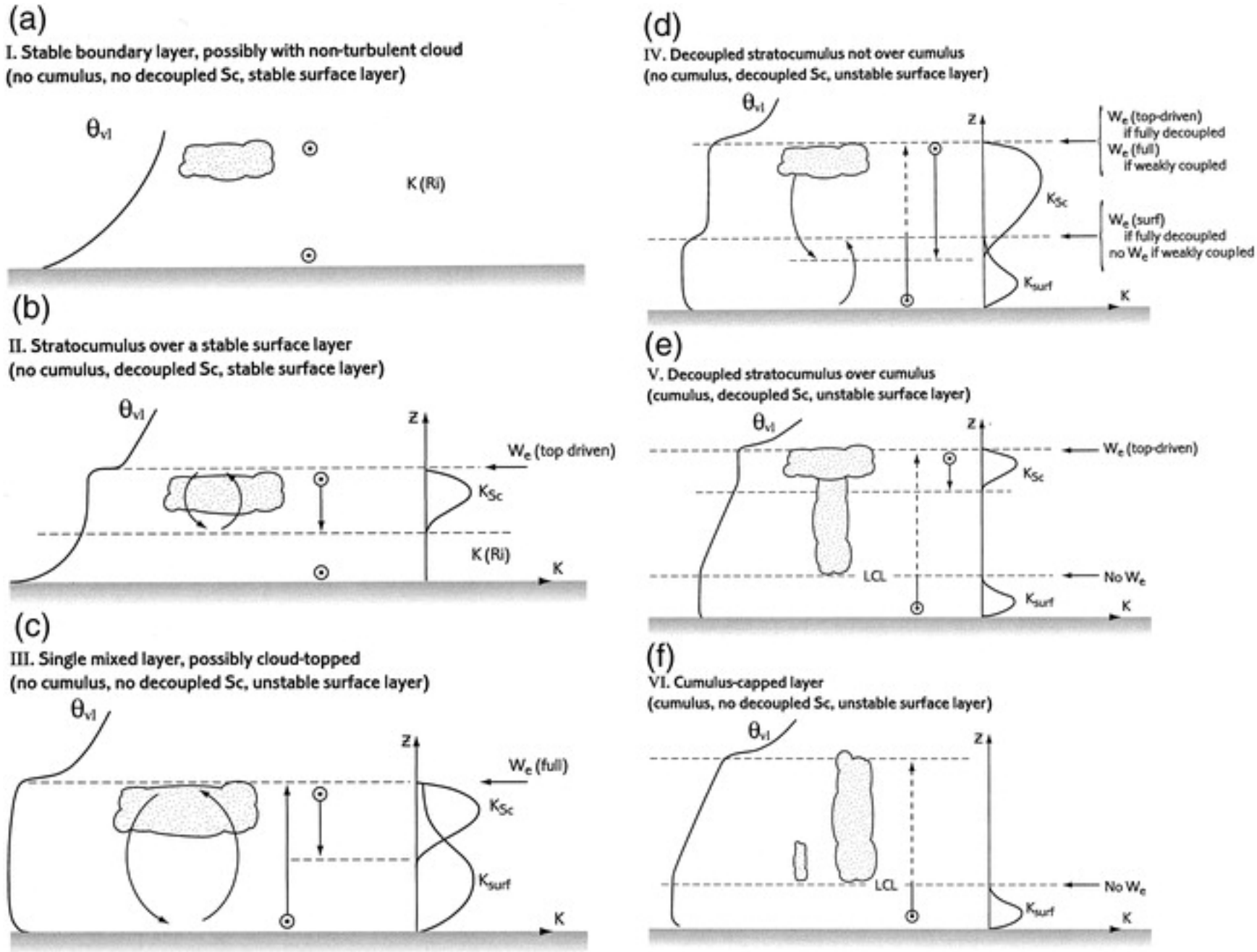
- Relate entrainment, turbulence to cloud radiative cooling
- Account for possible decoupling
- Cumulus parameterization active where decoupled

A first success: Lock et al. 2000 scheme in HadAM3

- Sc-top radiatively-driven K-profile and entrainment rate
- Classification of boundary layer types
- Cloud-top, surface K-profiles may separate (decoupling)

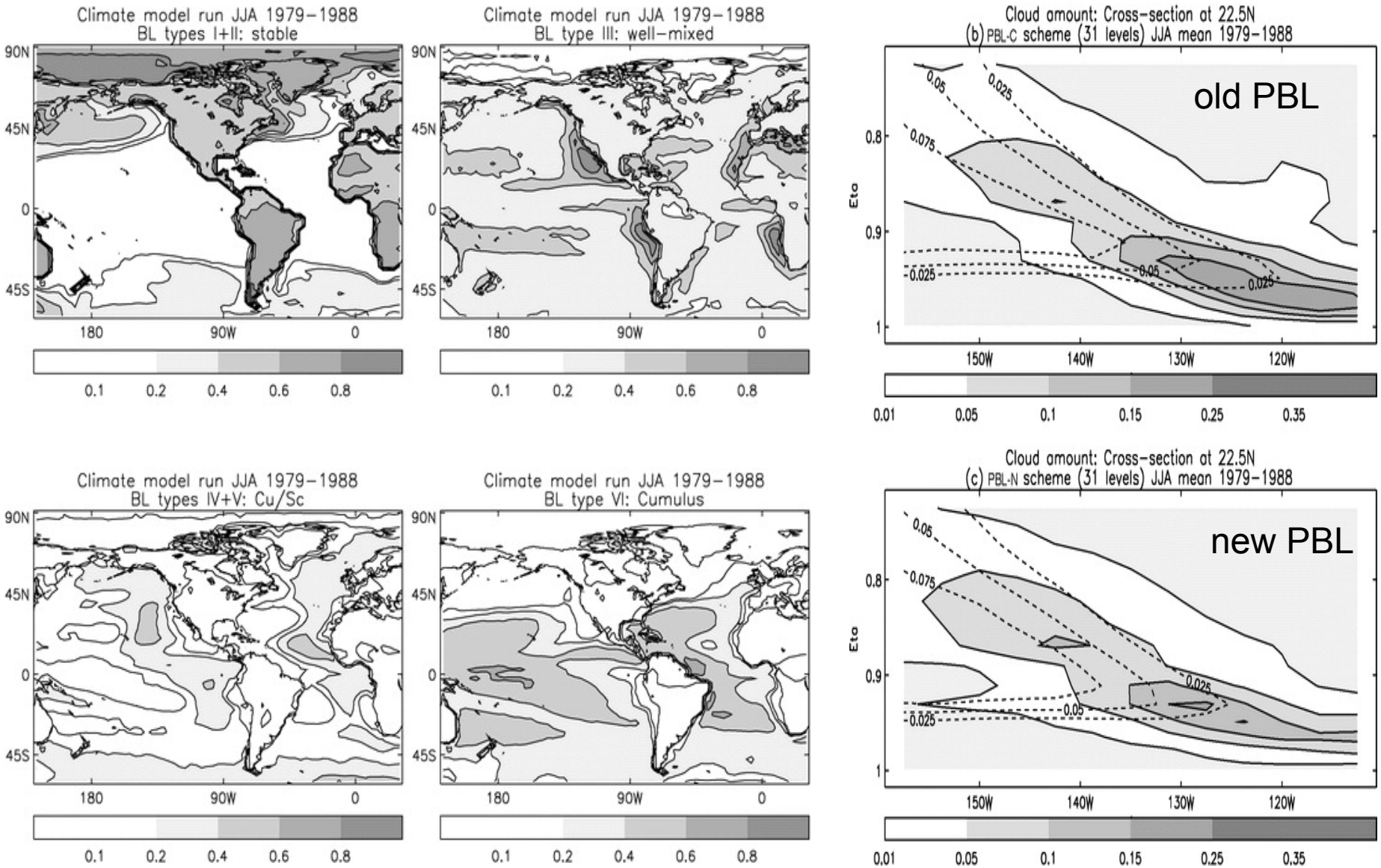
Examples of other approaches successful in global models:

- McCaa et al. (2004 MM5), Bretherton-Park (2009, CAM5) moist TKE scheme + shallow Cu param
- Koehler et al. (2009, ECMWF)
- Eddy-diffusion mass-flux (EDMF)



Lock et al. 2000

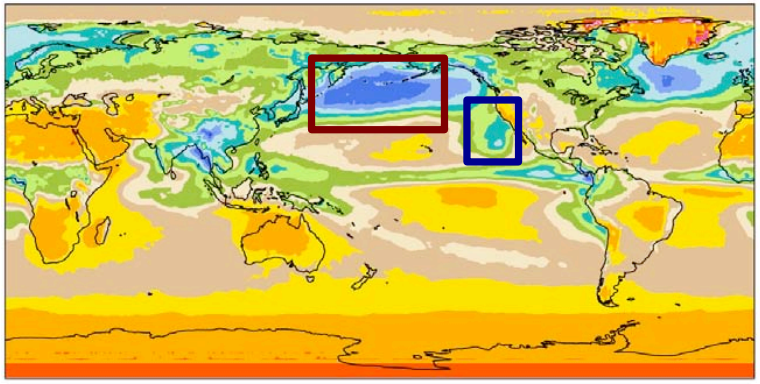
Simulates lots of decoupled PBLs, deeper inversion



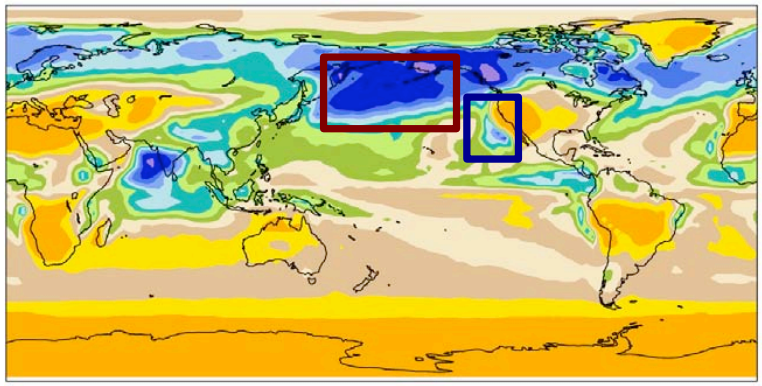
Martin et al. 2000

SWCF, JJA: CAM versus CERES-EBAF

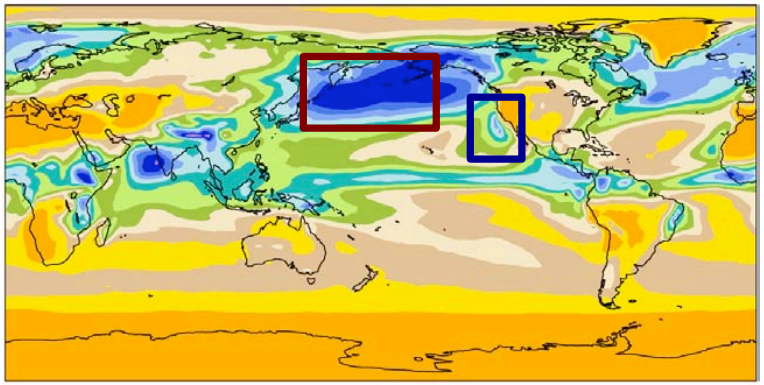
CERES-EBAF Mean: -45.0 W/m^2



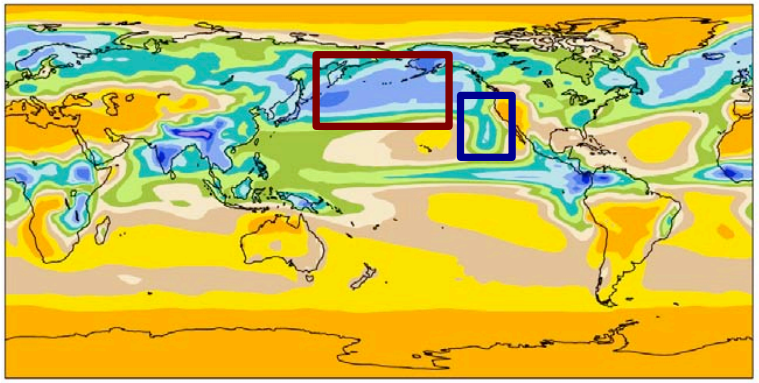
CAM3 Mean: -54.4 W/m^2 RMSE: 23.4 W/m^2

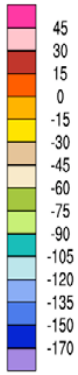


CAM4 Mean: -54.7 W/m^2 RMSE: 23.0 W/m^2



CAM5 Mean: -50.4 W/m^2 RMSE: 19.2 W/m^2



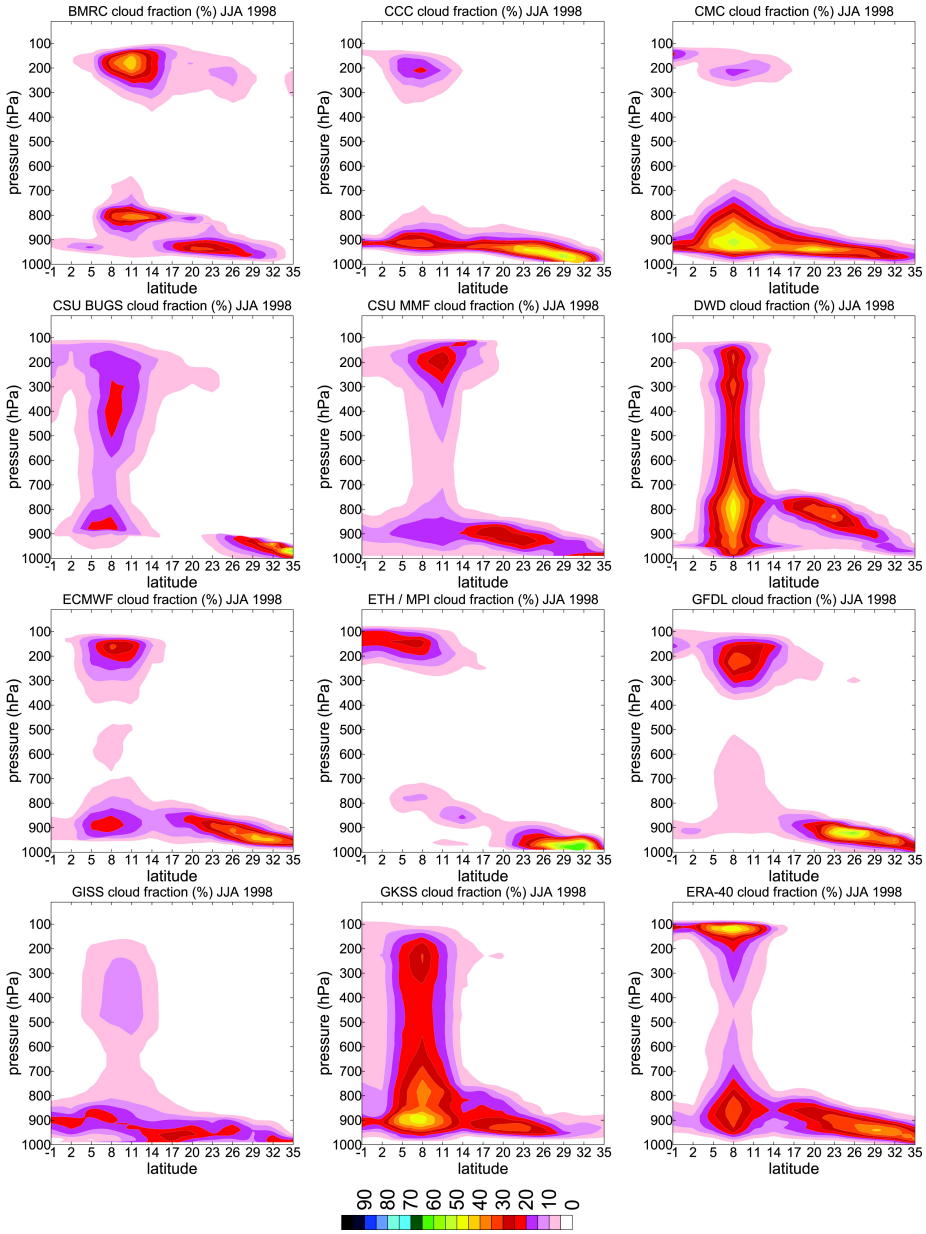


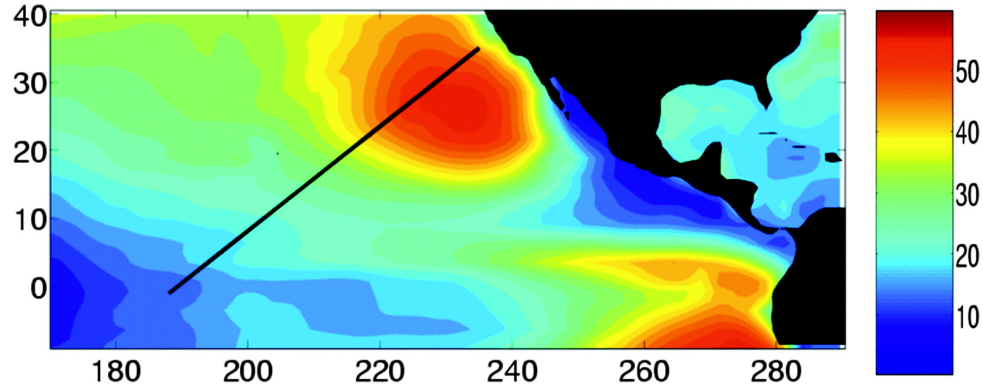
- Excessive SWCF in North Pacific (in CAM3 and CAM4) is reduced in CAM5.
- CAM5 improves stratocumulus and trade cumulus
- CAM5 reduces RSME error (true even if compared to ERBE)

C. Hannay

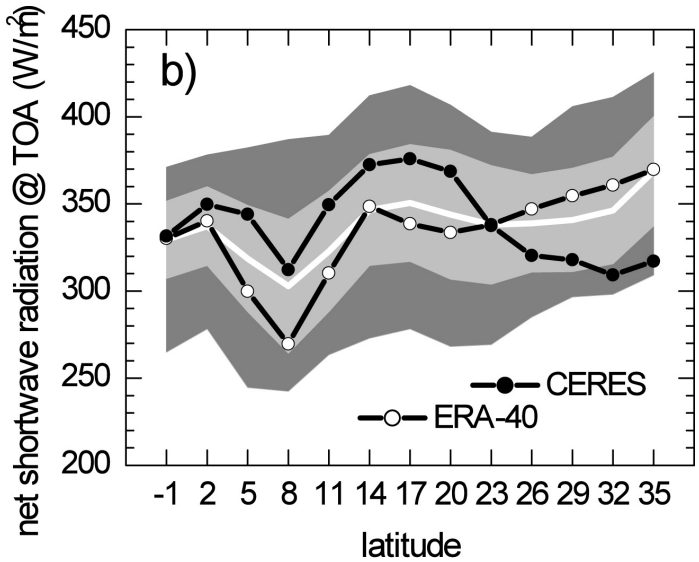
Tropical and Subtropical Cloud Transitions in Weather and Climate Prediction Models: The GCSS/WGNE Pacific Cross-Section Intercomparison (GPCI)

Teixeira et al. 2011, J. Climate

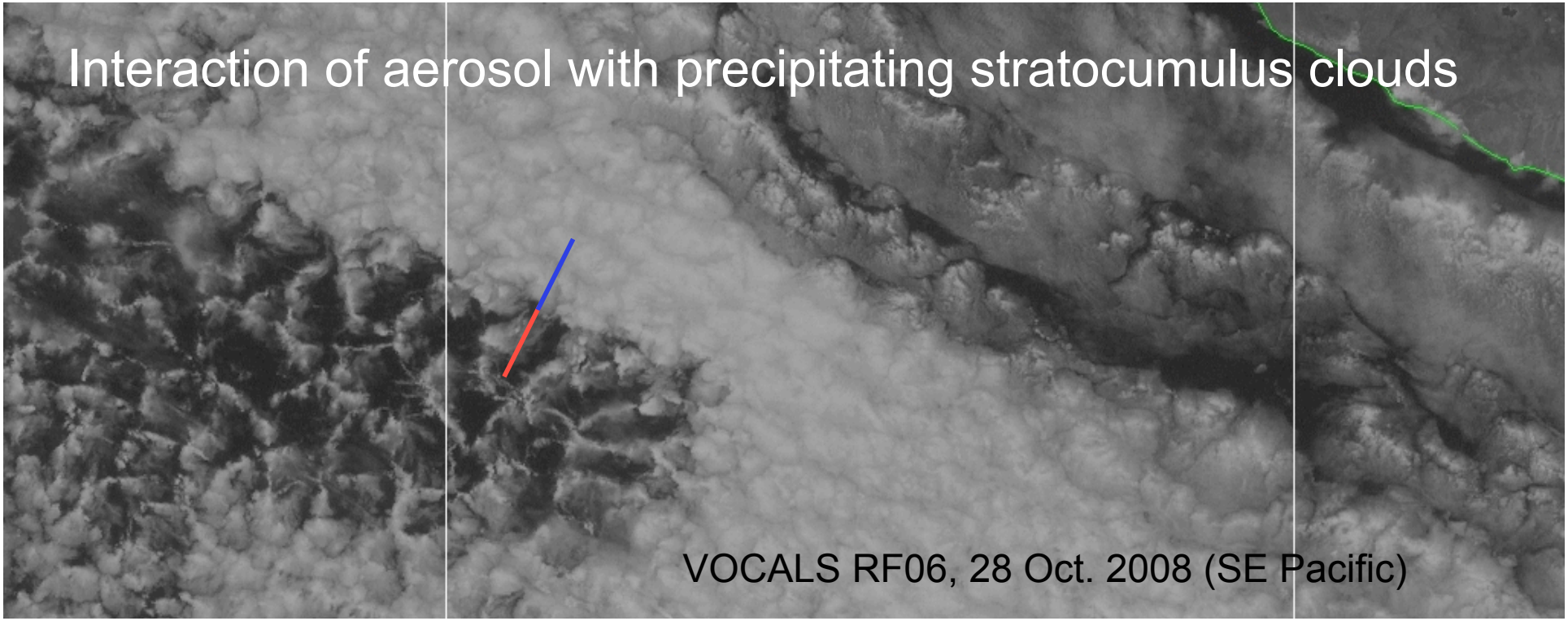


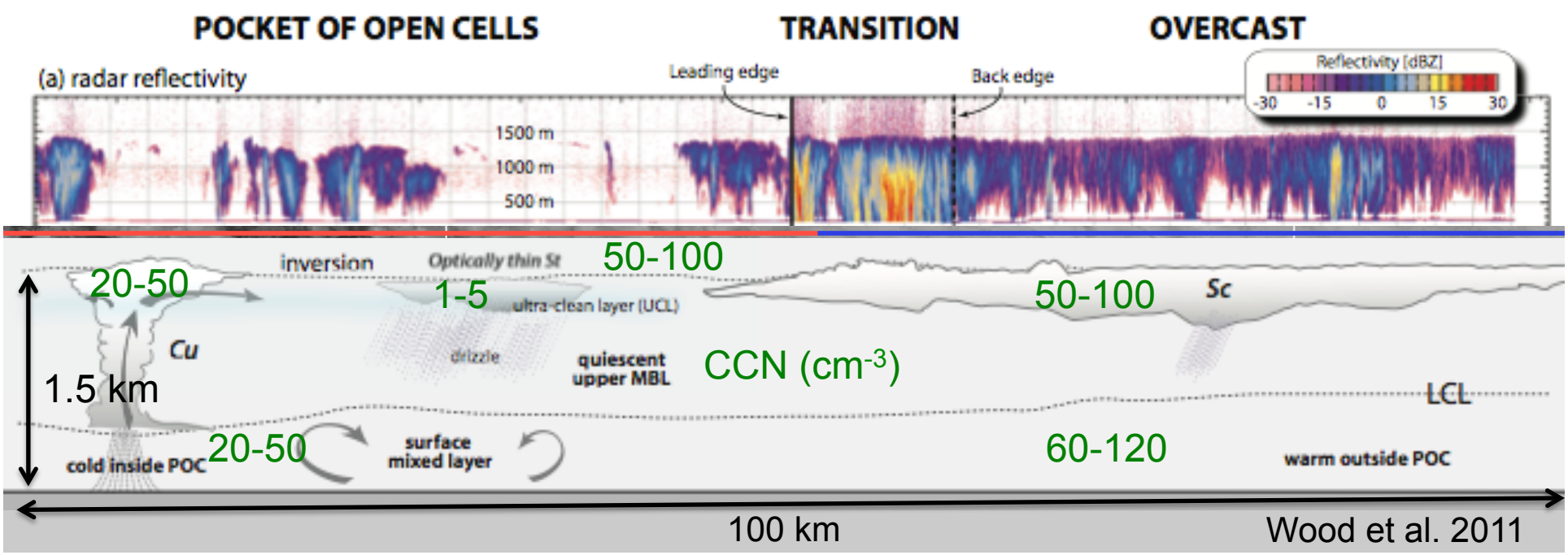


Through the GPCI, the NE Pacific Sc-Cu transition has become a well-documented test case for diagnosing model cloud biases.

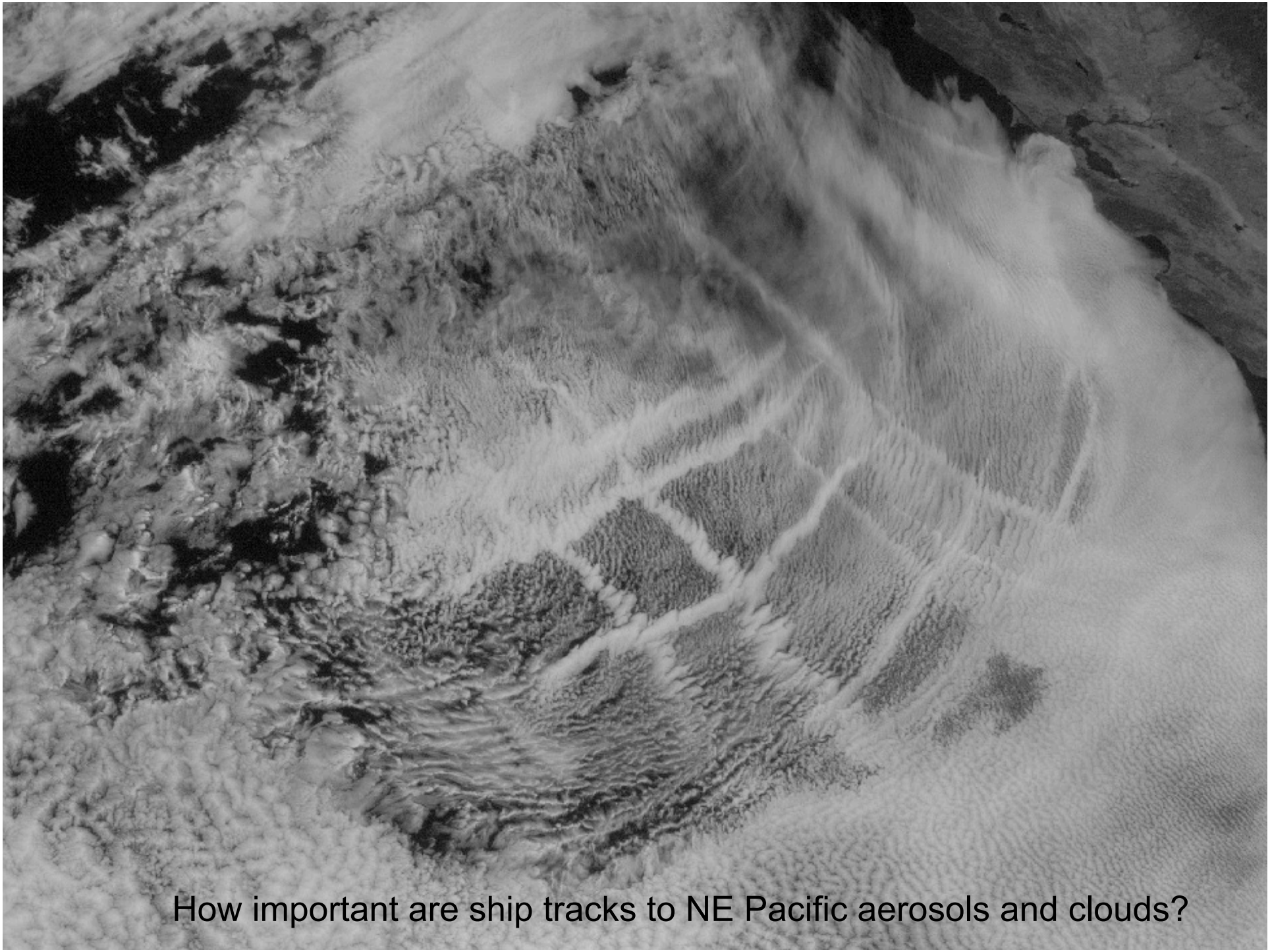


Interaction of aerosol with precipitating stratocumulus clouds



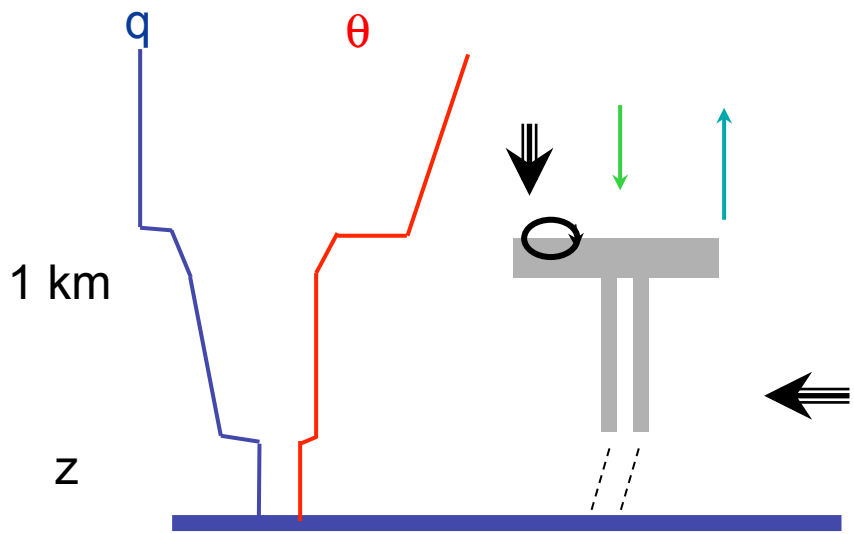


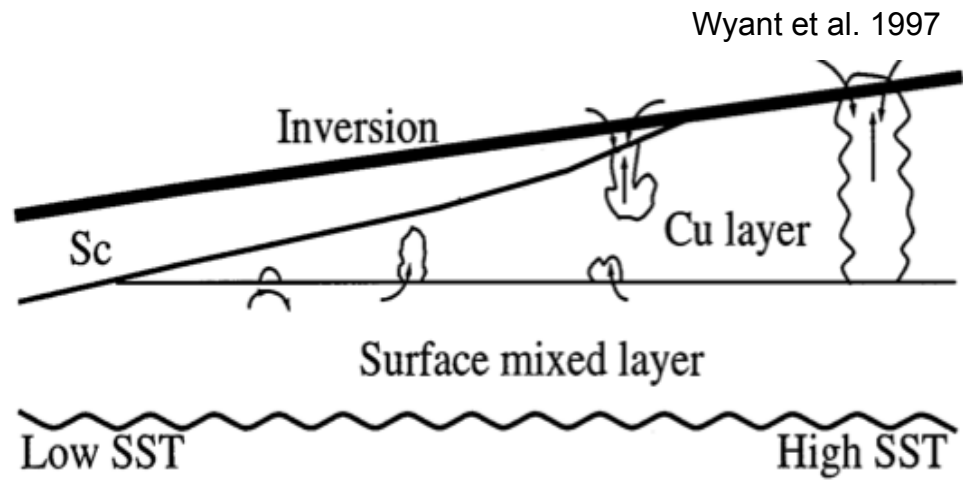
Wood et al. 2011



How important are ship tracks to NE Pacific aerosols and clouds?

Review of subtropical marine low cloud dynamics





- Clouds turbulently maintained by longwave cooling and surface moistening/heating.
- Clouds reinforce turbulence which drives entrainment
- Shallow PBL is well mixed with Sc, deep PBL is 'Cu-coupled'
- As PBL deepens, cumuli penetrative entrainment breaks up Sc
- Precipitation accentuates decoupling, feeds back with aerosol
- All subtropical Sc-Cu transitions behave similarly vs. LTS.

Can LES quantitatively simulate the Sc-Cu transition?

Dussen et al. 2013

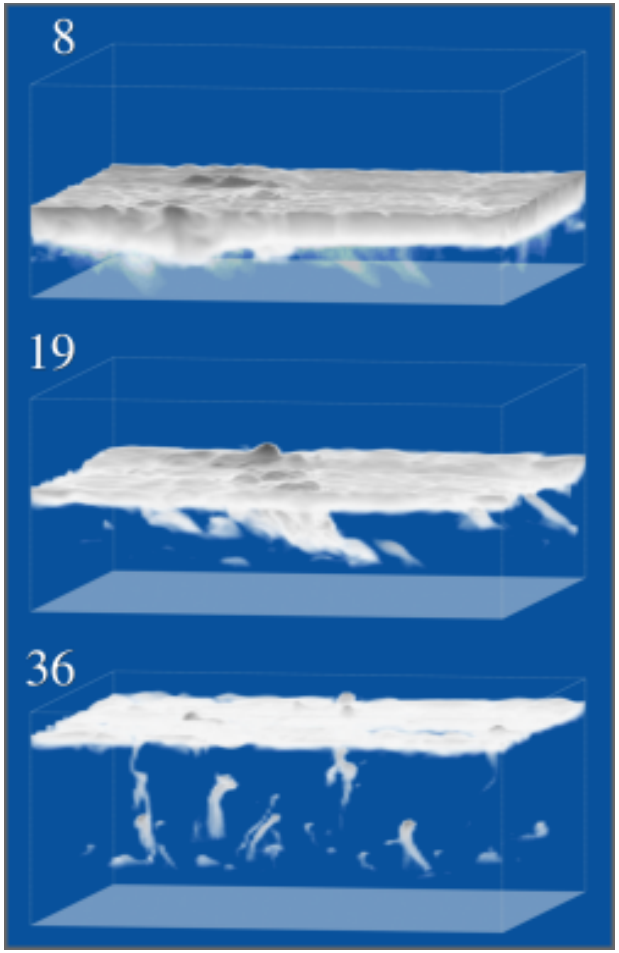
ASTEX Lagr. 1

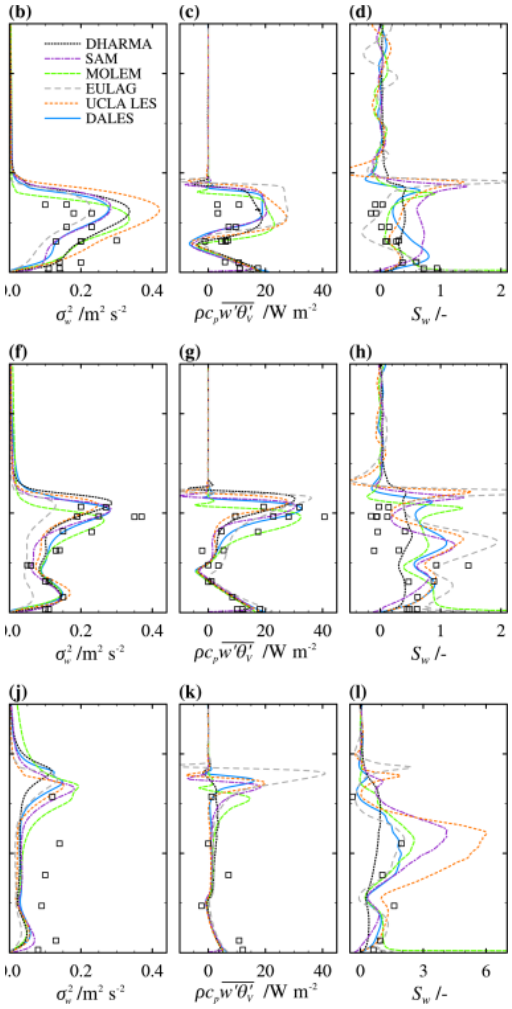
6 LES models

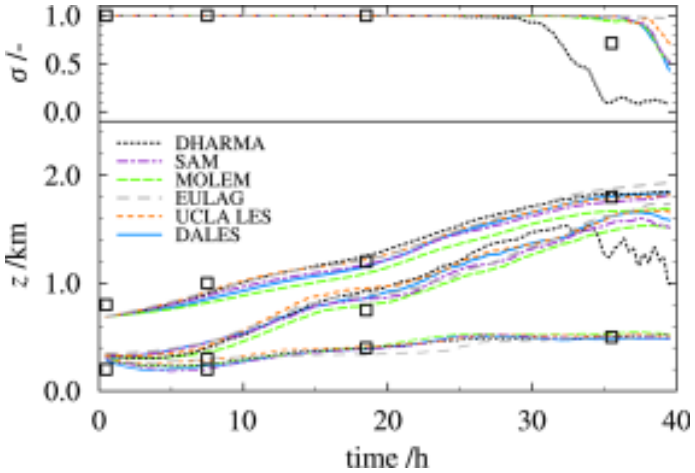
Cloud-layer dz = 5 m

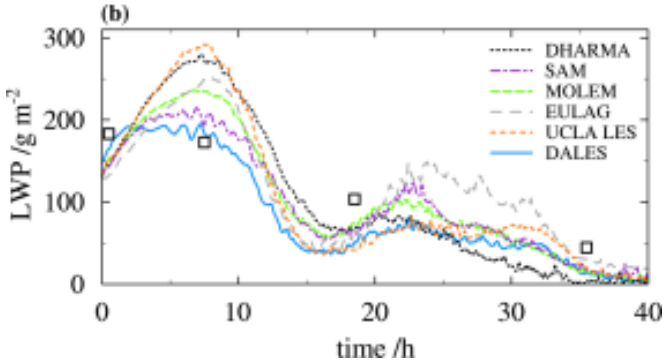
$L_x = L_y = 4.45$ km

Nice agreement w obs



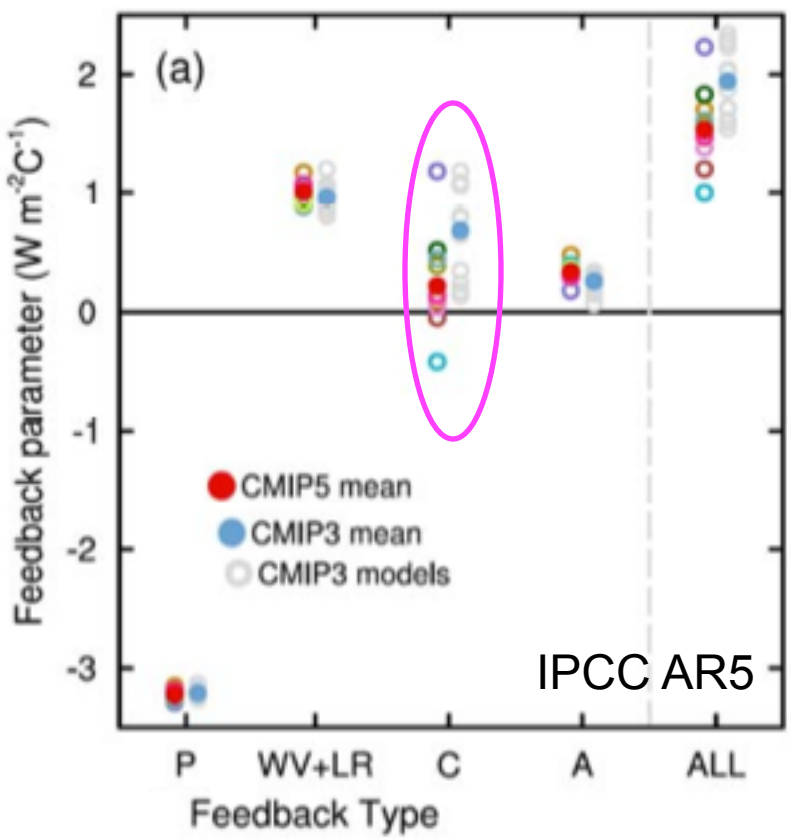


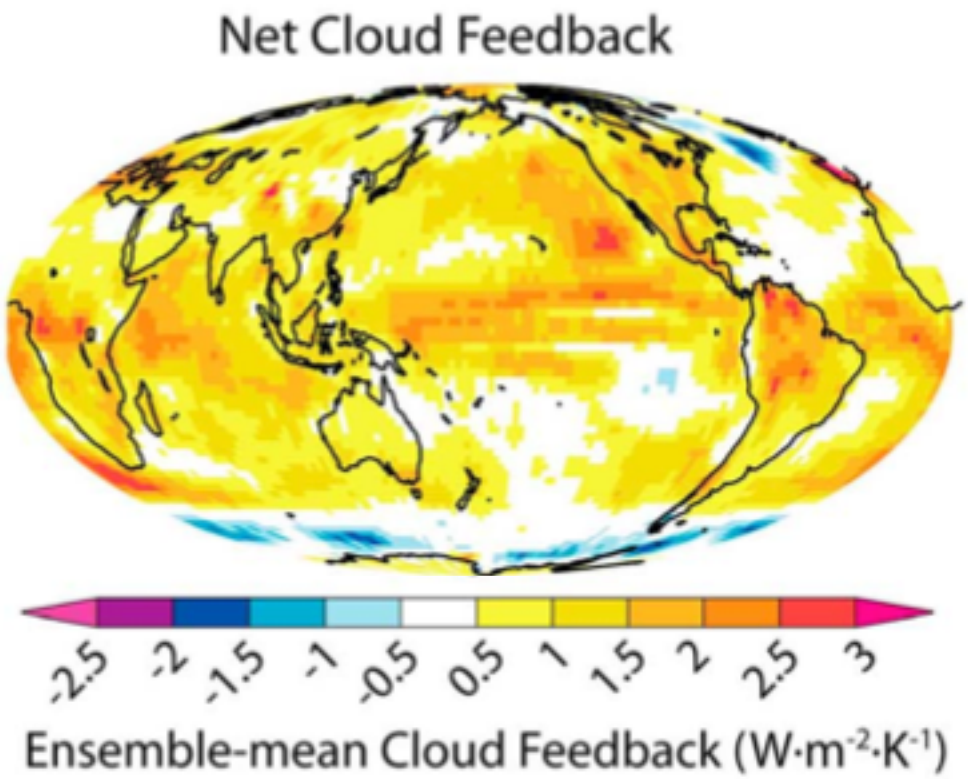




Subtropical cloud feedbacks in GCMs

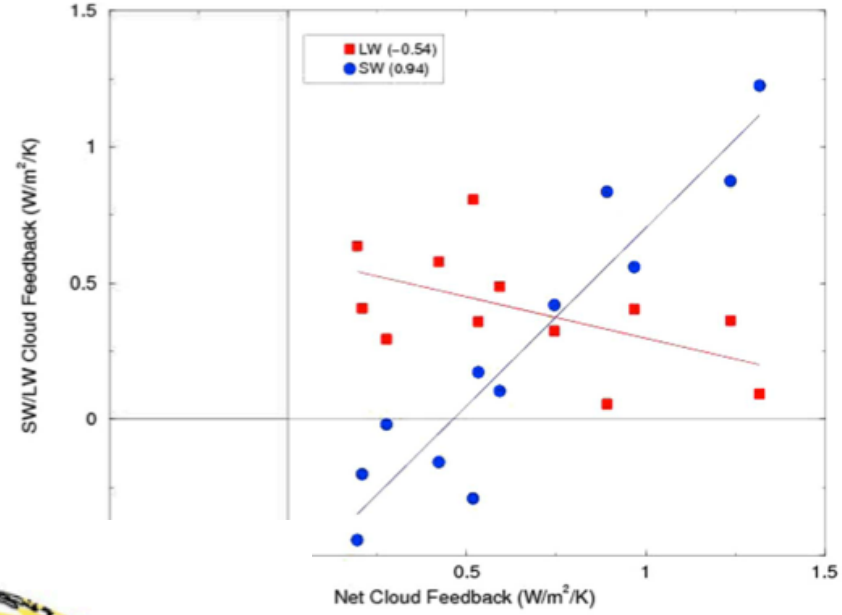
IPCC AR5 SPM: ‘The net radiative feedback due to all cloud types combined is *likely* positive. Uncertainty in the sign and magnitude of the cloud feedback is due primarily to continuing uncertainty in the impact of warming on low clouds.’

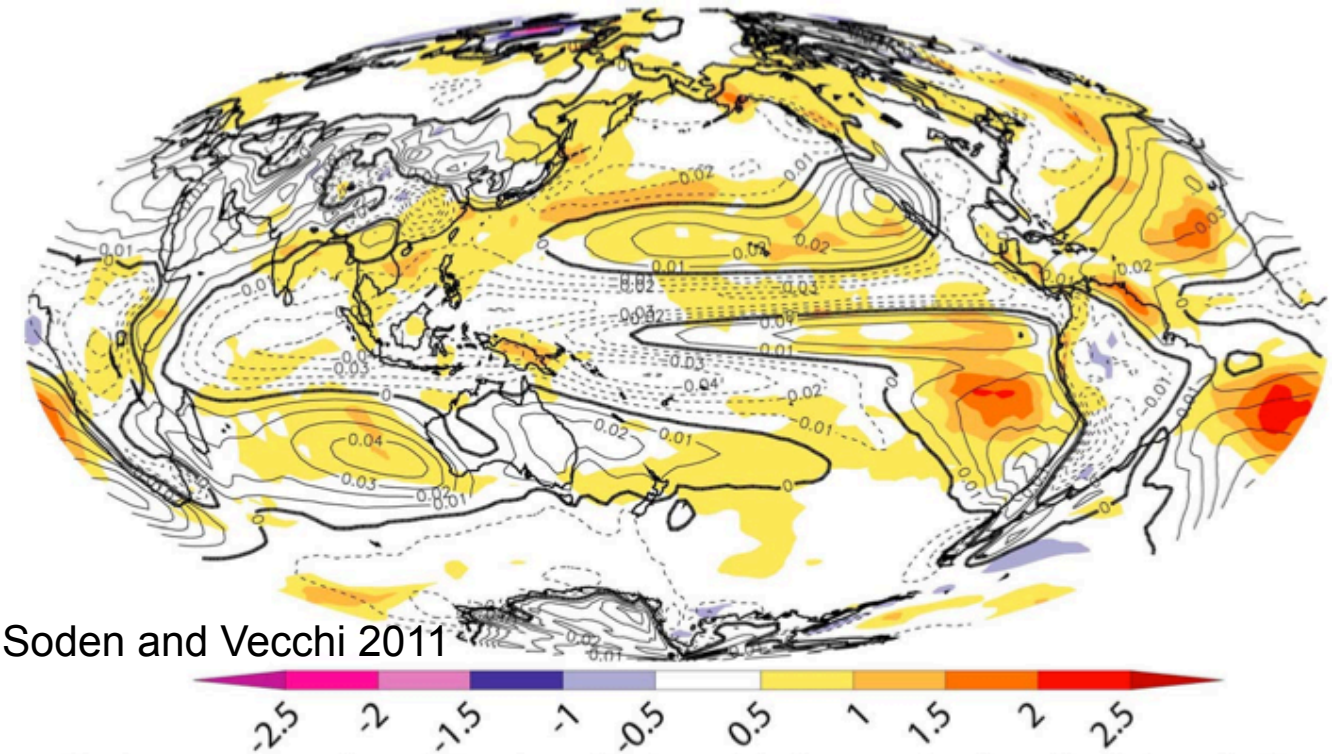




Soden and Vecchi 2011, based on CMIP3

Intermodel spread in cloud feedback largest in subtropical subsidence regions





Soden and Vecchi 2011

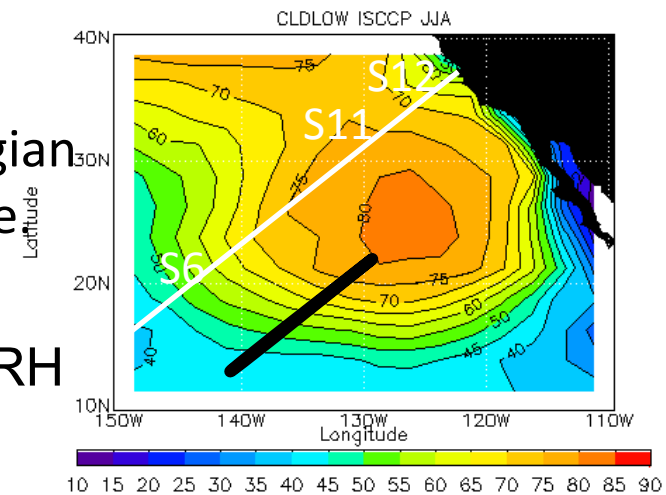
Shade: Regression of Local Cloud Feedback to Global-mean Cloud Feedback ($W \cdot m^{-2} \cdot K^{-1}$)
Contour: Background 500hPa Pressure Velocity ($Pa \cdot s^{-1}$)

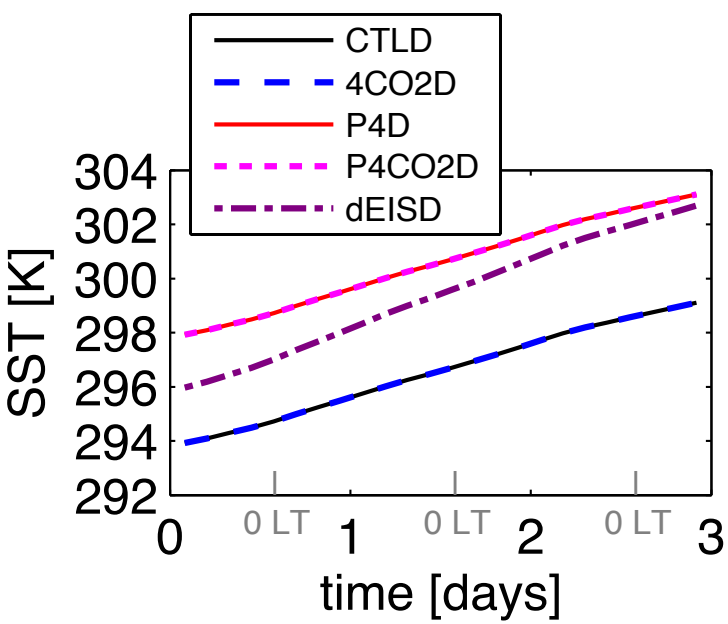
…so try harder to understand response of subtropical boundary-layer cloud to climate change

A Lagrangian View of Cloud Evolution and Feedbacks

(Bretherton and Blossey 2014)

- GASS Sc-Cu transition: a composite case from the Northeast Pacific (Sandu & Stevens, 2011);
- LES of BL evolution on summer composite Lagrangian trajectory over warmer SSTs with weak subsidence
- Add climate perturbations to control (CTL) case:
  - P4: 4K warming of air column, SST, but same RH
  - 4xCO2: with no warming of air column
  - P4 4x (combined warming and 4xCO2).
  - dEIS: P4 with initial ΔSST halved to 2 K





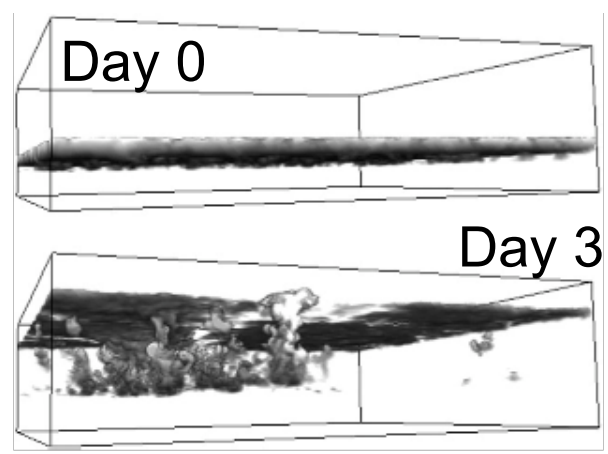
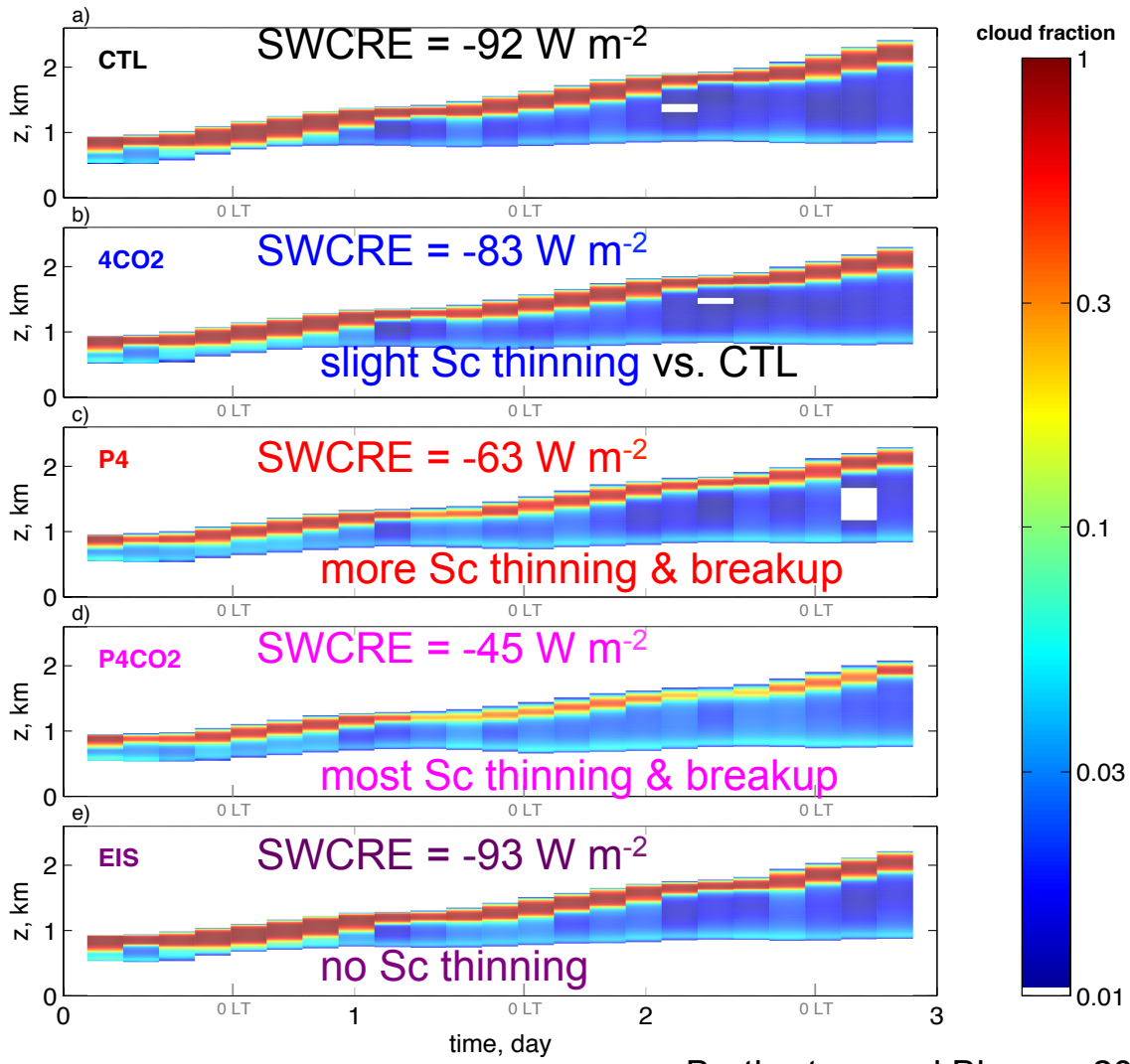


FIG. 3. An image of the cloud field simulated in the REF case, at (top) the beginning and (bottom) the end of the simulation.

Sandu and Stevens 2011

Lagrangian case cloud fraction

SAM6.7 LES,
$\Delta x = \Delta y = 35$ m, $\Delta z = 5$ m,
4.5x4.5 km doubly-periodic
RRTM w. diurnal insolation
$N_d = 100$ cm^{-3}



Bretherton and Blossey 2014

- Like CGILS, Sc cloud thins in 4CO2, more in P4, most in P4 4x.
- dEIS simulation recovers CTL cloud due to stronger inversion.
- Both warming and increased GHG decrease Sc-Cu transition cld.

So, what's MAGIC's role in this?

- The seasonal and synoptic diversity will test cloud responses in GCMs and LES over a broad range of conditions with enough different types of observations to provide strong constraints.
- Better sampling of the Cu part of the Sc-Cu transition
- Aerosol and cloud radar measurements will help test GCM simulation of aerosol variability and may be useful for assessing downstream effects of ship emissions on clouds.
- Beautiful case studies showing interesting extreme conditions, with the rich context of modern satellite observations and reanalyses.