The challenge of simulating cloudy boundary layers

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ASR Atmospheric System Research

NOAA MAPP Modeling, Analysis, Predictions, and Projections

CMMAP Reach for the sky.

Cloudy boundary layers are important…

- For Earth's albedo
- For air mass transformation and the Hadley circulation
- For air-sea and air-land interaction
- For weather and the diurnal cycle over land
- For cloud feedbacks on climate
- For cloud-aerosol interaction

Why do cloudy boundary layers challenge global models?

How can we better simulate them?

Are we having fun yet?

Some marine boundary-layer cloud types

Stratocumulus (Sc)

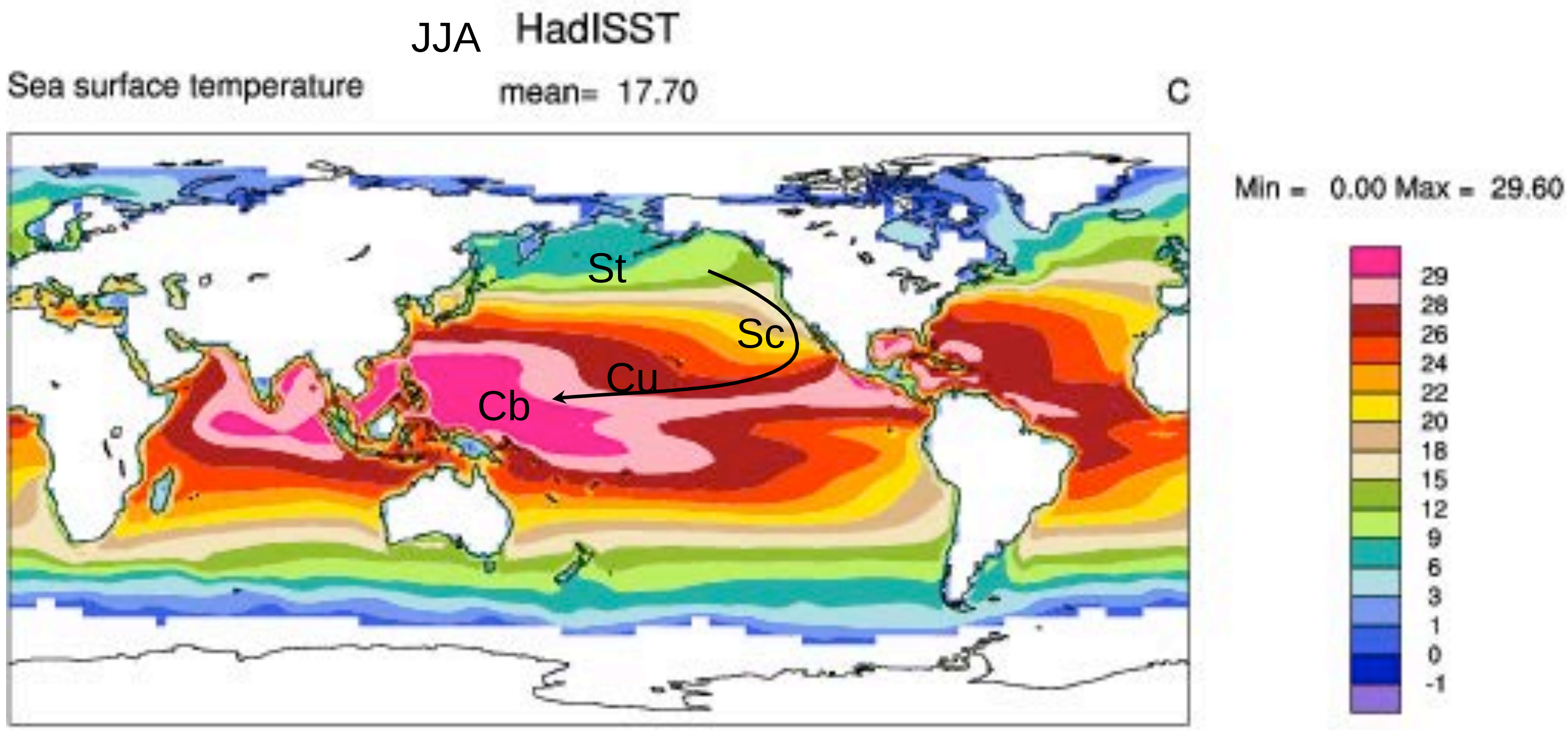
Stratus (St)

Cu under Sc

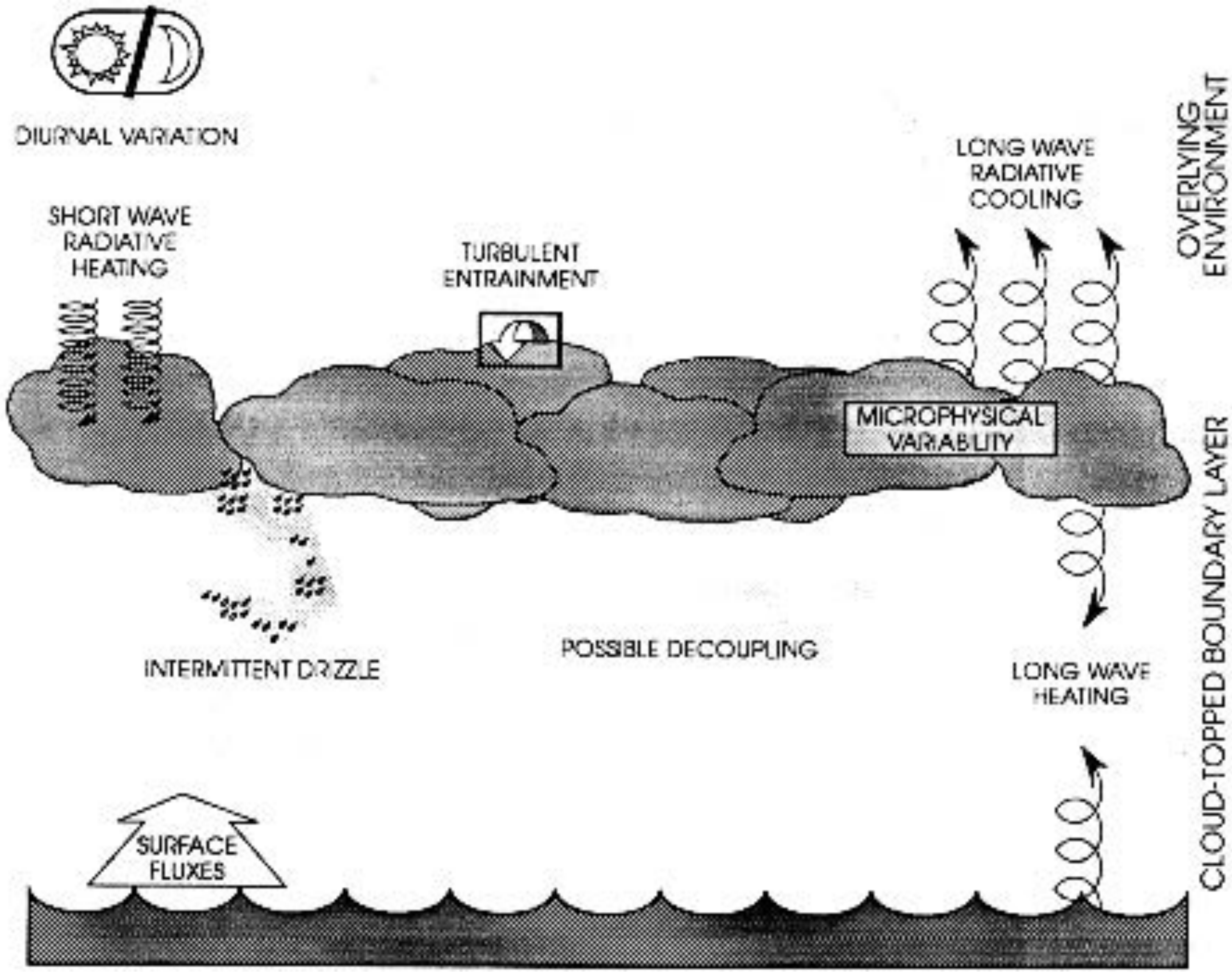
Cumulus (Cu)

Observations over the oceans

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



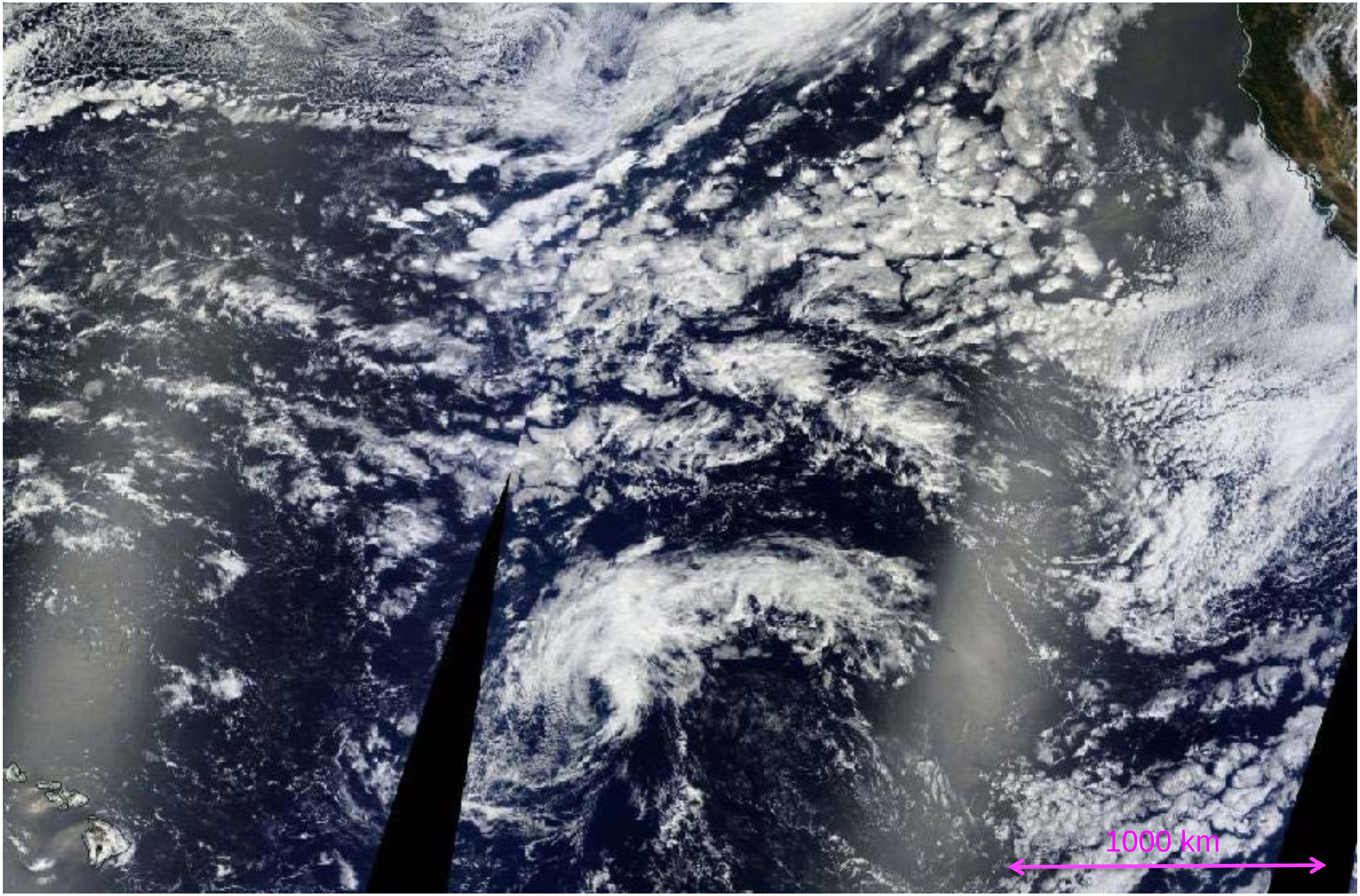
Cloud-topped BL processes



Siems et al. 1993

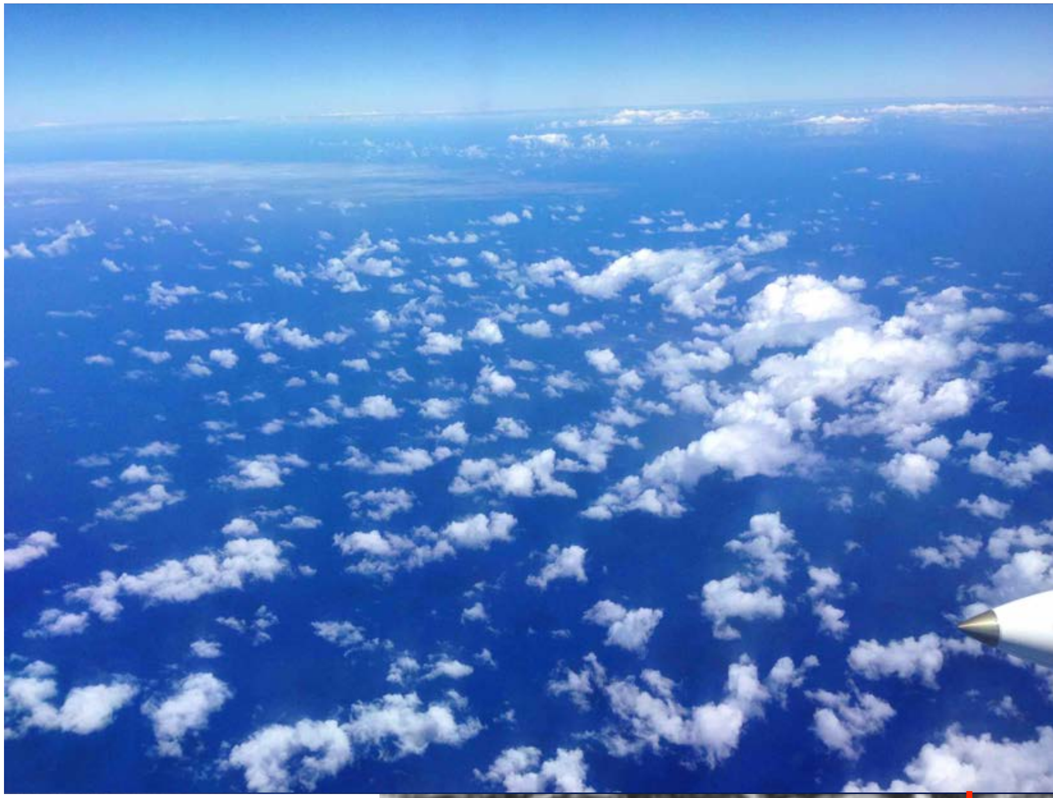
22 July 2015, ~10:30 LT (MODIS/Terra)

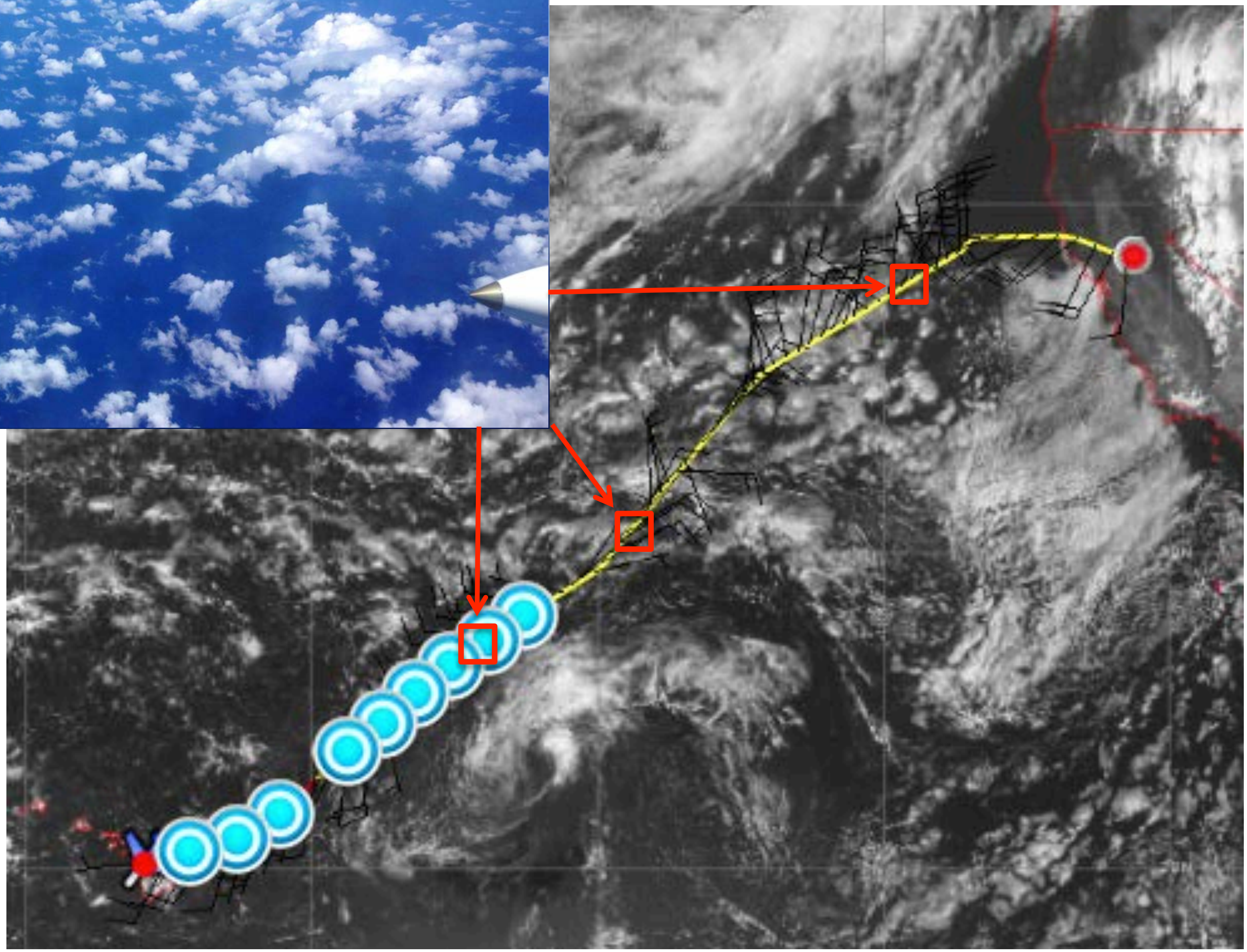
EOSDIS Worldview



Cloudy PBL has rich vertical and mesoscale structure!

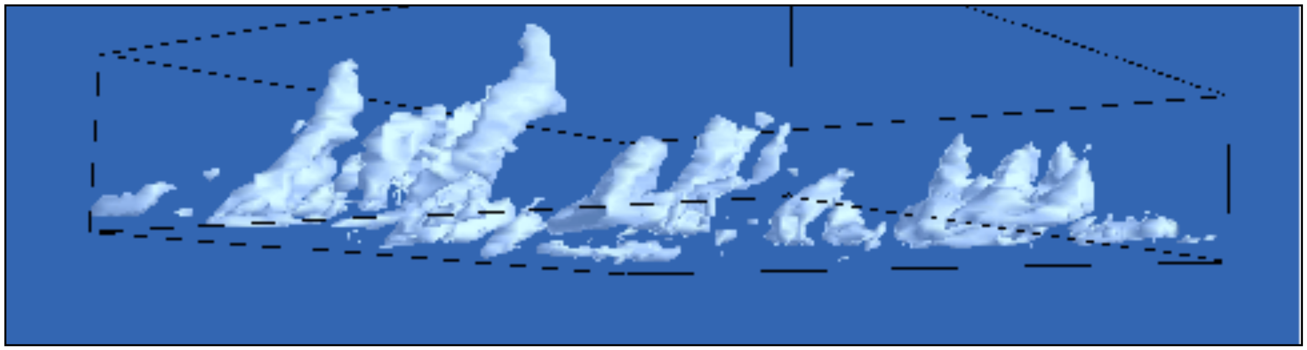
RF08 22 July 2015





Can this rich cloudy PBL structure be simulated?

Vertical structure qualitatively well simulated by LES



LES can quantitatively simulate the Sc-Cu transition

Dussen et al. 2013

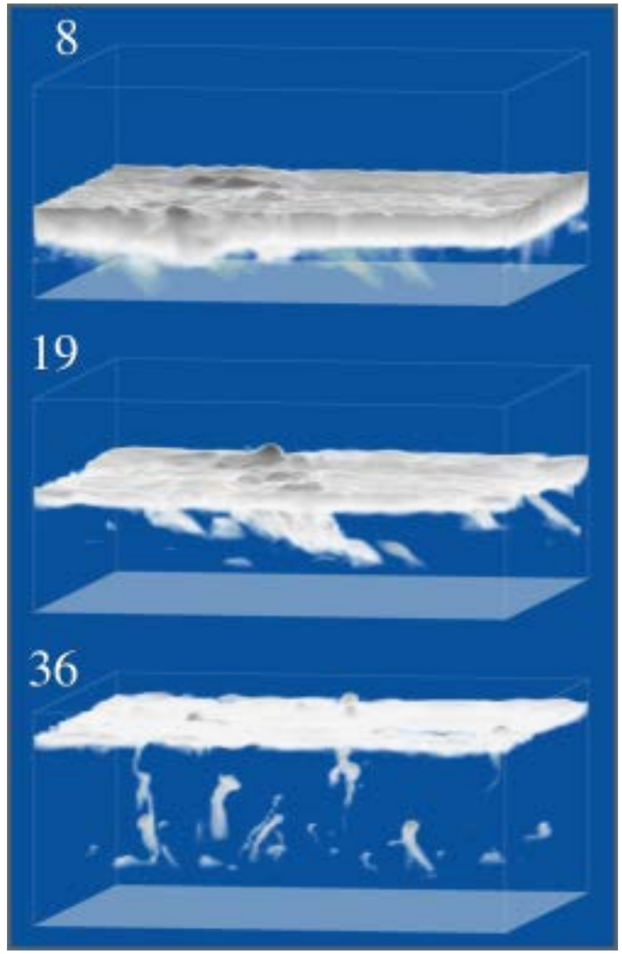
ASTEX (1992) Lagr. 1

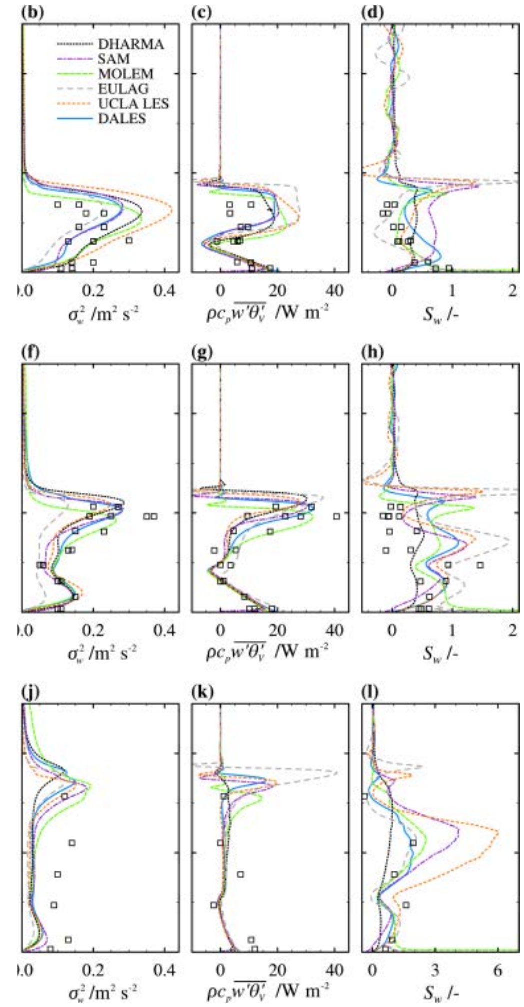
6 LES models

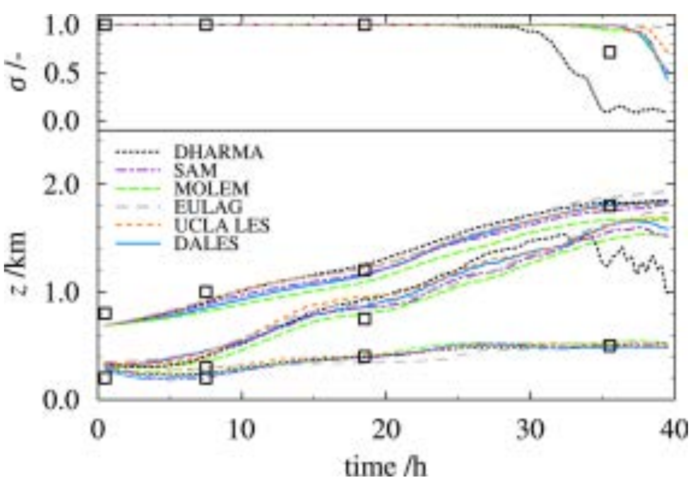
Cloud-layer Δz = 5 m

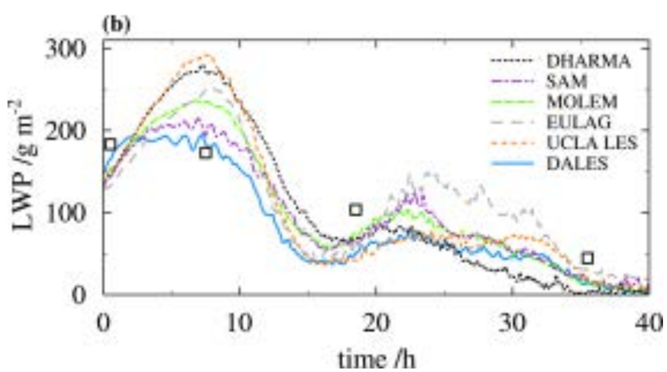
$L_x = L_y$ = 4.45 km

Nice agreement w obs







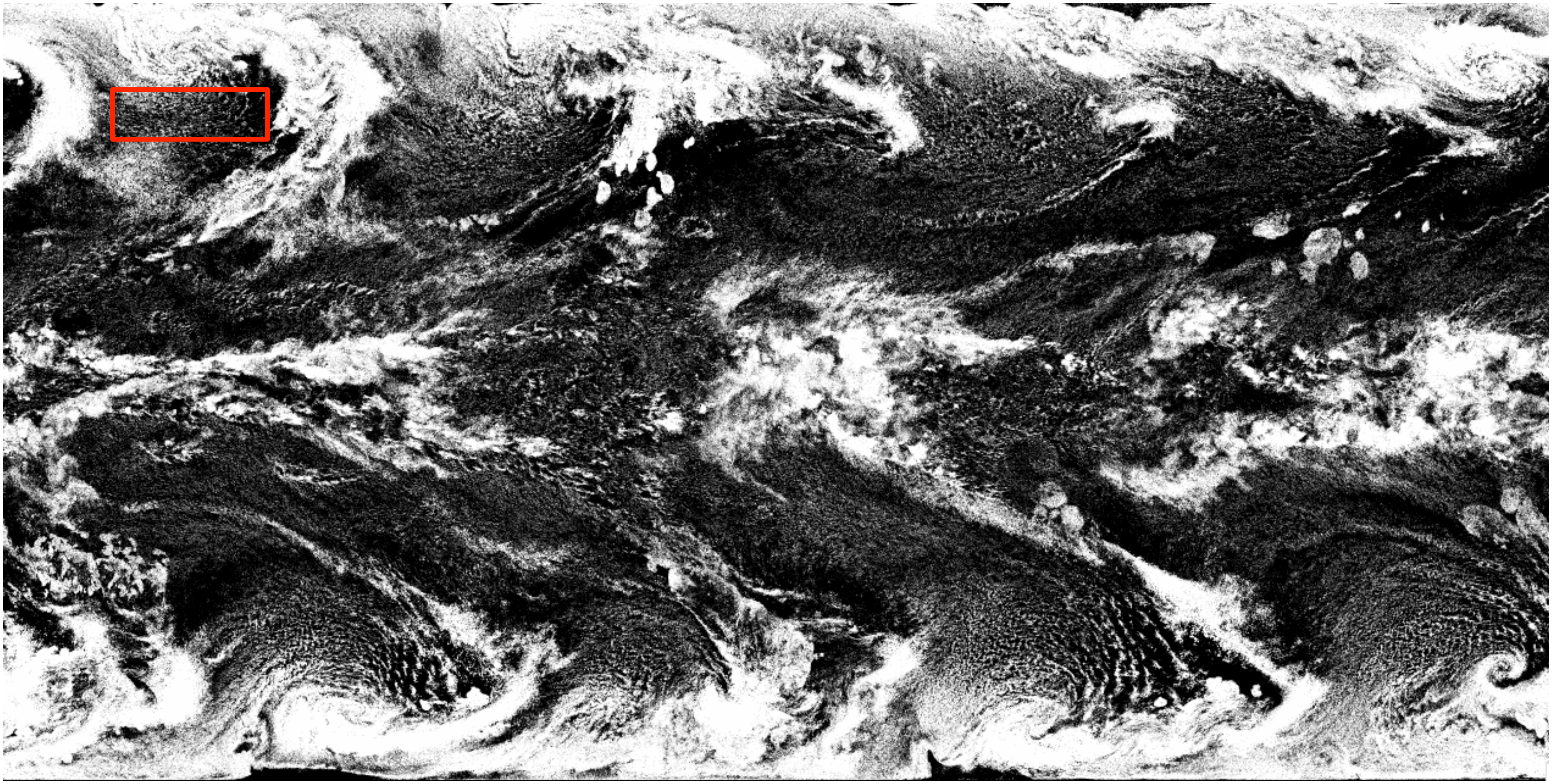


Mesoscale cloudy PBL structure simulated in GCRMs, other hi-res models

4 km near-global aquaplanet CRM
Bretherton and Khairoutdinov 2015

Cloud cover at t=0

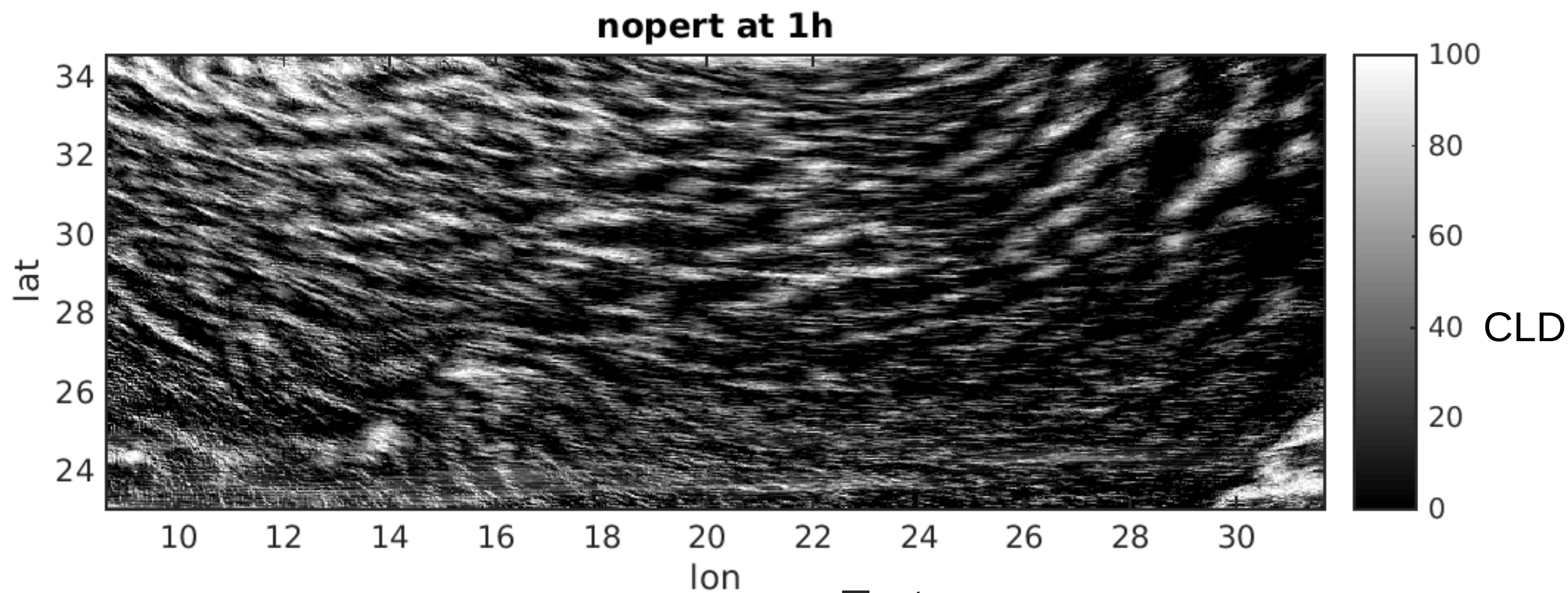
46°N



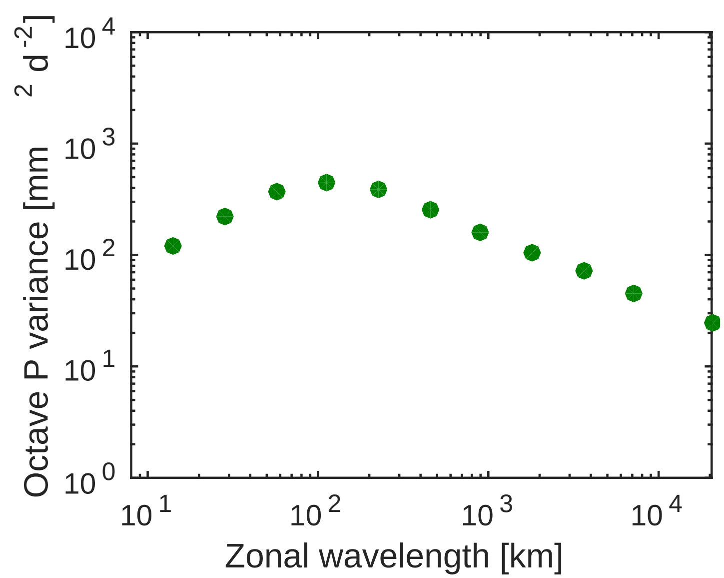
46°S

20480 km = 184° longitude

Zoom in on subtropics –mesoscale PBL cloud organization

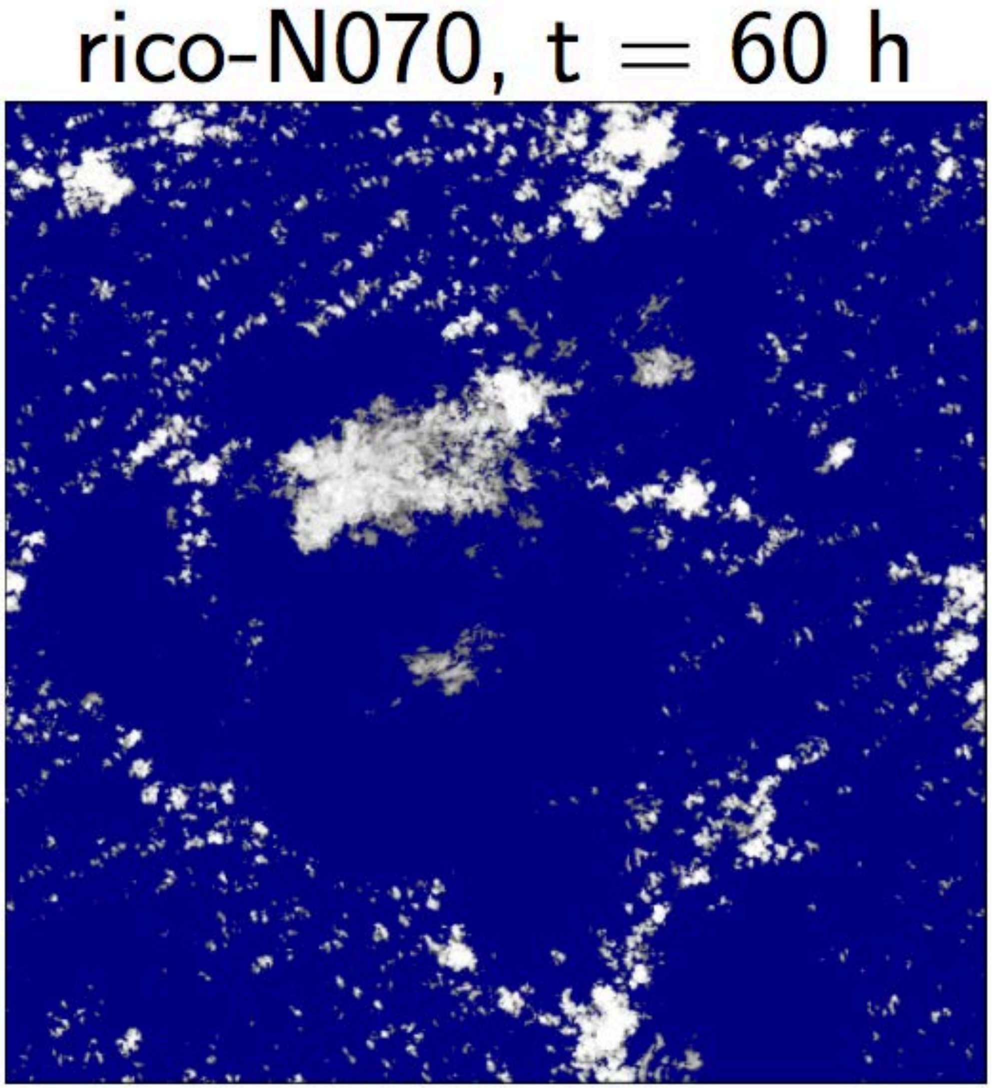


Latent heat energy and buoyancy production of turbulence in PBL clouds are injected at all resolved scales, convectively energizing the mesoscale (DeRoode et al. 2004 JAS)



Large-domain LES also simulate mesoscale organization

51x51x5 km, Δx = Δy = Δz = 25 m
Precipitating shallow cumulus



Seifert et al. 2015
JAMES submitted

So process models work pretty well - why is cloudy PBL a GCM parameterization challenge?

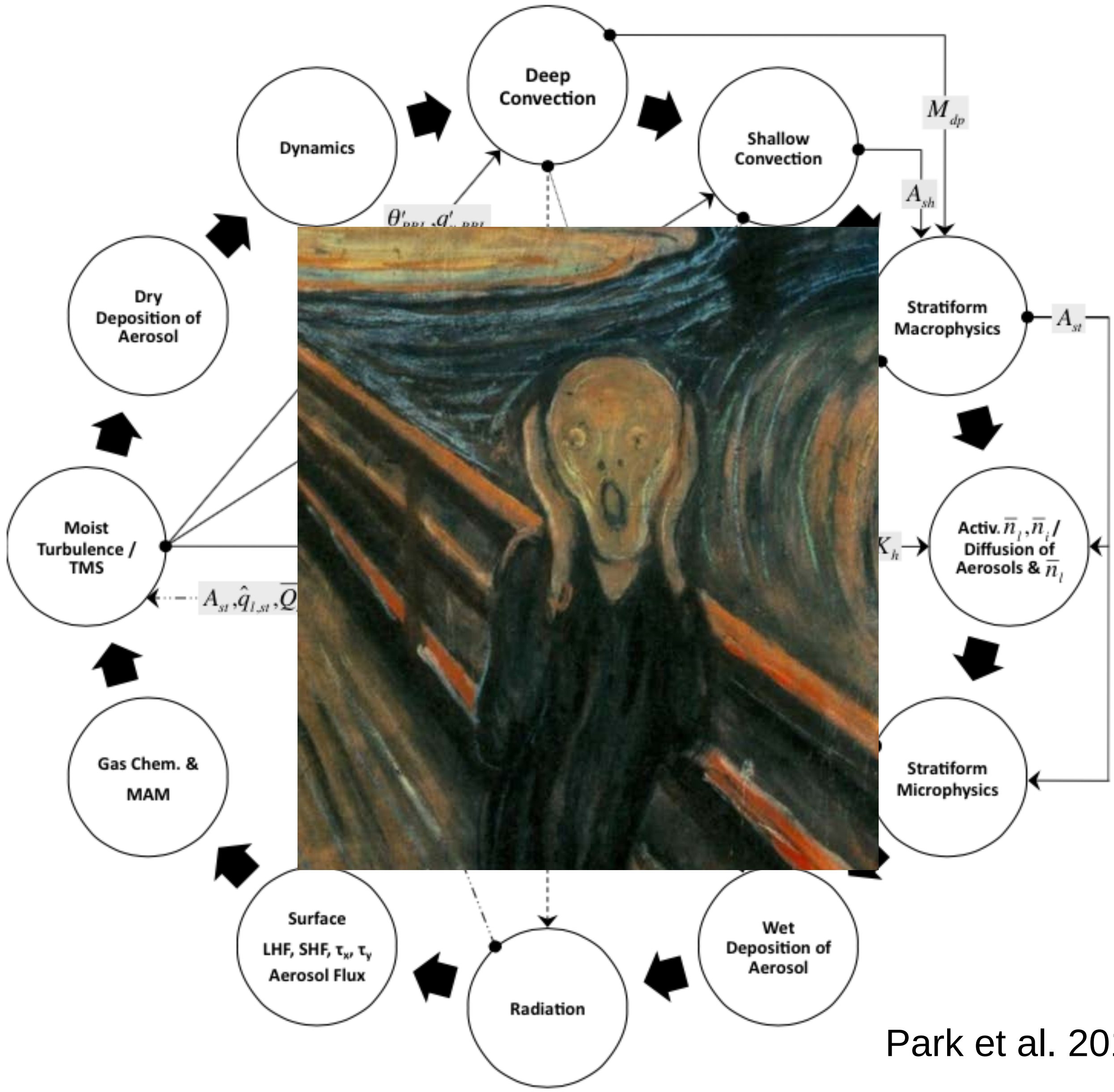
Crux issue

Many interacting moist processes (microphysics, convection, turbulence, radiation)	$\Longleftrightarrow$	Complex subgrid organization (cumulus updrafts, turbulent eddies, cold pools)

- And don’t forget t, z discretization issues due to rapid timescales and cloud thinness/smallness!

Contrast this with LES/CRM, where cloud-generating circulations are resolved and all parameterizations can act locally on the grid-box mean thermodynamic state, without need for a complex subgrid model.

The CAM5 family of physical parameterizations



Park et al. 2014 J Clim

The challenge of simulating PBL cloud processes

- Tight interactions between parameterizations
- Strong subgrid covariability
- Discretization issues and parameterization interactions are as challenging as uncertainties within parameterizations.

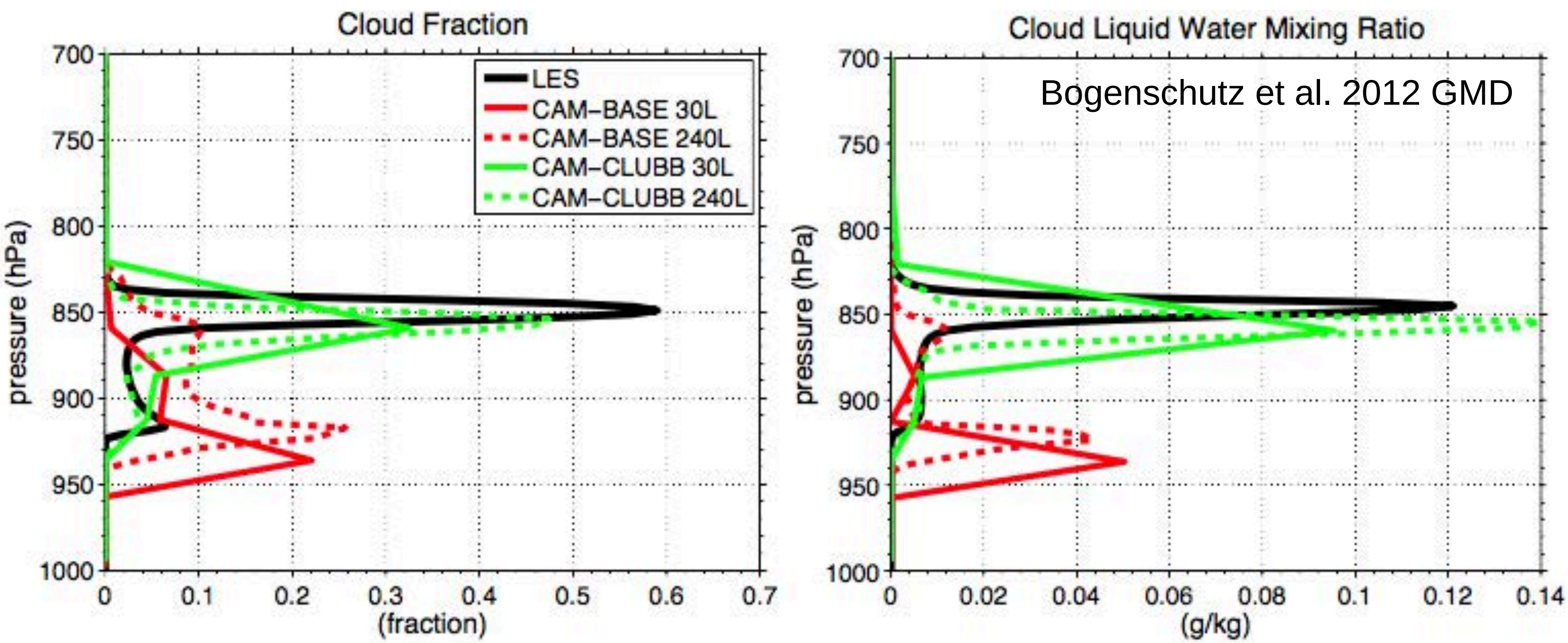
…require a ‘system view’ with focus on:

- Parsimony and balanced complexity
- Internal consistency
- Smooth transitions between PBL/cloud types
- Incremental evidence-based improvement
- Good easily-viewed documentation and code

Unified schemes - CLUBB

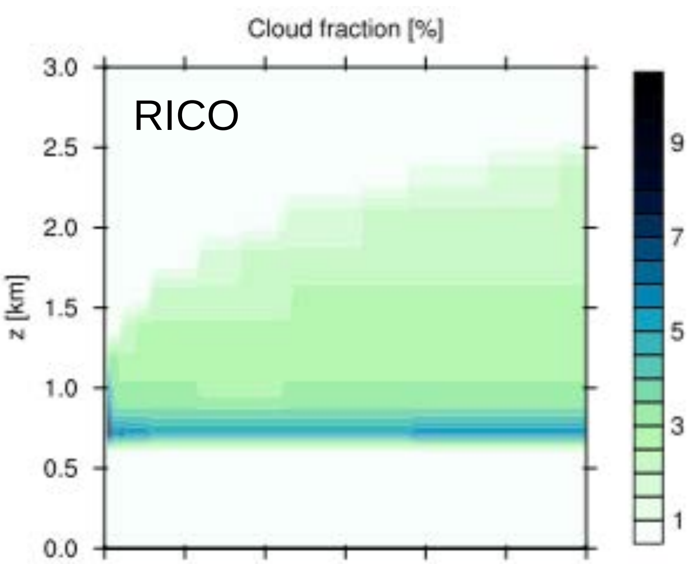
- Simplified 3rd-order turbulence closure with correlated double-Gaussian PDFs for w, q_t, θ_l used for turbulence/Cu/cloud statistics (Golaz et al. 2002; Larson et al. 2002)
- Nicely represents Sc, Cu and decoupled Cu/Sc PBLs with adequate grid resolution in z, t in SCM tests
- Adapted for global models and recently adopted for CAM6

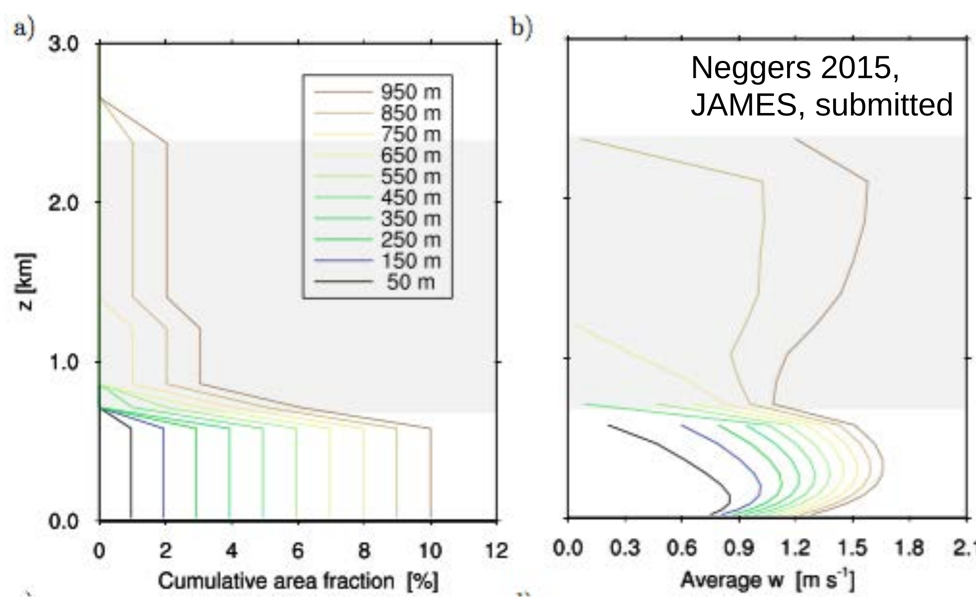
GCSS ATEX Cu under Sc case



Unified schemes: ED(MF)^n

- Simplified elegant multiplume shallow Cu parameterization (Neggers 2015), following his 2009 Dual-M scheme
- Coupled to eddy-diffusion local turbulence scheme.
- Subcloud plume area equipartitioned between plumes of different radii governing entrainment/detrainment rates
- Vertical velocity equation for plume heights.
- Competition between plumes dictates Cu mass flux
- Natural transition between dry convective PBL and Cu-topped PBL

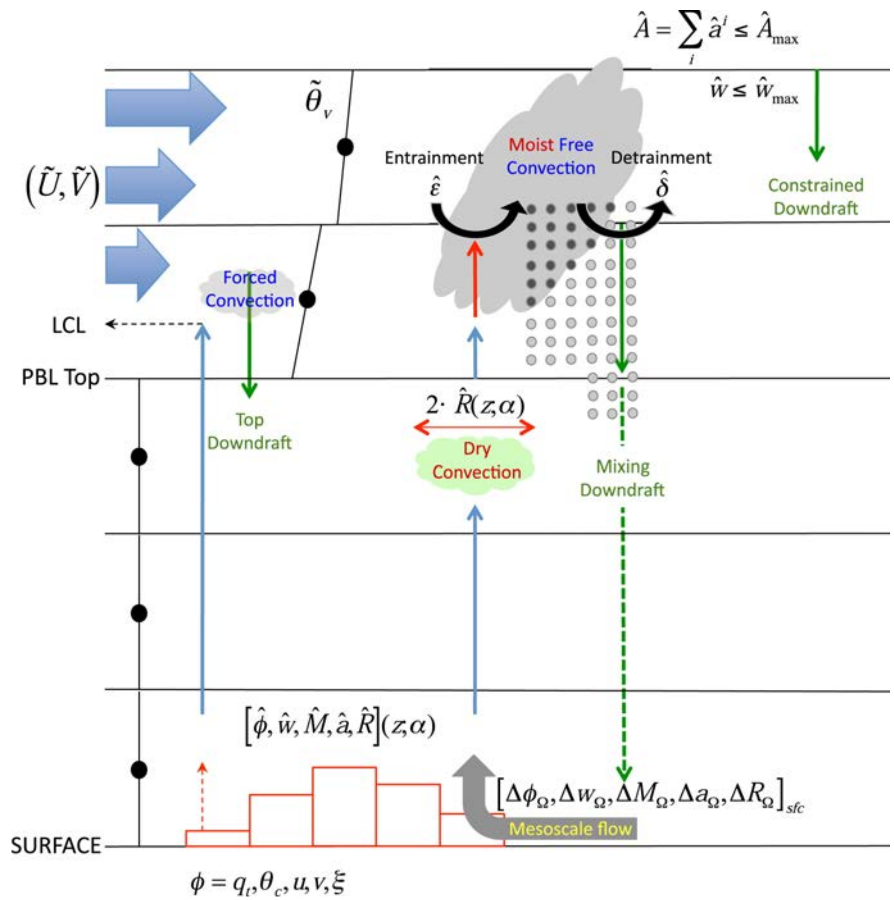




Unified schemes - UNICON

- A comprehensive cumulus and nonlocal turbulence parameterization for CAM5 designed to work with a local turbulent mixing scheme (Park et al. 2014 JAS)

- Buoyancy sorting updrafts of varying initial radius in the surface layer, each with multiple downdraft types
- PDF of area fractions for different updraft radii.
- Complex scheme for cold pool formation and mesoscale circulations in PBL, interacting with plume properties



UNICON simulation of SE Pacific Sc-Cu transition

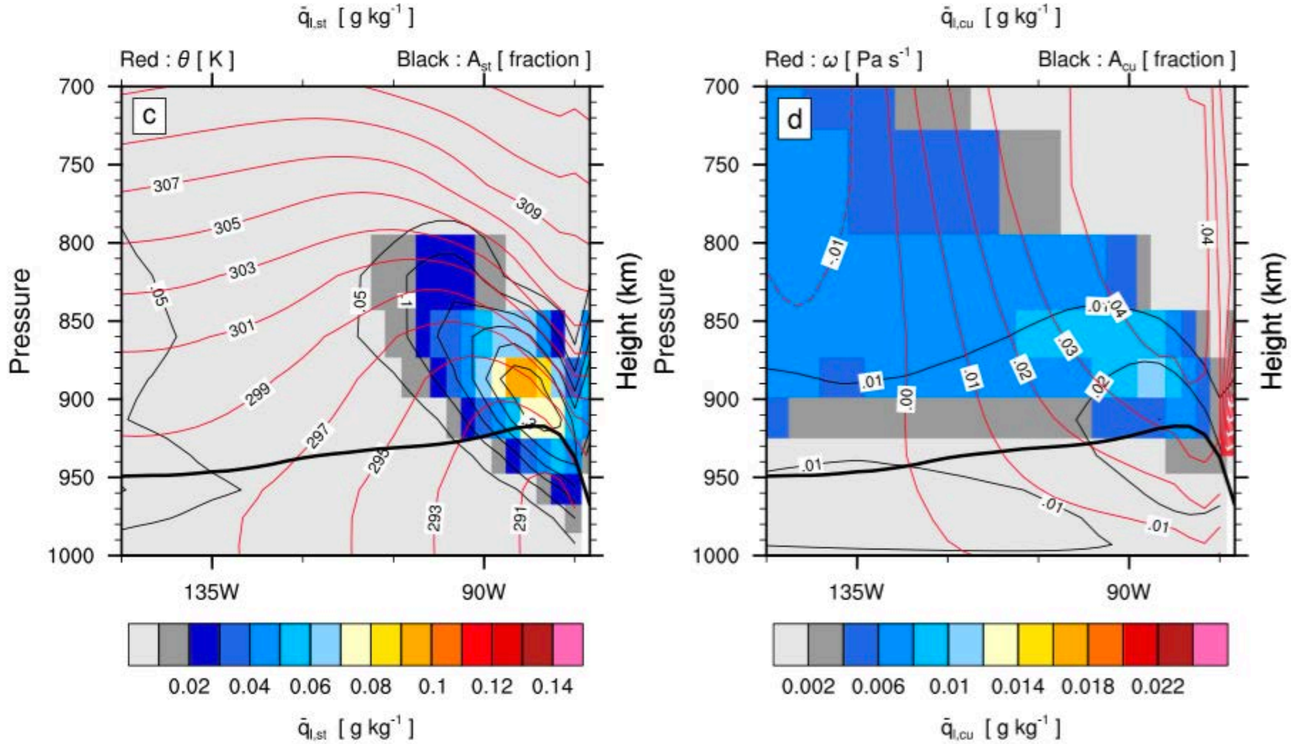


FIG. 16. Vertical cross sections of (a),(c) grid-mean potential temperature $\overline{\theta}$, stratus fraction A_{st}, and grid-mean stratus LWC $\overline{q}_{l,st}$ and (b),(d) grid-mean subsidence rate $\overline{\omega}$, cumulus fraction A_{cu}, and grid-mean cumulus LWC $\overline{q}_{l,cu}$ along 20°S during SON from (a),(b) CAM5 and (c),(d) UNICON. In each panel, a thick, solid black line denotes the simulated PBL height.

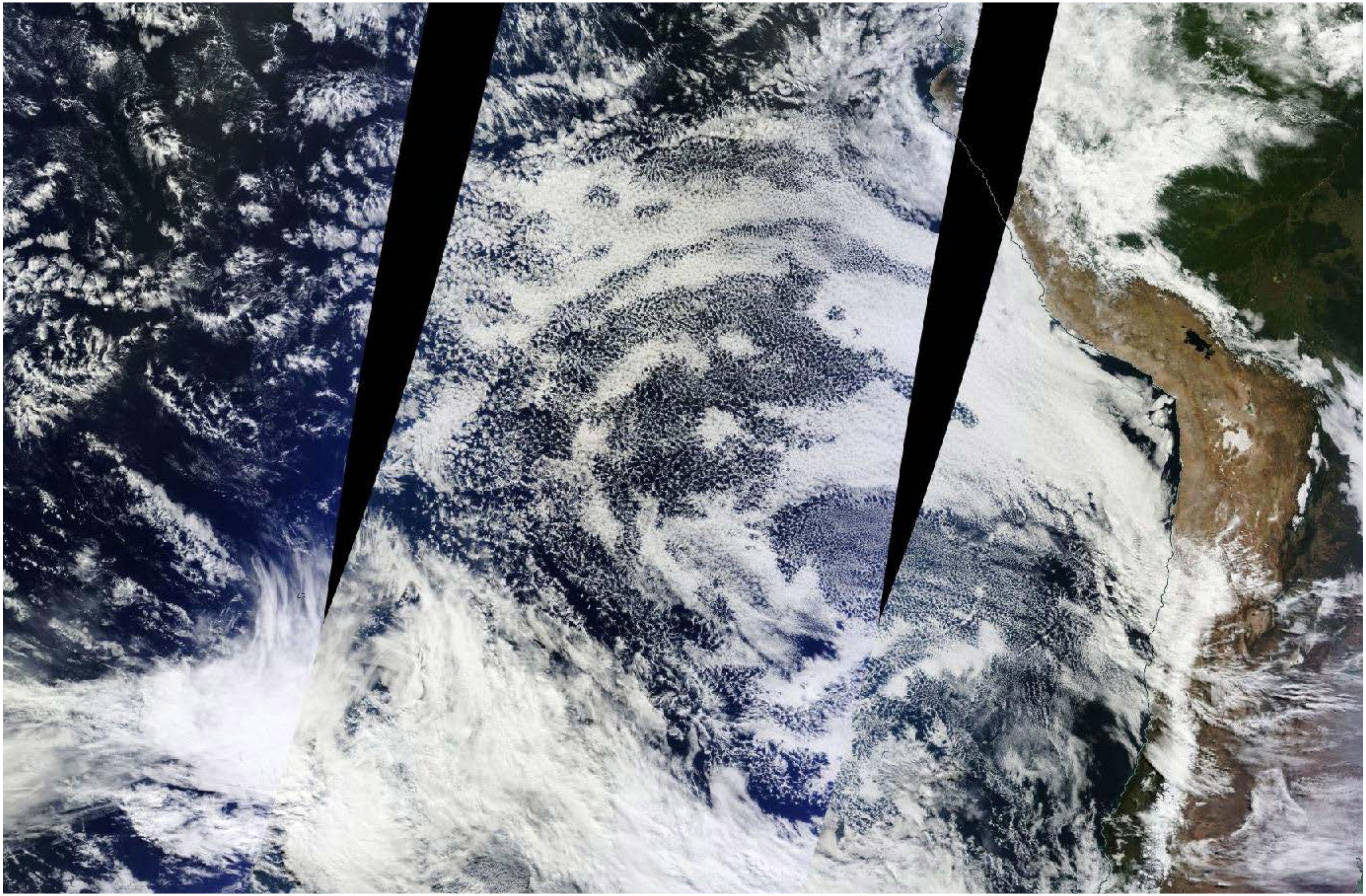
Also improves MJO, deep Cu diurnal cycle, double-ITCZ bias

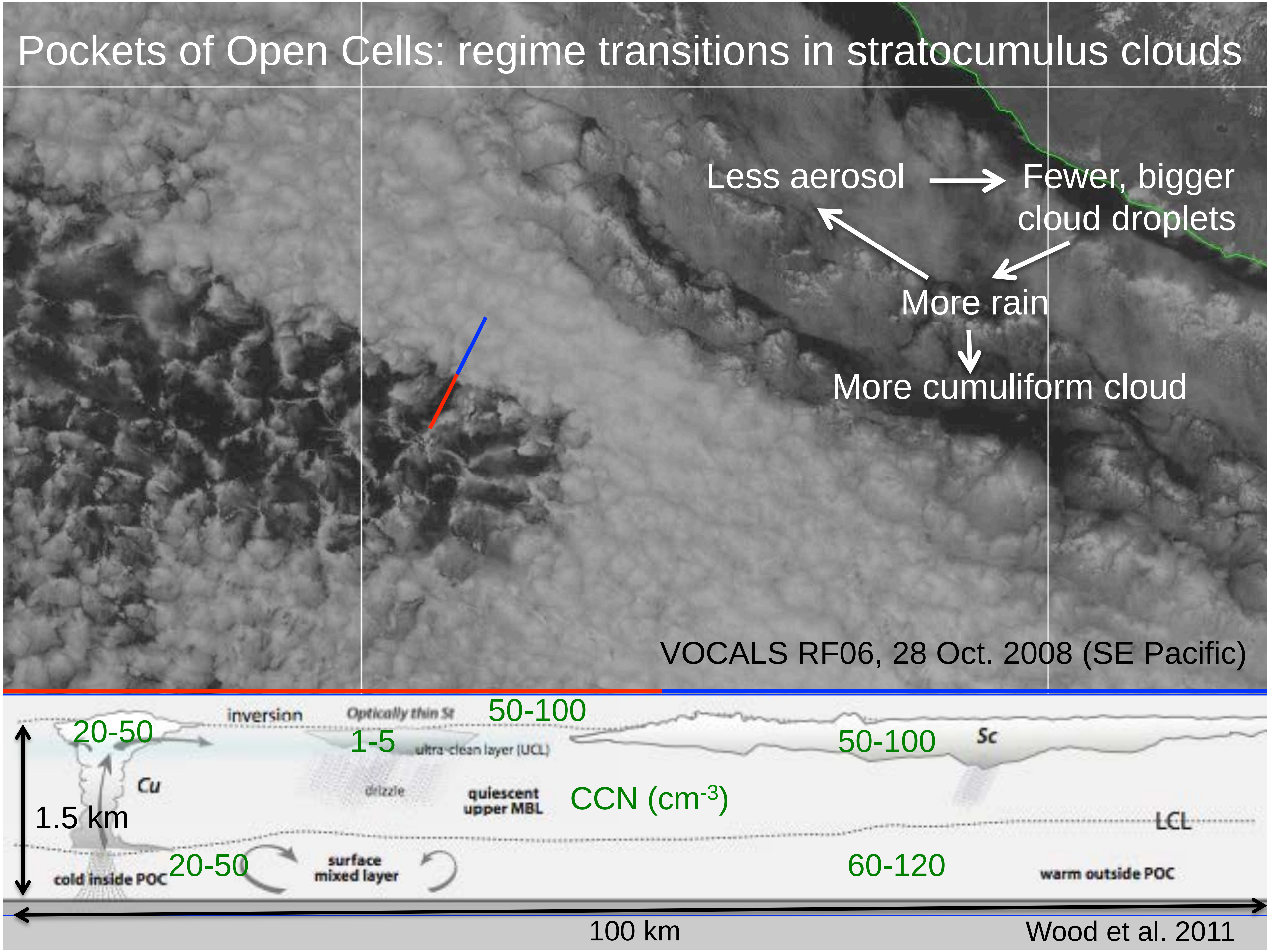
One scientist's brainchild:

- Consistent, careful, complete
- complex, subtle, challenging to collaboratively improve

22 July 2015, ~10:30 LT (MODIS/Terra)

EOSDIS Worldview

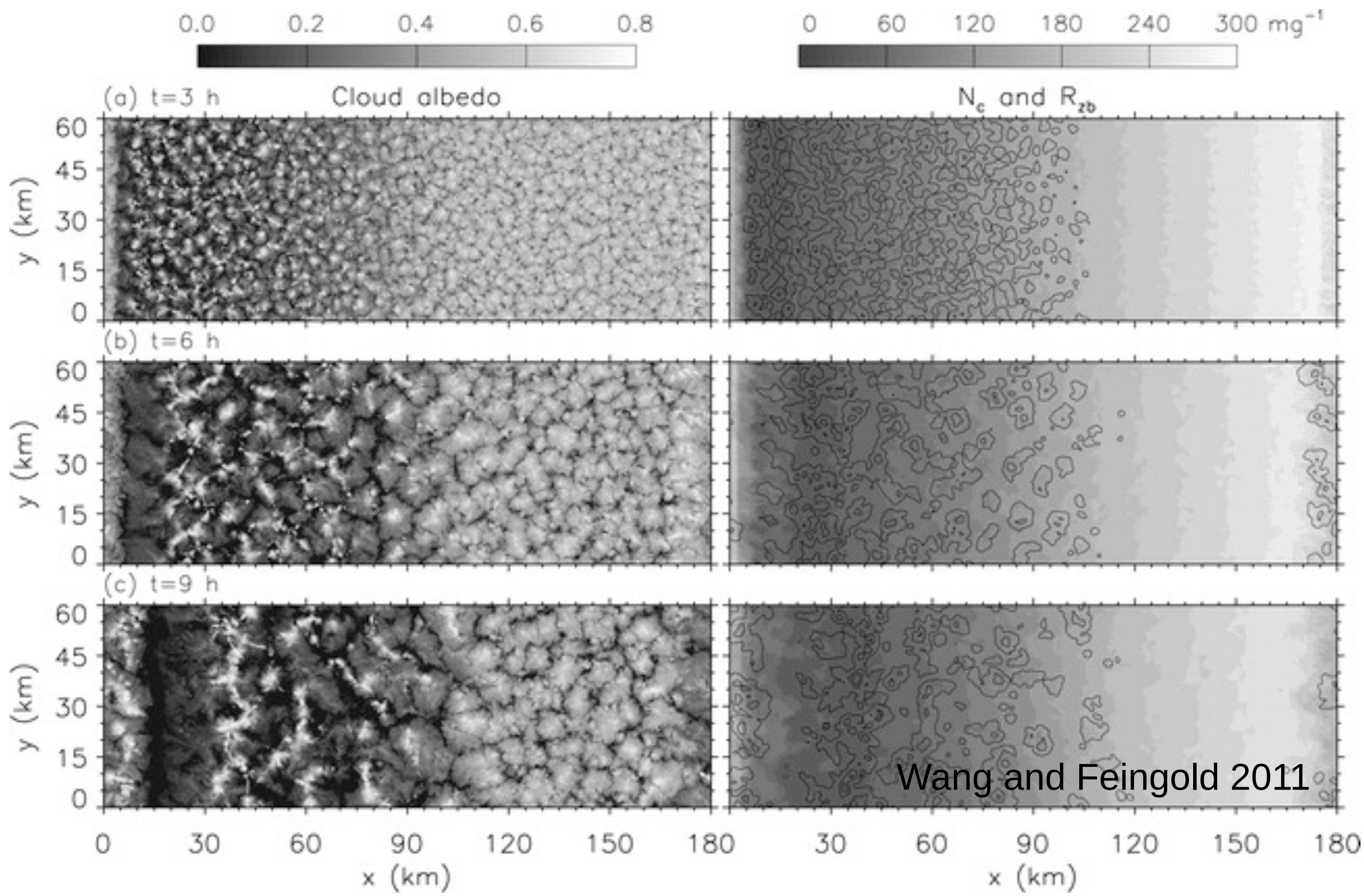




Pockets of Open Cells: regime transitions in stratocumulus clouds
Less aerosol
Fewer, bigger cloud droplets
More rain
More cumuliform cloud
VOCALS RF06, 28 Oct. 2008 (SE Pacific)
inversion
Optically thin St
50-100
20-50
1-5
ultra-clean layer (UCL)
50-100
Sc
Cu
drizzle
quiescent upper MBL
CCN (cm-3)
1.5 km
LCL
20-50
surface mixed layer
60-120
cold inside POC
warm outside POC
100 km
Wood et al. 2011

Do smooth aerosol variations make abrupt cloudiness variations?

- No. The cloud morphology is a continuous function of the imposed CCN conc.

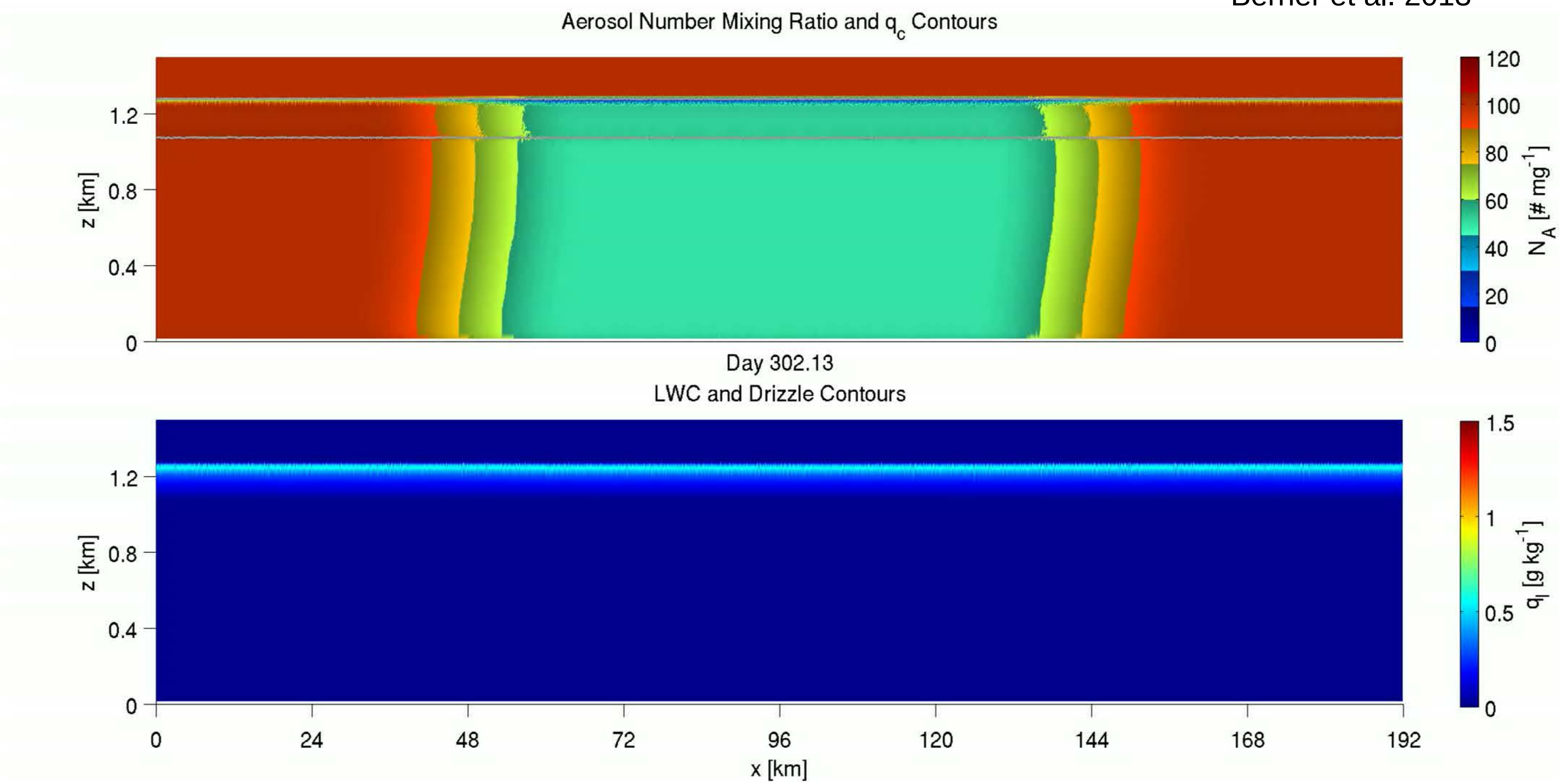


Wang and Feingold 2011

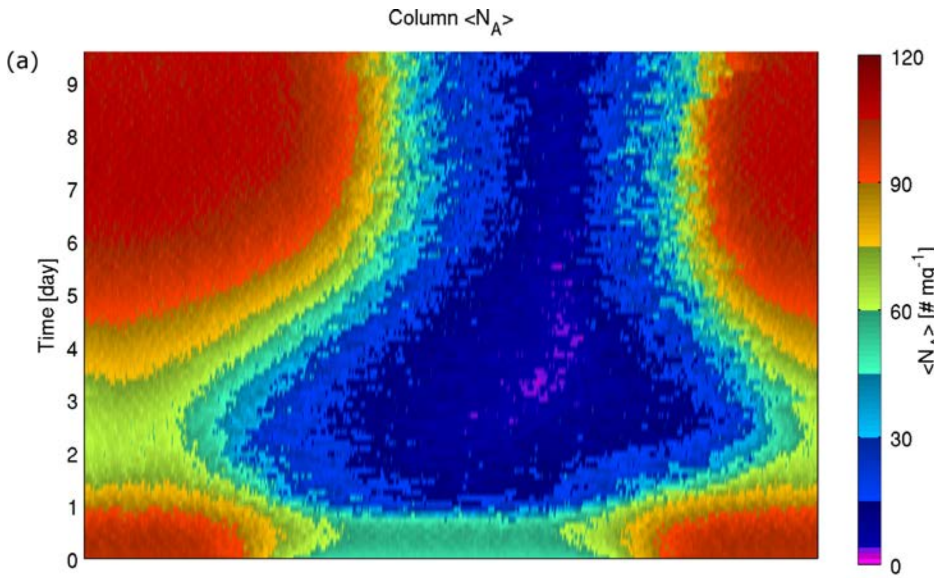
POC development in aerosol-coupled LES

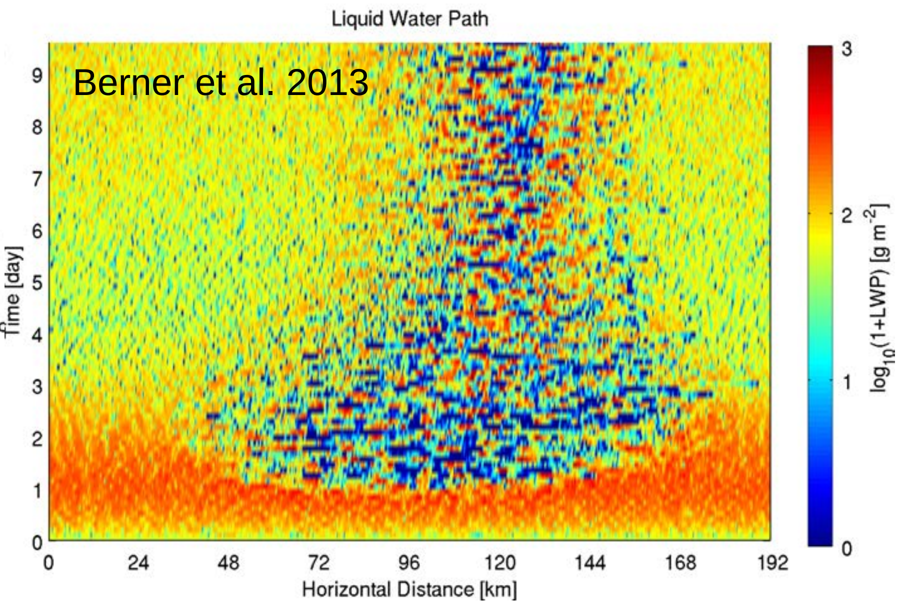
Model setup: Initial RF06 case with uniform initial thermodynamic sounding but with PBL aerosol concentration varying from 100 to 50 mg^{-1} across a 192 km domain.

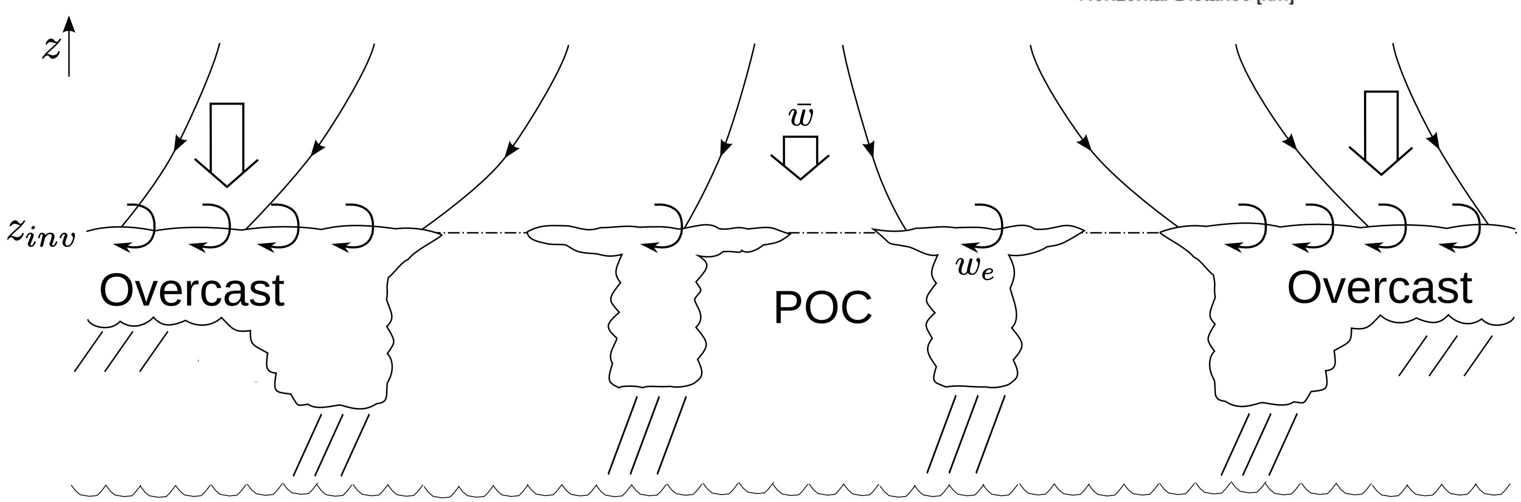
Berner et al. 2013



POCs: Mutually supporting cloud-aerosol regimes



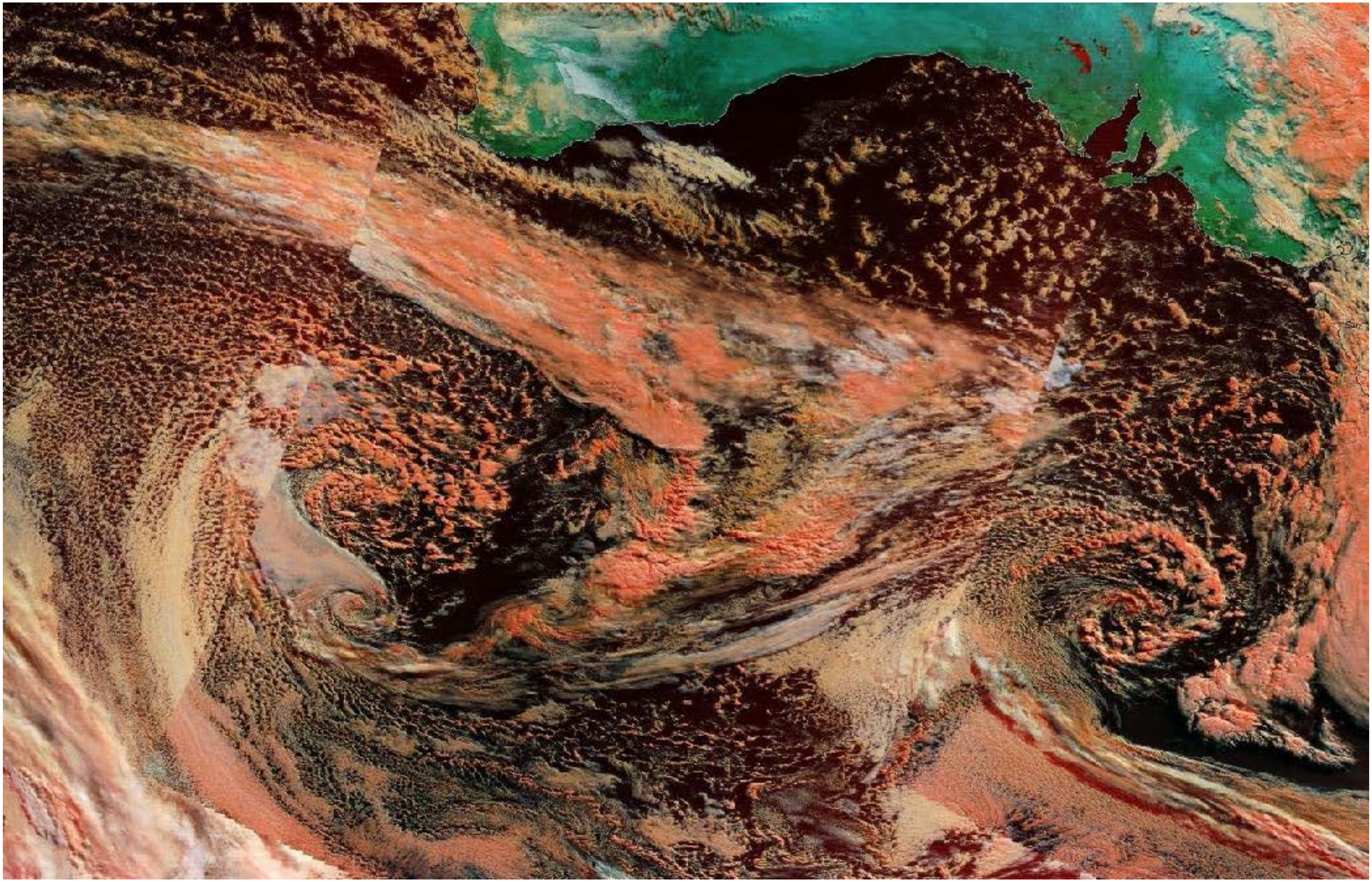




Inversion height locked between ‘bistable’ overcast and open-cell regimes
Strong entrainment in overcast regime keeps inversion up, prevents POC collapse
Weak entrainment in open-cell regime keeps inversion down and overcast Sc thin.

22 July 2015, ~10:30 LT (MODIS/Terra 3-6-7)
orange= ice (+sun angle+large drops+…?)

EOSDIS Worldview

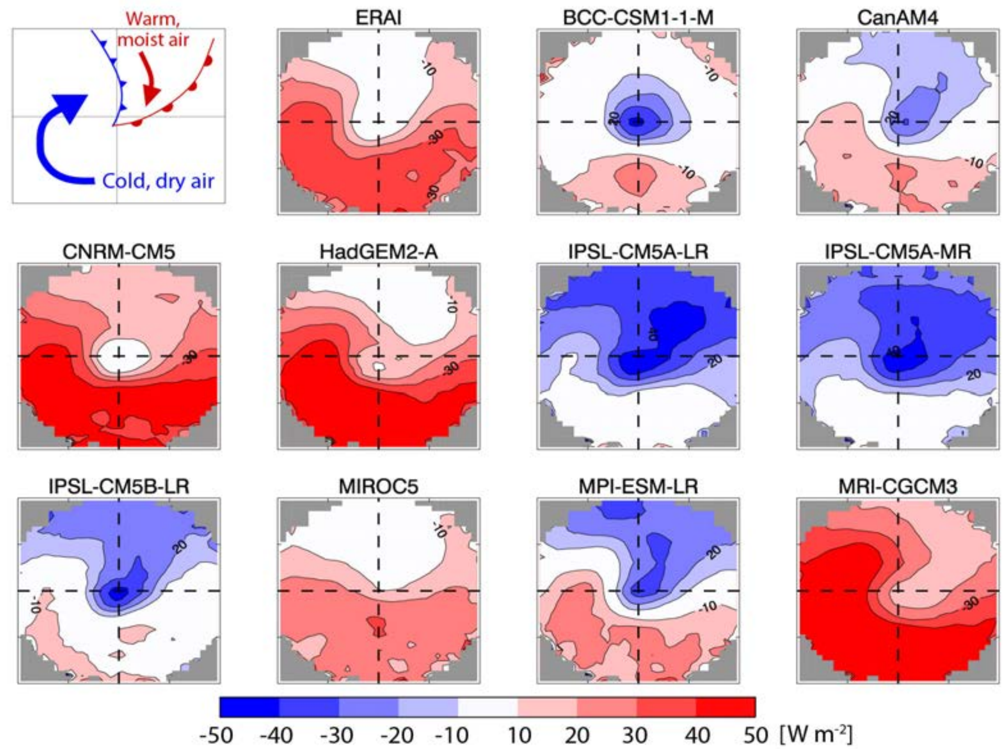


Extratropical cloudy PBL challenges

In the cold sector of extratropical cyclones, most global models simulate too little PBL cloud.

1. Vertical profile biases due to Cu/turb schemes?
2. Too little supercooled liquid water?
3. Precip efficiency too high?

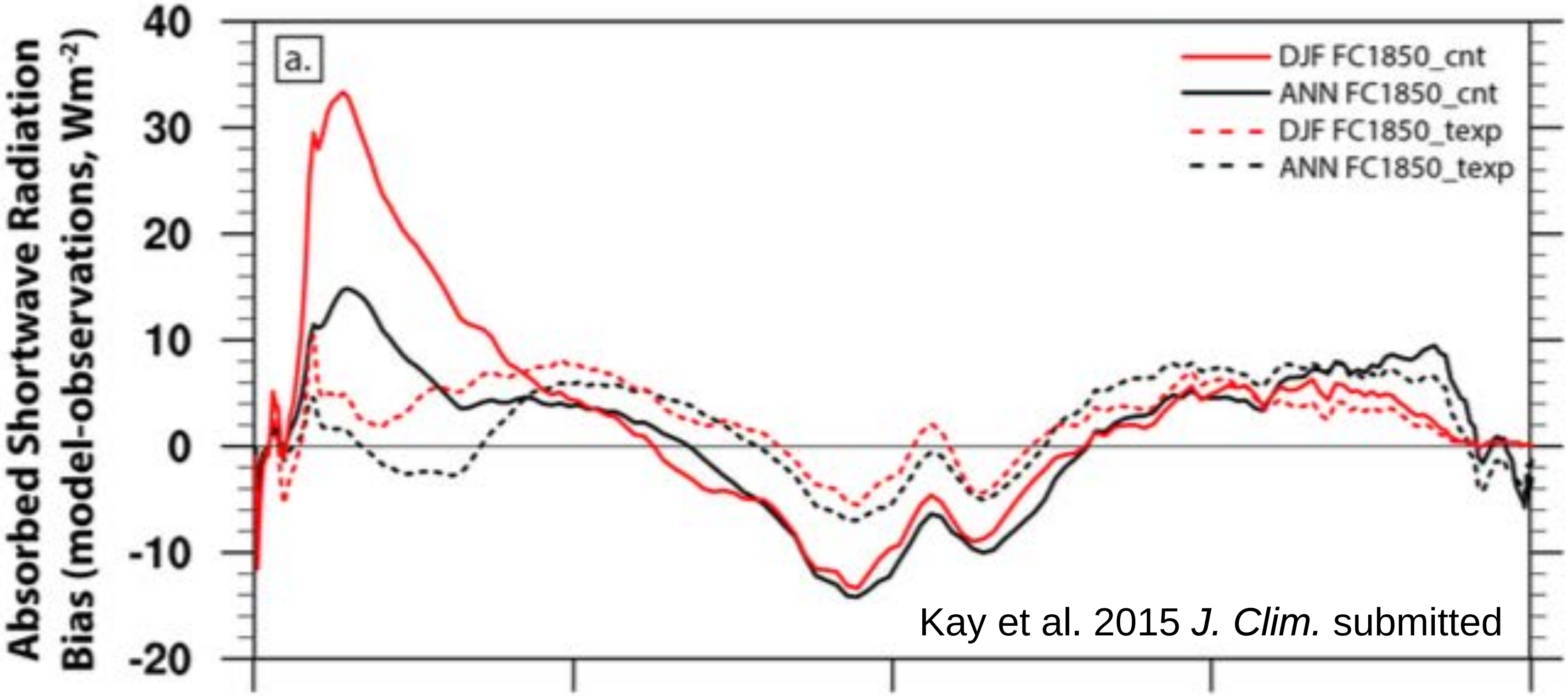
Aerosol/CCN/IN biases could play into these issues.



Cyclone compositing indicates consistent patterns of insufficient reflected shortwave in the cold, dry regions of the cyclones. *Figure shows bias in absorbed shortwave radiation for AMIP models from Bodas-Salcedo et al. (2013).*

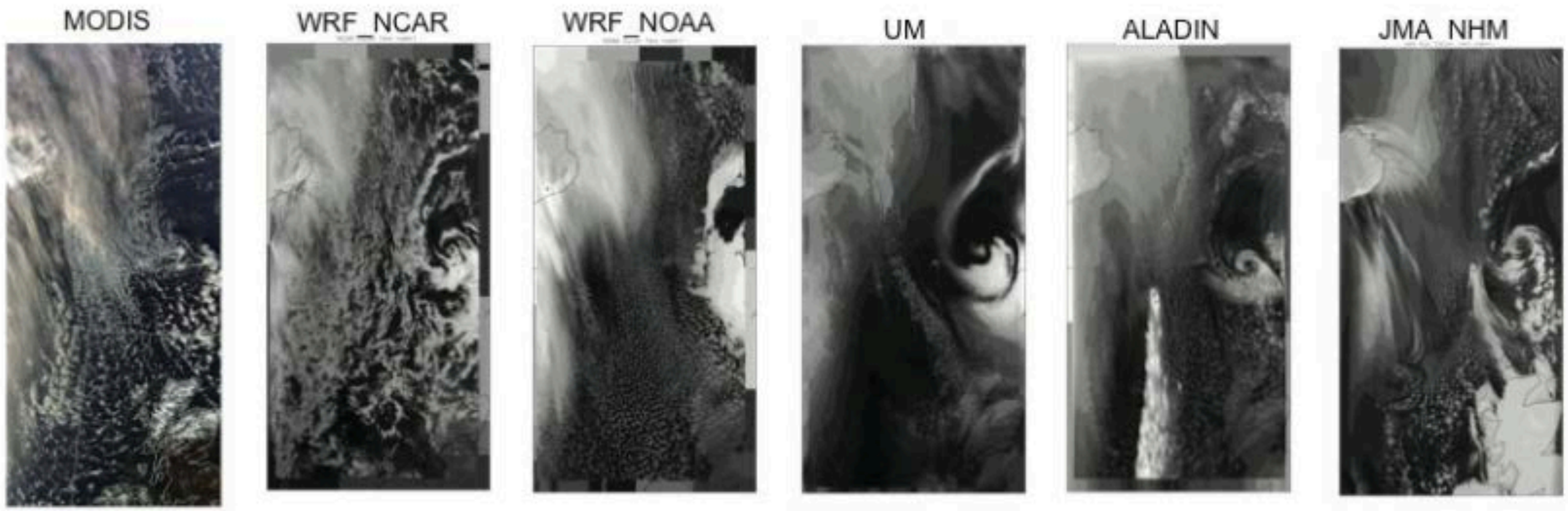
Cold sector cloud albedo sensitive to cloud phase

- CESM Southern Ocean net radiation bias removed by shifting temperature ramp in CAM5 ShCu parameterization to colder cloud glaciation temperatures



GASS Grey Zone intercomparison

- N Atlantic cold air outbreak case
- Based on Field et al. 2013 CONSTRAIN obs vs. UM
- WGNE/GASS intercomparison of LES/mesoscale/global simulations (led by Pier Siebesma) indicate PBL cloud sensitive to ice, aerosols, parameterization, resolution…



A Moderate-resolution Imaging Spectroradiometer (MODIS) longwave image of the cold air outbreak (left panel) and snapshots of simulations of five different mesoscale models. Lighter colors correspond to lower longwave radiation (colder temperatures). Overall the large-scale features are well reproduced and most models simulate a transition to a cumulus regime with a cellular structure. See the workshop report by P. Siebesma on page 7.

GEWEX News Feb. 2015

Conclusions: We *are* having fun with this…

- Cloudy PBLs: rich multiscale variability and vertical structure
- The turbulent dynamics of PBL cloud are well represented by LES, and their mesoscale dynamics by CRMs
- For global models, a key challenge is achieving a minimal consistent representation of the covarying subgrid structure of cloud and turbulence-related fields
- ‘Unified’ parameterizations have the best chance of achieving a realistically smooth dependence of cloud and PBL structure on environmental conditions
- Internal feedbacks can lead to PBL cloud regimes with sharp transitions (e.g. cloud-aerosol-precipitation➔POCs)
- Parameterization of supercooled liquid water and ice phase important for cold-topped PBL clouds
- Cloud-aerosol interaction and microphysics parameterizations are uncertainties for all model types