Aerosol-coupled LES of stratocumulus and POCs

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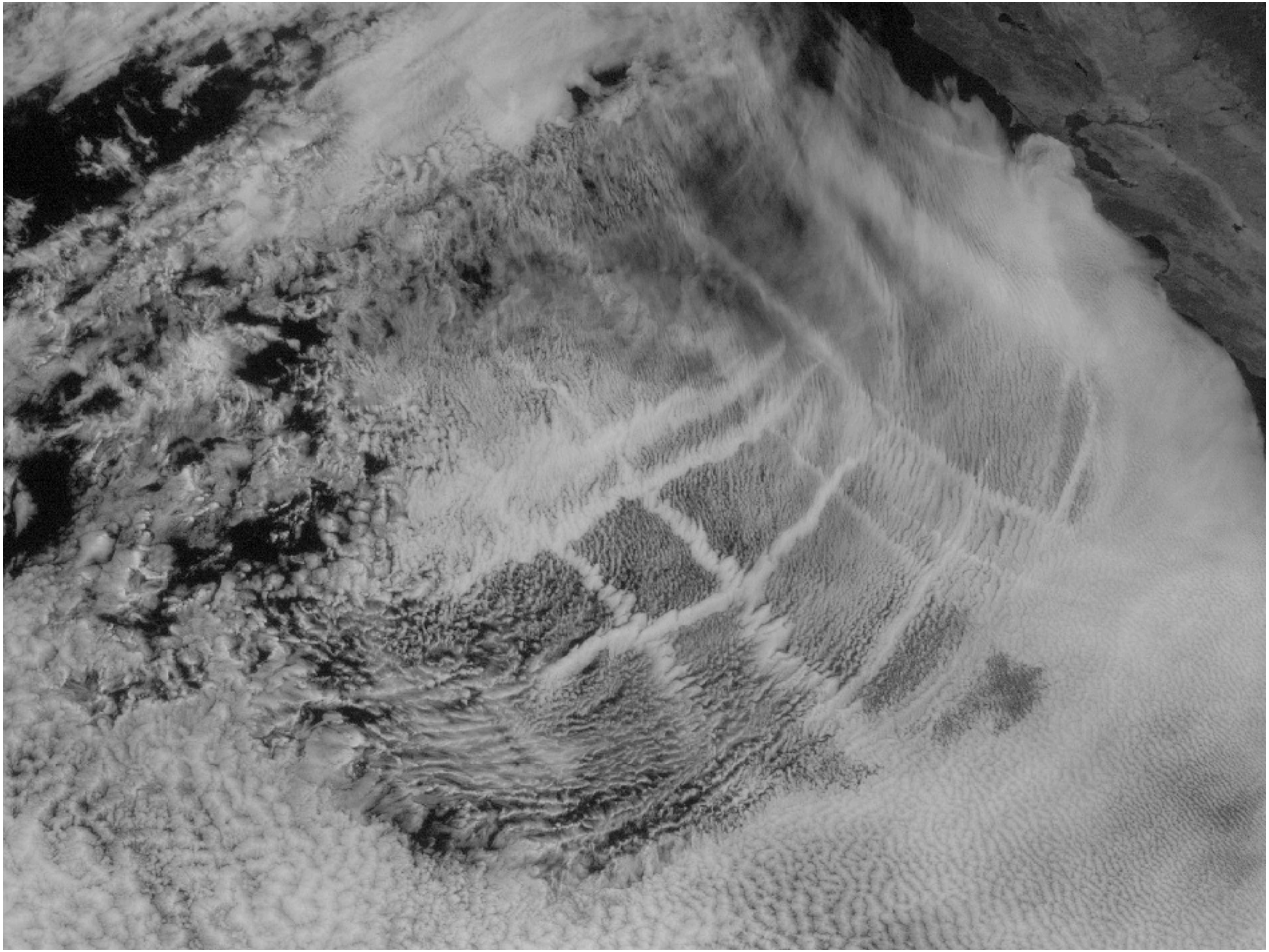
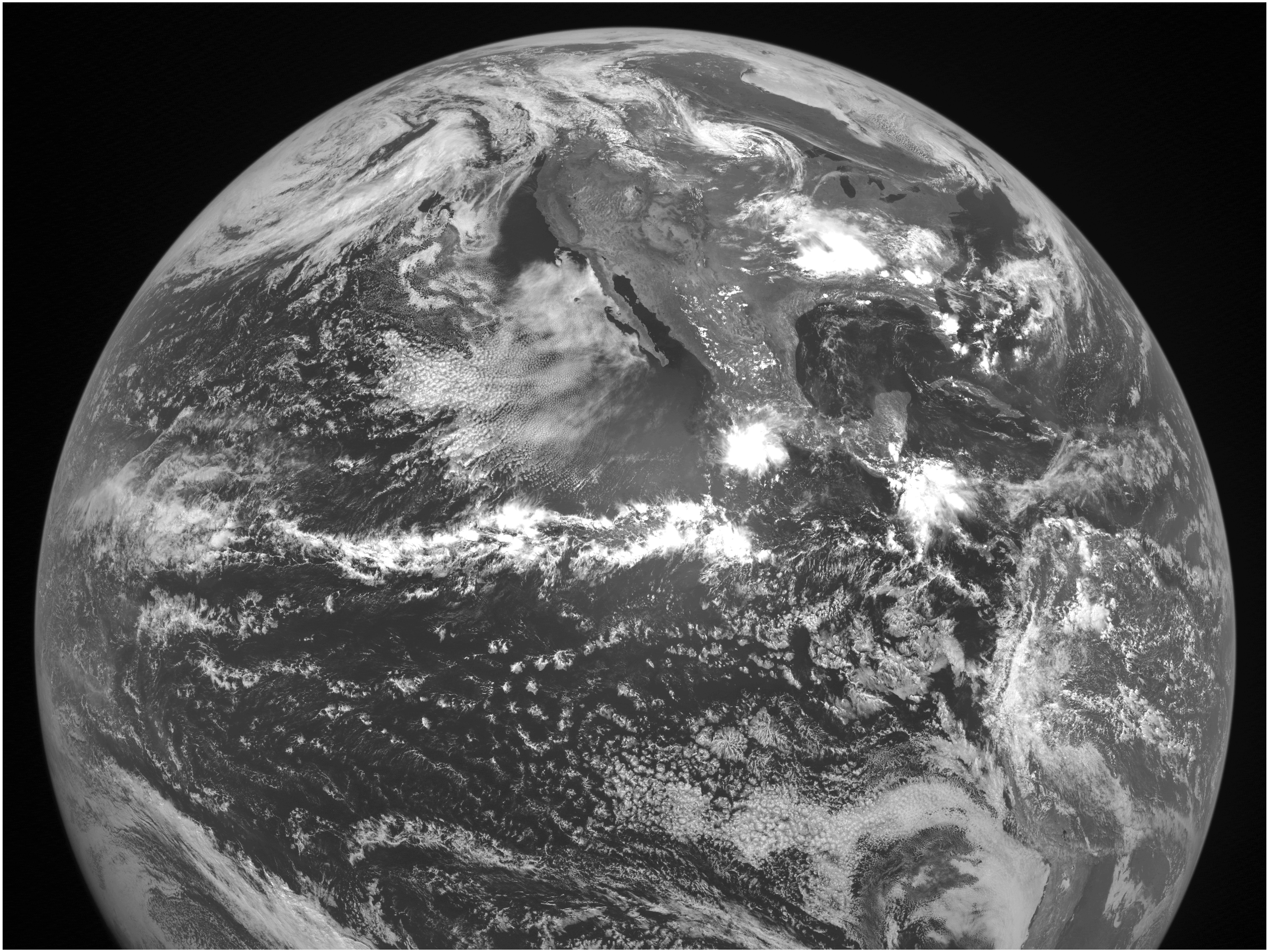
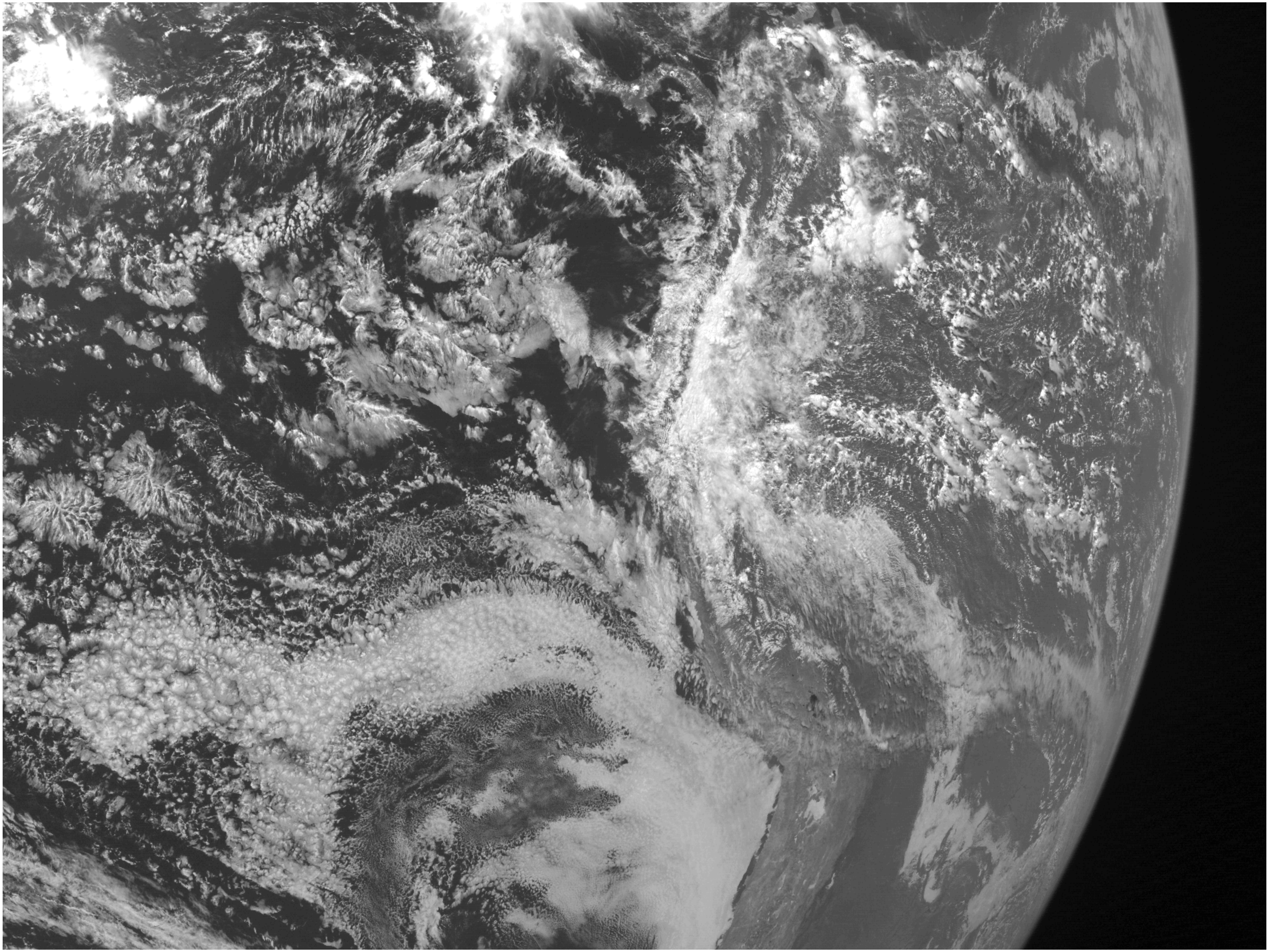
Marat Khairoutdinov (Stony Brook U.)



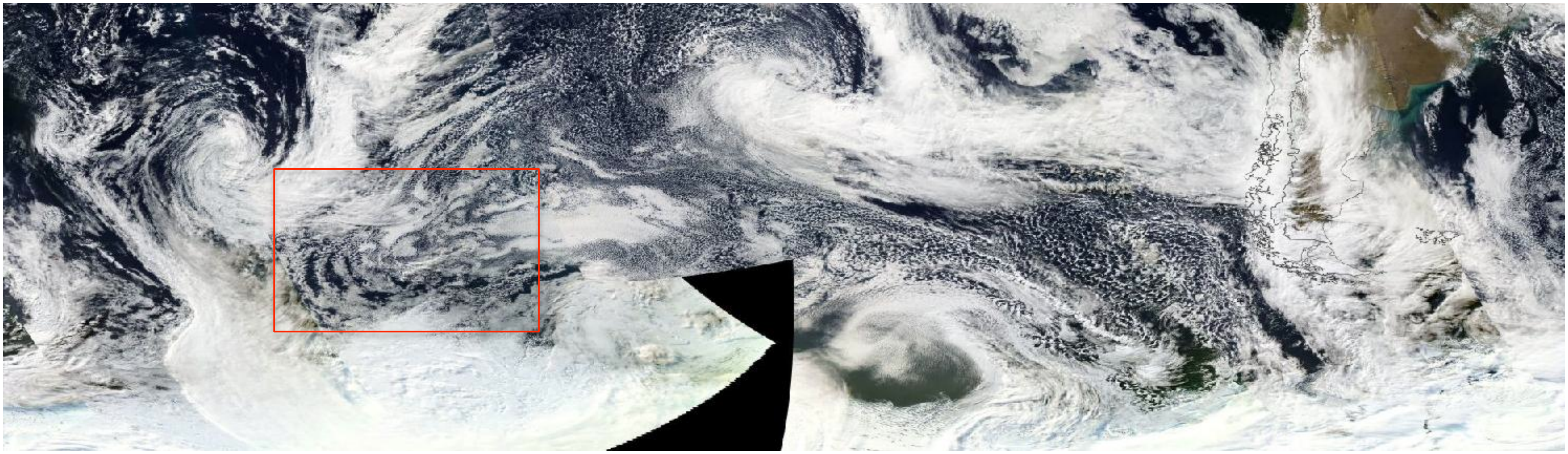




Low cloud patterns in the Southern Ocean

26 Aug 2013 Aqua composite (EOSDIS Worldview)

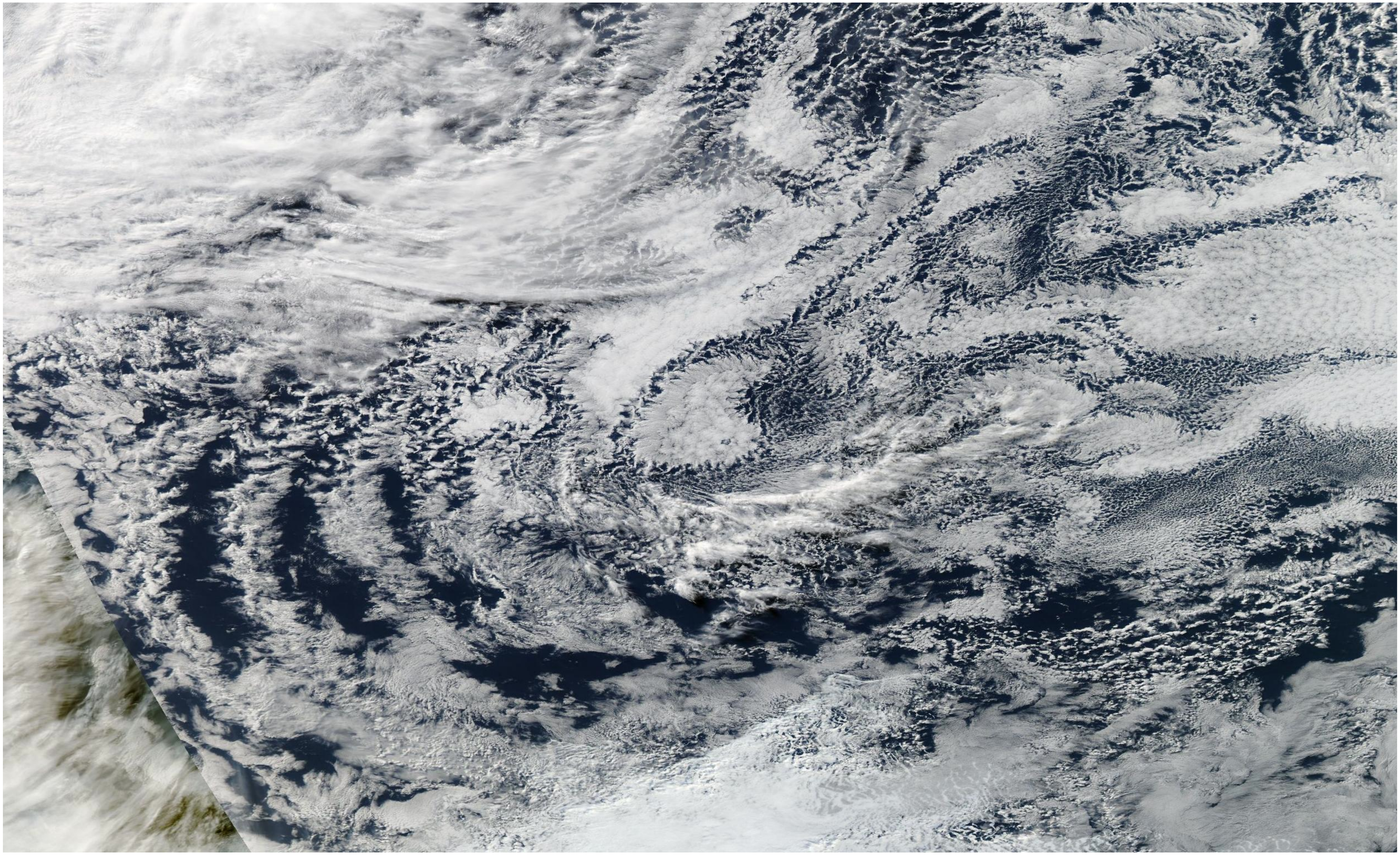
33S



73S 180W

50 W

Zoom in



1000 km

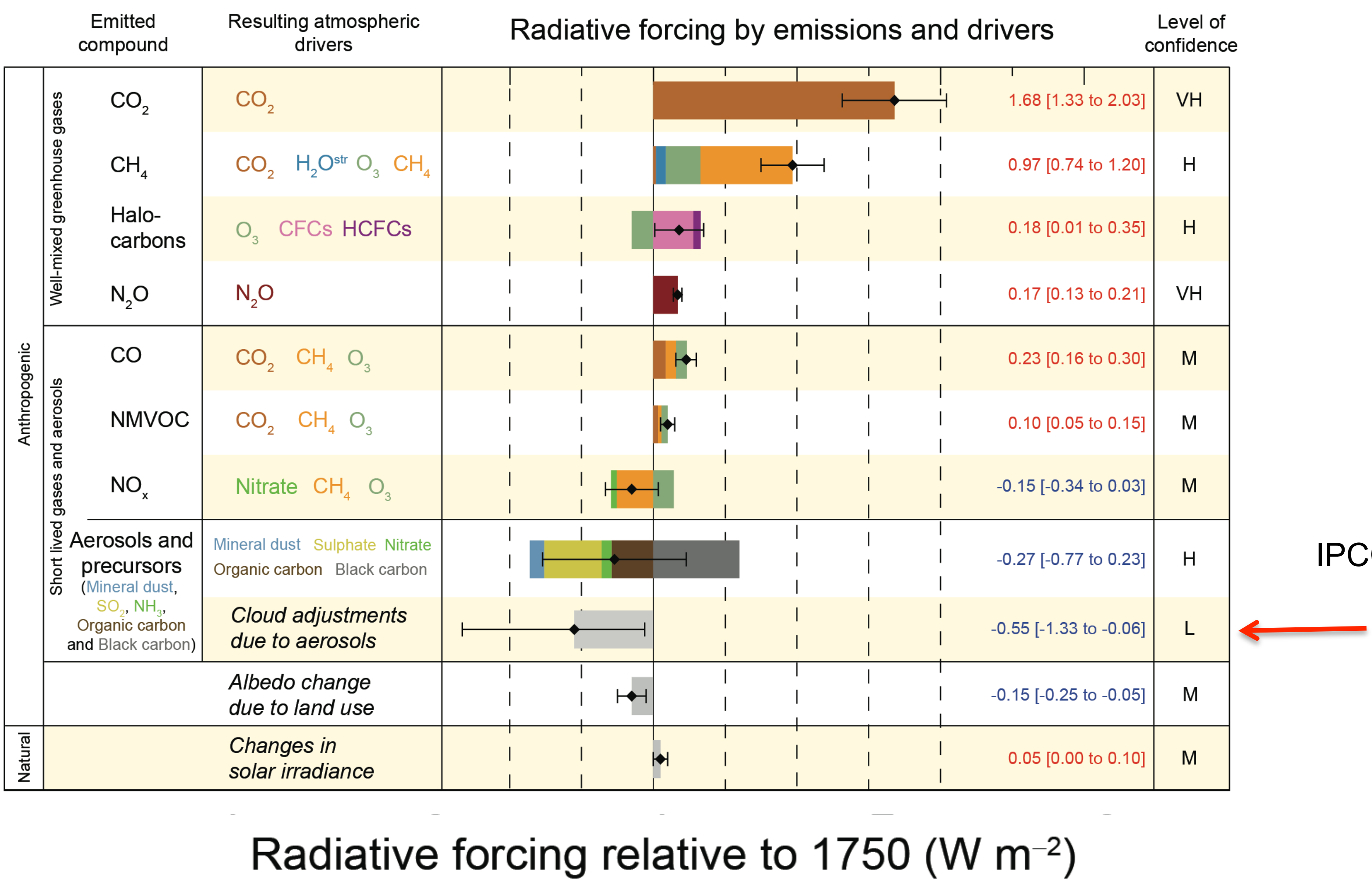
Roadmap

Explore how cloud-aerosol interaction helps promote distinct marine boundary-layer regimes with different characteristics and sensitivities.

1. Climate modeling context – aerosol indirect effects
2. Large-eddy simulation as a tool for this problem
3. Response of Sc to a specified change in droplet concentration
4. Regime-like behavior in LES of interactive Sc-aerosol system and pockets of open cells (POCs)

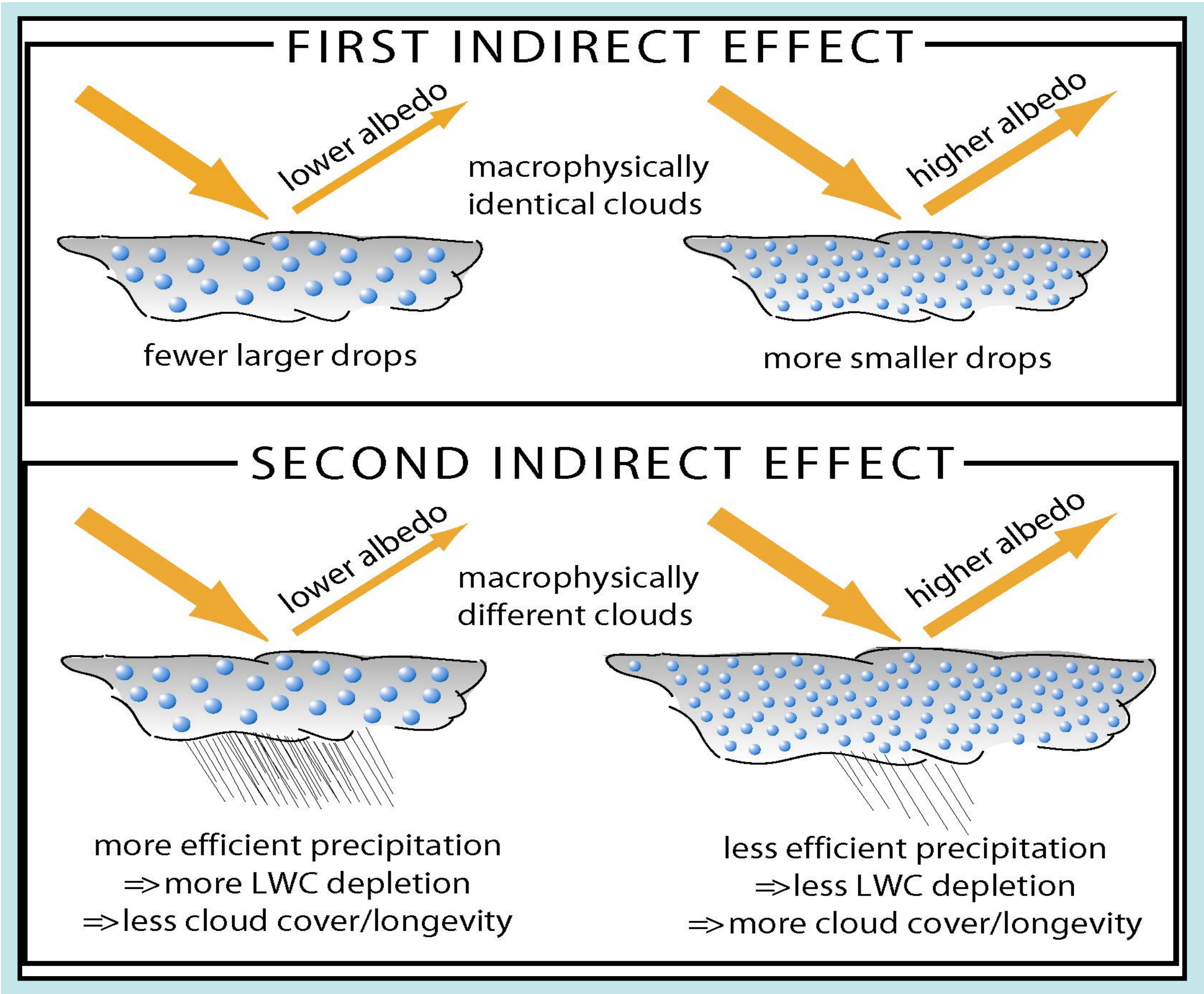
Anthropogenic aerosol radiative forcing of climate

Aerosol effects (esp. via cloud changes) induce largest RF uncertainty.



IPCC 2013

Aerosol Impacts on (Liquid) Clouds



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

Twomey effect

} ERF_{aci}

(= aerosol indirect effect)

Implicit assumption:
Smaller droplets ➔
Less rainout ➔
More cloud
Is this always true?
How important?

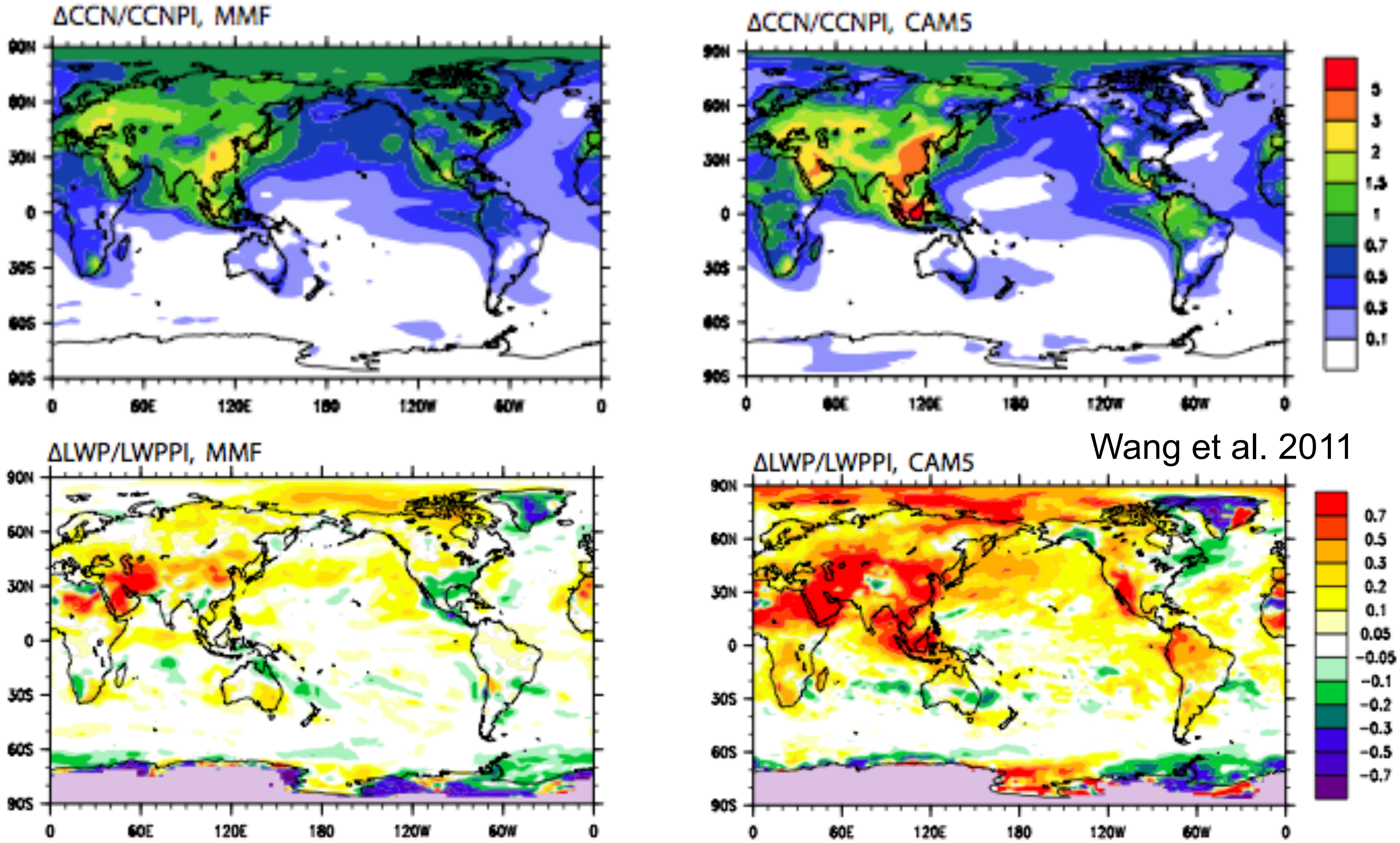
ACI is a difficult climate modeling problem

- Multiscale – subgrid heterogeneity of cloud, turbulence
- Multiphase – liquid, ice, mixed, aerosols, ice nucleii
- Uncertainties in preindustrial aerosol sources and lifecycles
- Numerous interacting processes (aerosol evolution, surface fluxes, cloud microphysics/precipitation, turbulence/convection, large-scale transport, chemistry, etc.) on timescales of seconds – days.
- Result: Wide range of climate model ERF_{aci} predictions, mostly more negative than inferences from satellite-based studies.

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}

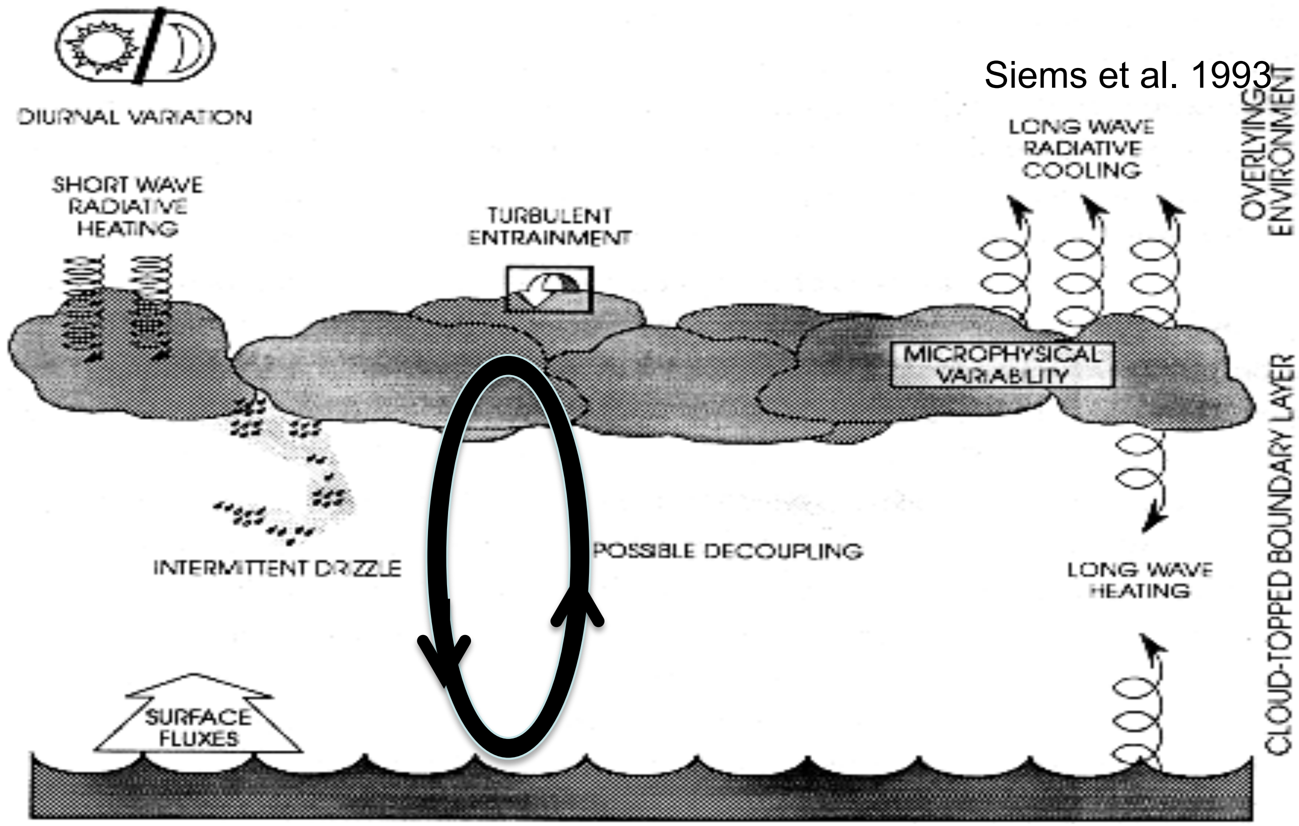


Same aerosol enhancement makes CAM5 clouds brighten more due to more liquid water

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

Stratocumulus-topped boundary layers and aerosols

Physics of stratocumulus-topped boundary layers



Coupled feedback loops

Radiation ← **Cloud** → Precipitation

Turbulence → Entrainment → **Aerosol**

Key points: (1) More cloud radiatively drives more entrainment

(2) More rain stabilizes PBL, cloud is more cumuliform, less entrainment

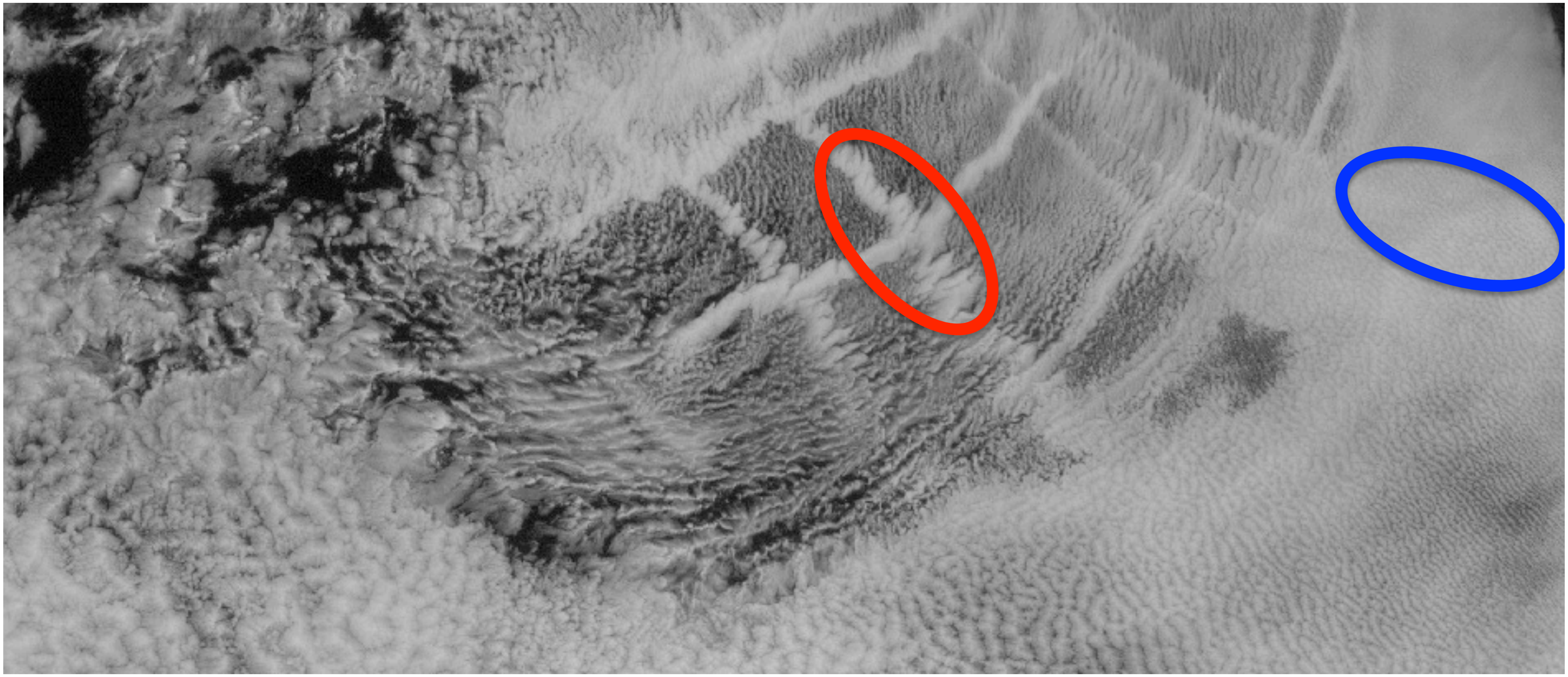
(3) Rain efficiently removes aerosol

Two albedo susceptibility limits

Observations and LES suggest two extreme behaviors:

Drizzling Sc/Cu: More aerosol increases cloud, enhancing Twomey effect to create a large albedo increase

Nonprecipitating Sc: More aerosol decreases cloud, buffering Twomey effect so albedo increase is small.



Large-eddy simulation (LES)

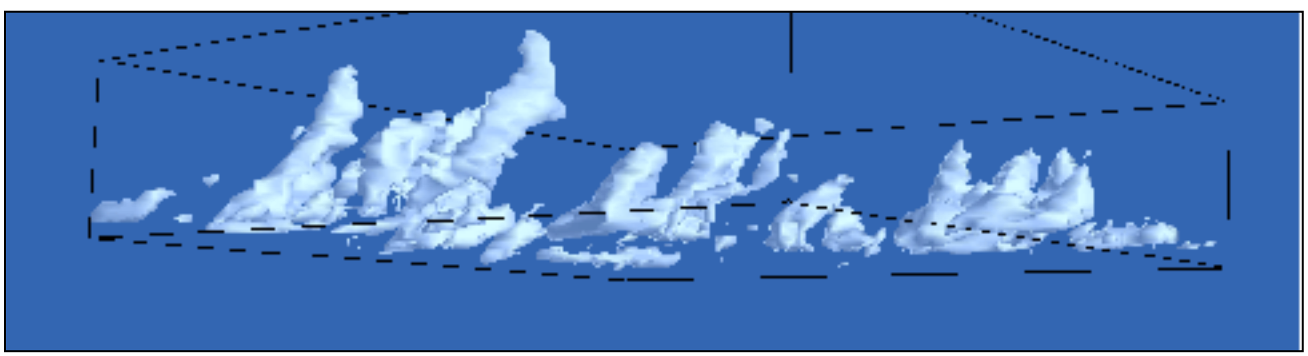
Turbulent energy cascade: Kinetic energy is generated in large eddies (e.g. warm air rising, cool air sinking). These eddies generate smaller eddies, which generate still smaller eddies dissipated by viscosity.

Idea of LES:

Accurately simulate the large, strong eddies that contain most of the kinetic energy and transport most of the moisture and heat. This requires a 3D grid with a spacing less that 20% of the large-eddy size: $(\Delta x, \Delta z, \Delta t)$ = (100m, 40 m, 5 s) for shallow Cu, $>100^3$ grid points.

Sources of T, q, u, v from large-scale advection, PGF, Coriolis, parameterizations of microphysics, radiation, surface fluxes.

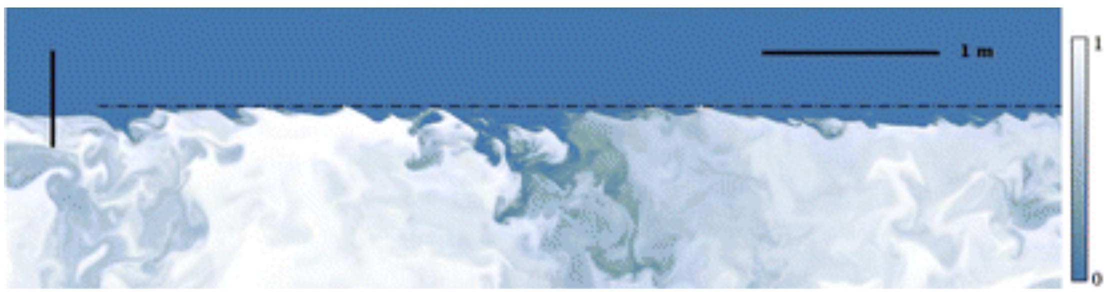
Simply represent effects of unresolved small eddies on resolved eddies (flow-dependent 'eddy viscosity' or grid-scale numerical damping).



Dussen et al. 2013

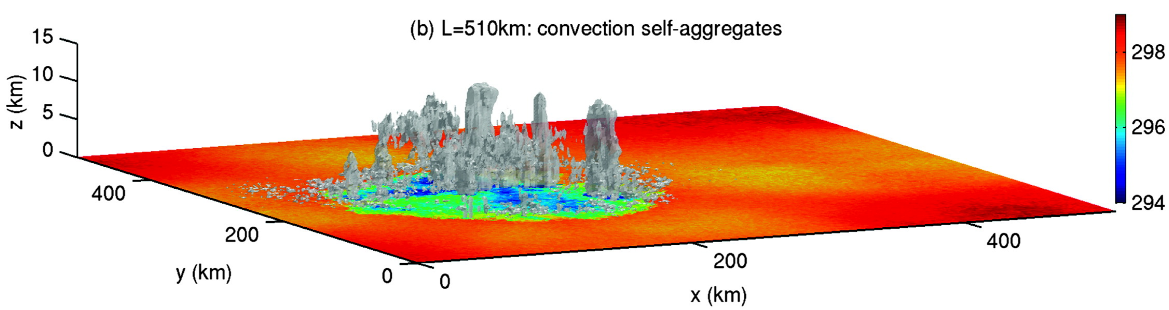
DNS vs. LES vs. CRM

DNS = Direct Numerical Simulation of a turbulent flow, resolving down to the finest scales allowed by molecular viscosity (~1 mm for atmosphere). Numerical domain limited to a few meters on a side



Mellado et al. 2014

CRM = Cloud-Resolving Modeling. Generalization of LES idea to deep convection. May use a grid too coarse to resolve most boundary-layer eddies, or may use a 2D grid.



Mueller and Held 2012

Simulating cloud-aerosol interaction with LES

Common one-way approach: Specify an aerosol size distribution or cloud droplet concentration. Use LES to determine sensitivity of clouds to aerosols.

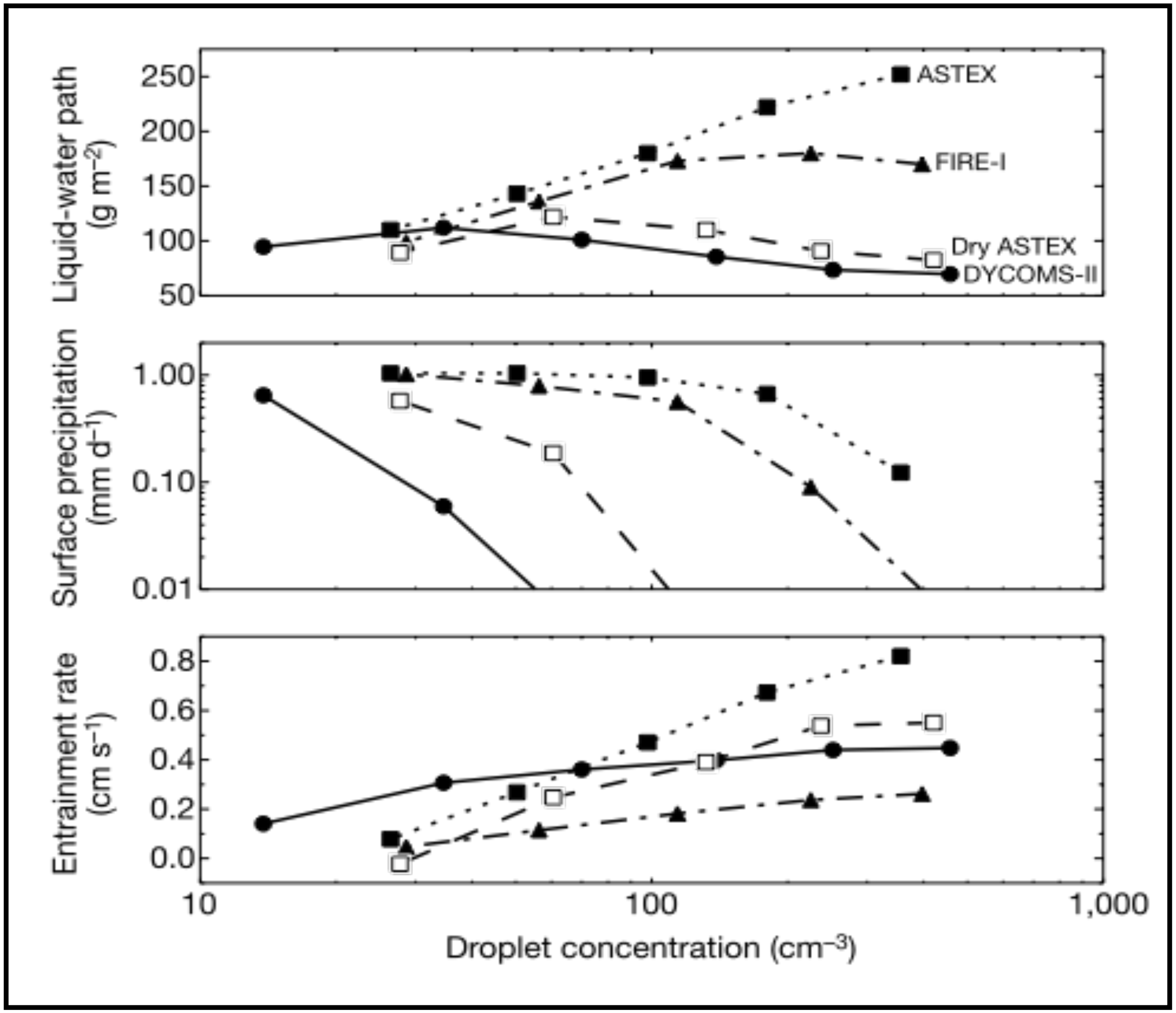
Two-way interaction: Cloud microphysics feeds back on the aerosol concentration and size distribution.

LES of Sc with a range of specified droplet conc N_d

In drizzly Sc
(P>0.1 mm/d)
LWP ↑ with N_d

If no drizzle
(P<0.1 mm/d)
LWP ↓ with N_d

Why the latter?
Entrainment ↑ with N_d, dries out cloud layer.



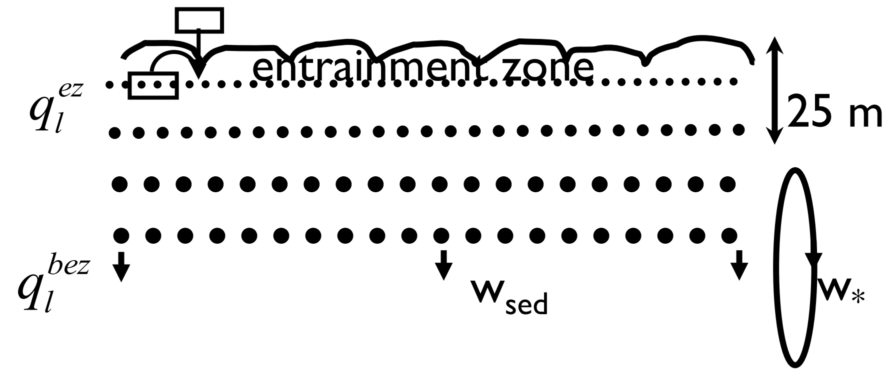
Ackerman et al. 2004

Entrainment feedback and Sc thinning with larger N_d

Nondrizzling cloud: Larger N_d

→ less droplet sedimentation
→ more droplets in entrainment zone
→ more evaporative cooling
→ more efficient entrainment

Cloud thins due to drier PBL (Bretherton et al. 2007). This sedimentation-entrainment feedback is not in most GCMs.



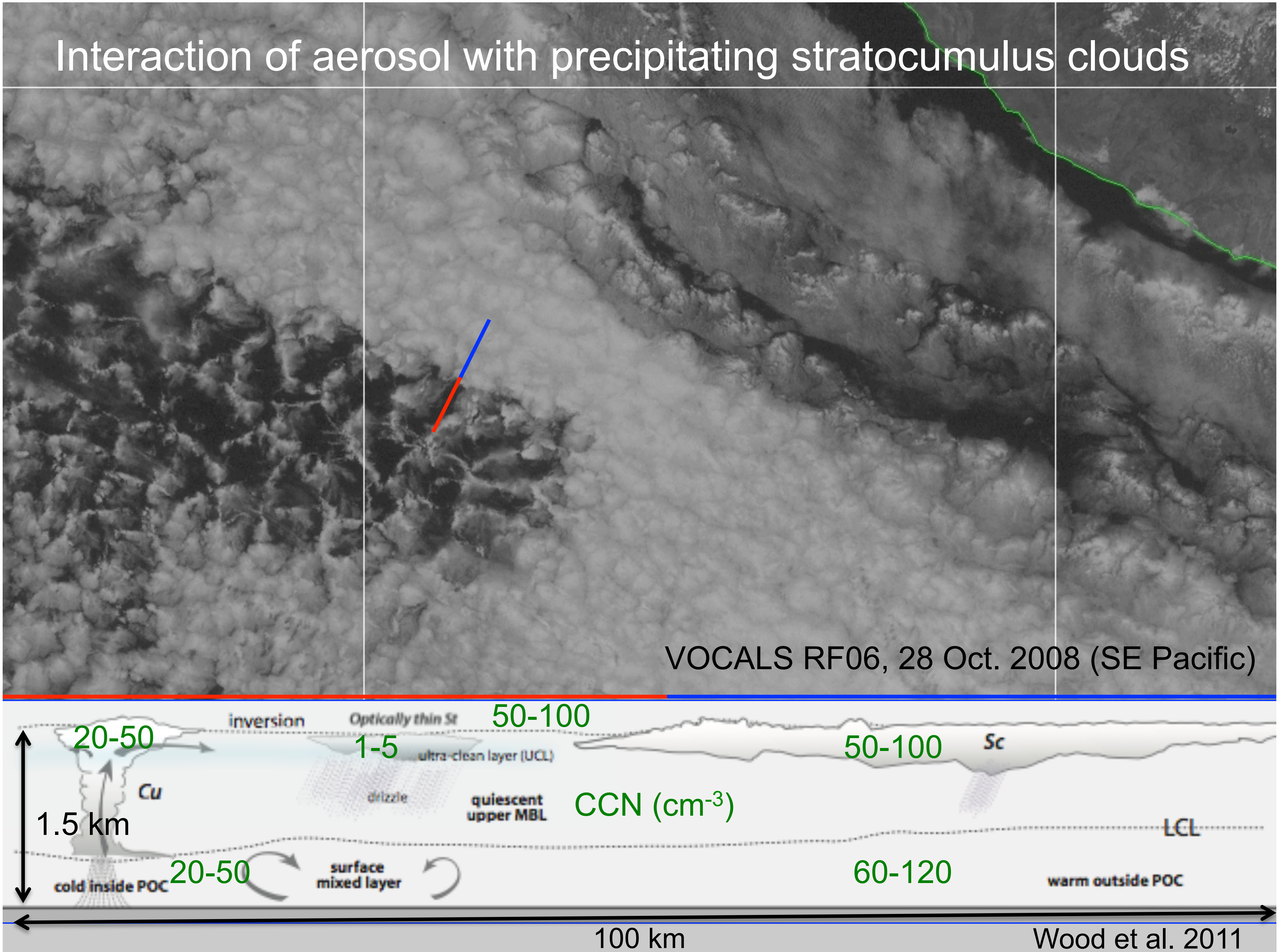
Drizzling cloud: Larger N_d

→ less evaporating drizzle
→ less stratified boundary layer
→ more turbulence
→ more entrainment

Cloud becomes less cumuliform, more stratiform and extensive. (Stevens et al. 1998; Ackerman et al. 2009).

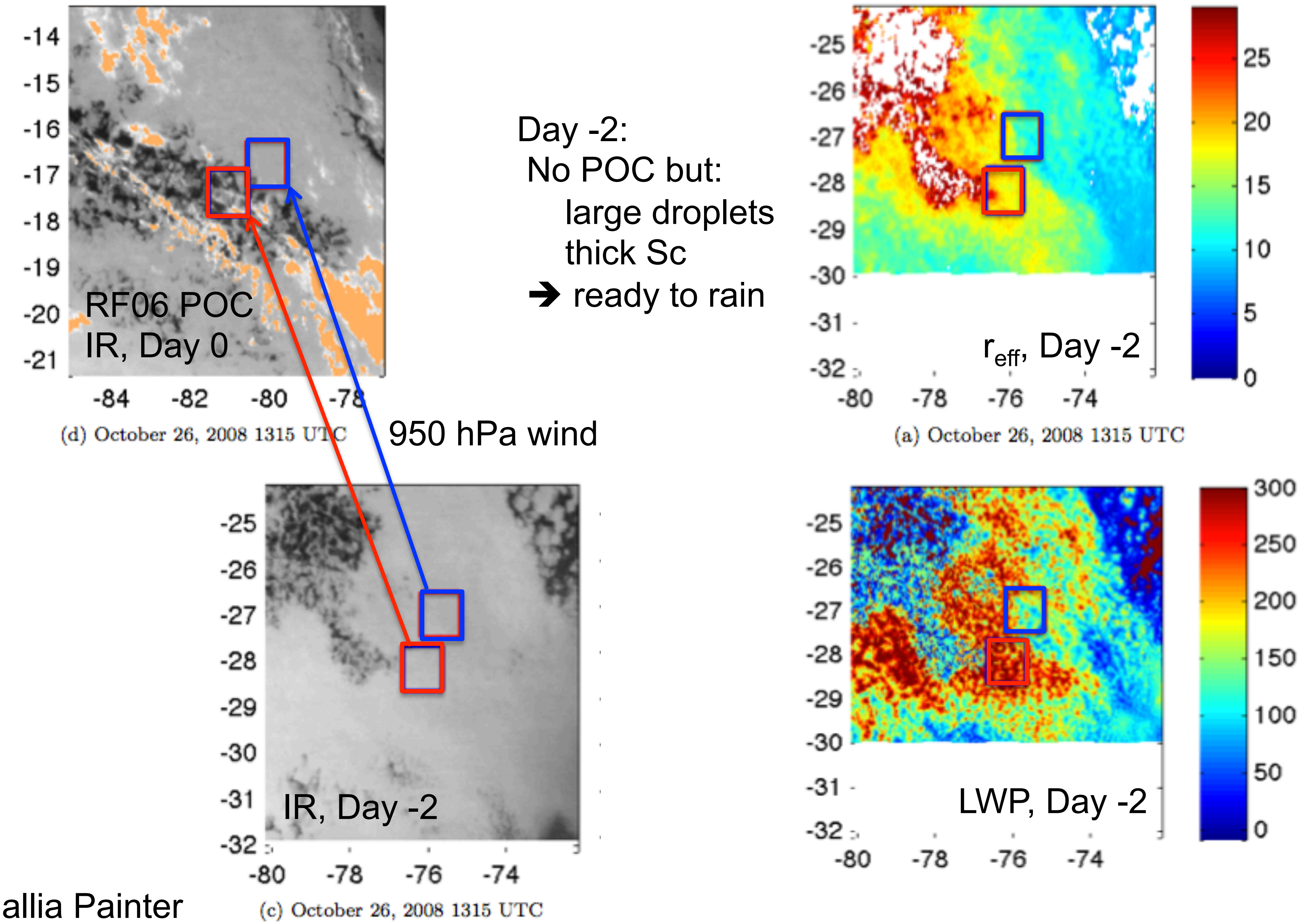
These feedbacks are important for naturally occurring cloud regimes as well as anthropogenic aerosol perturbations.

They are much harder to represent in GCMs than in LES.



Interaction of aerosol with precipitating stratocumulus clouds
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

POCs are rapidly-developing persistent Lagrangian features



Gallia Painter

Given aerosol change, do we get the cloud change?

Idea: Where aerosol is low, clouds precipitate more easily, so they become more cumuliform and patchy.

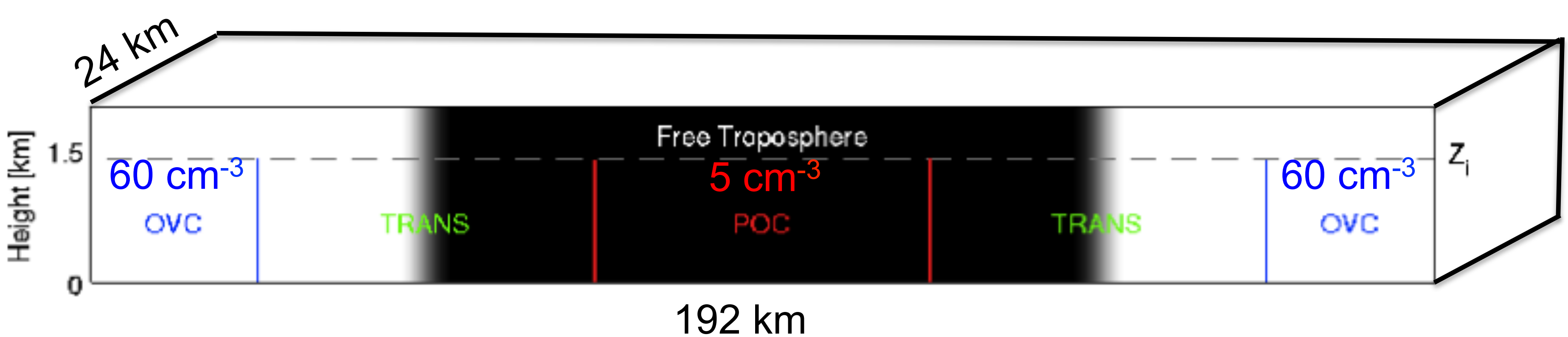
Large-domain LES, $\Delta x = \Delta y = 125$ m, $\Delta z = 5$ m near inversion

VOCALS RF06 thermodynamic profiles, winds, SST=19 C.

(very dry above 12 K inversion at 1.3 km, weak subsidence)

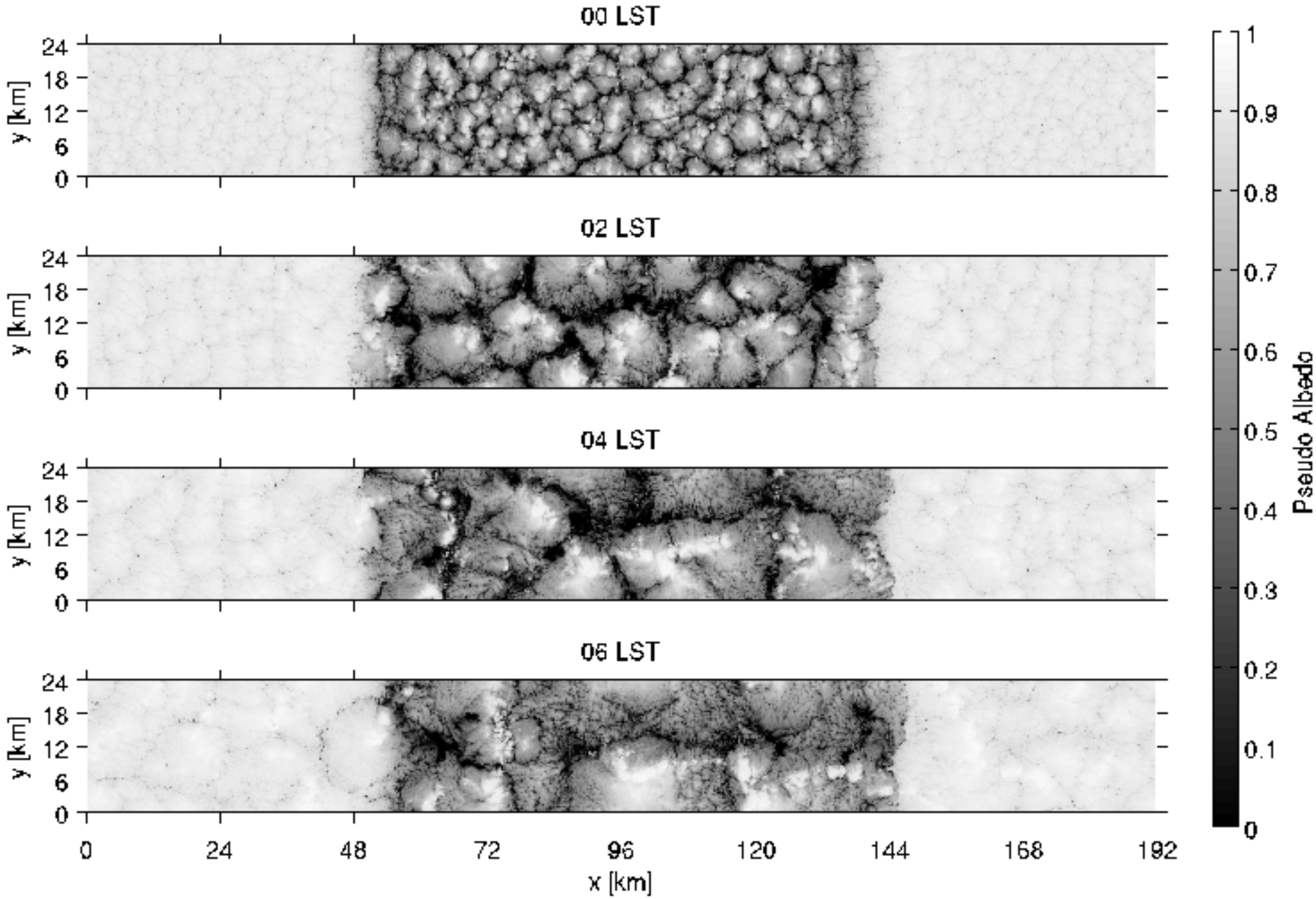
Specified cloud droplet concentration:

$N_d = 5\ \mathrm{cm}^{-3}$ in POC, 60 in overcast region (OVC).

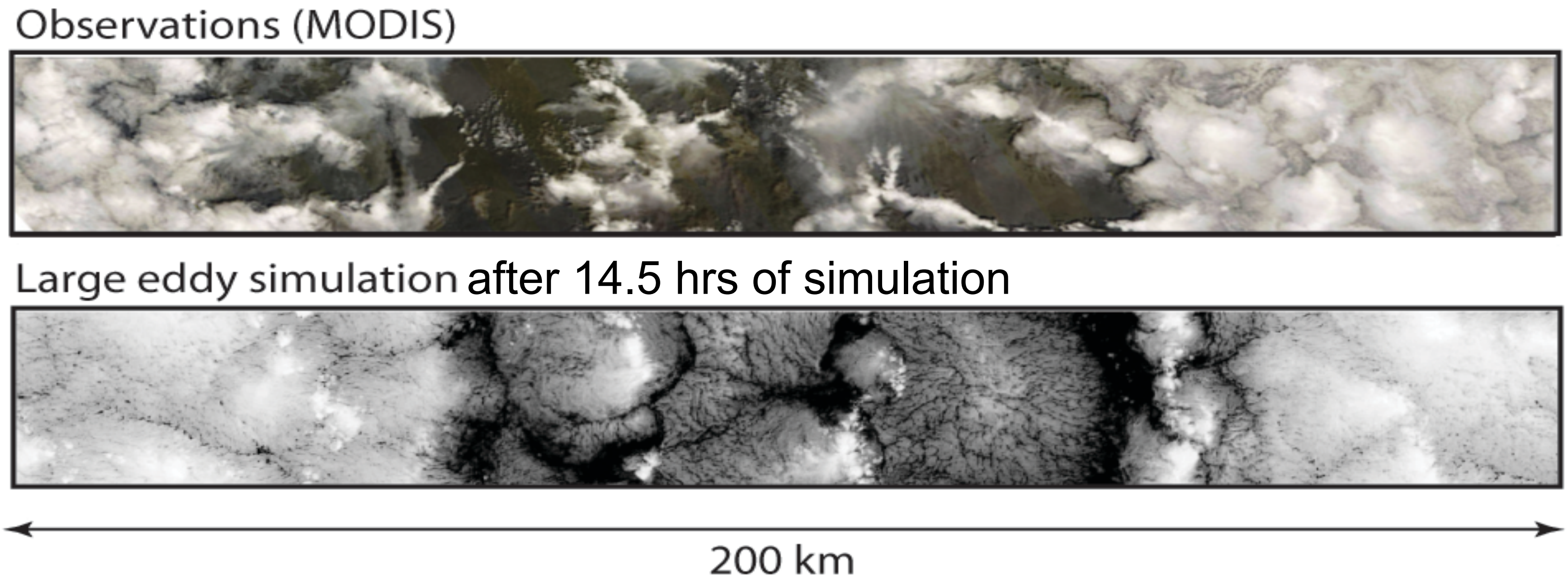


Berner et al. 2011

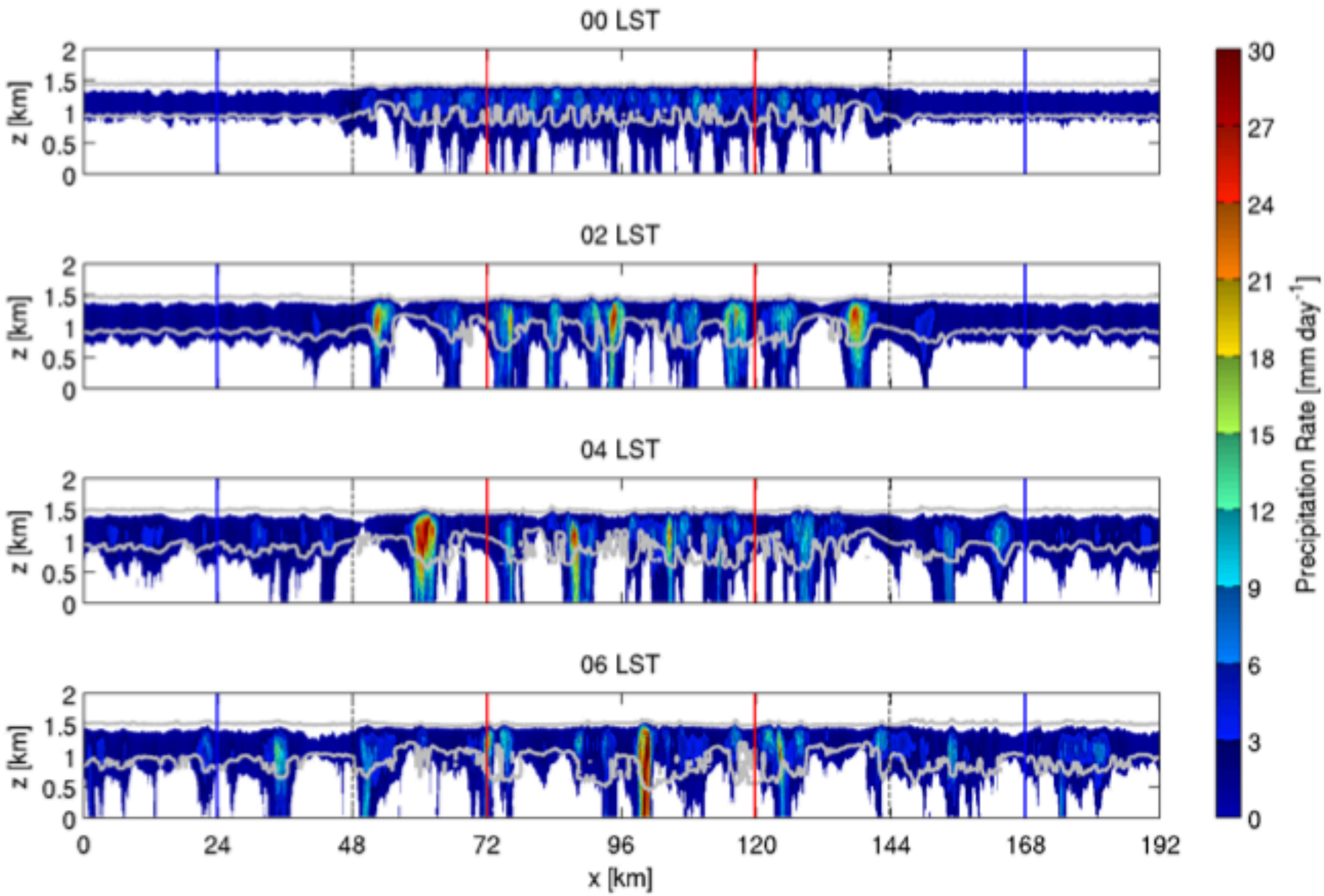
Satellite view of simulated clouds after 2,4,6,8 hrs



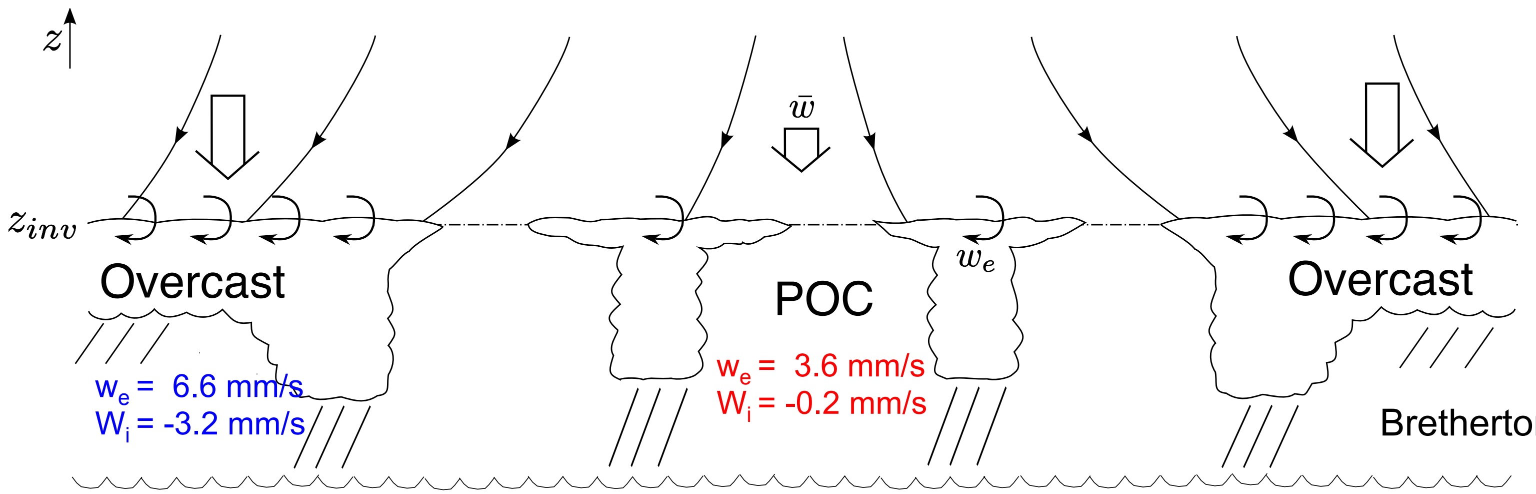
LES captures OVC-POC cloud differences



More cumuliform and precipitating in POC region



Conceptual view of POC mesoscale dynamics

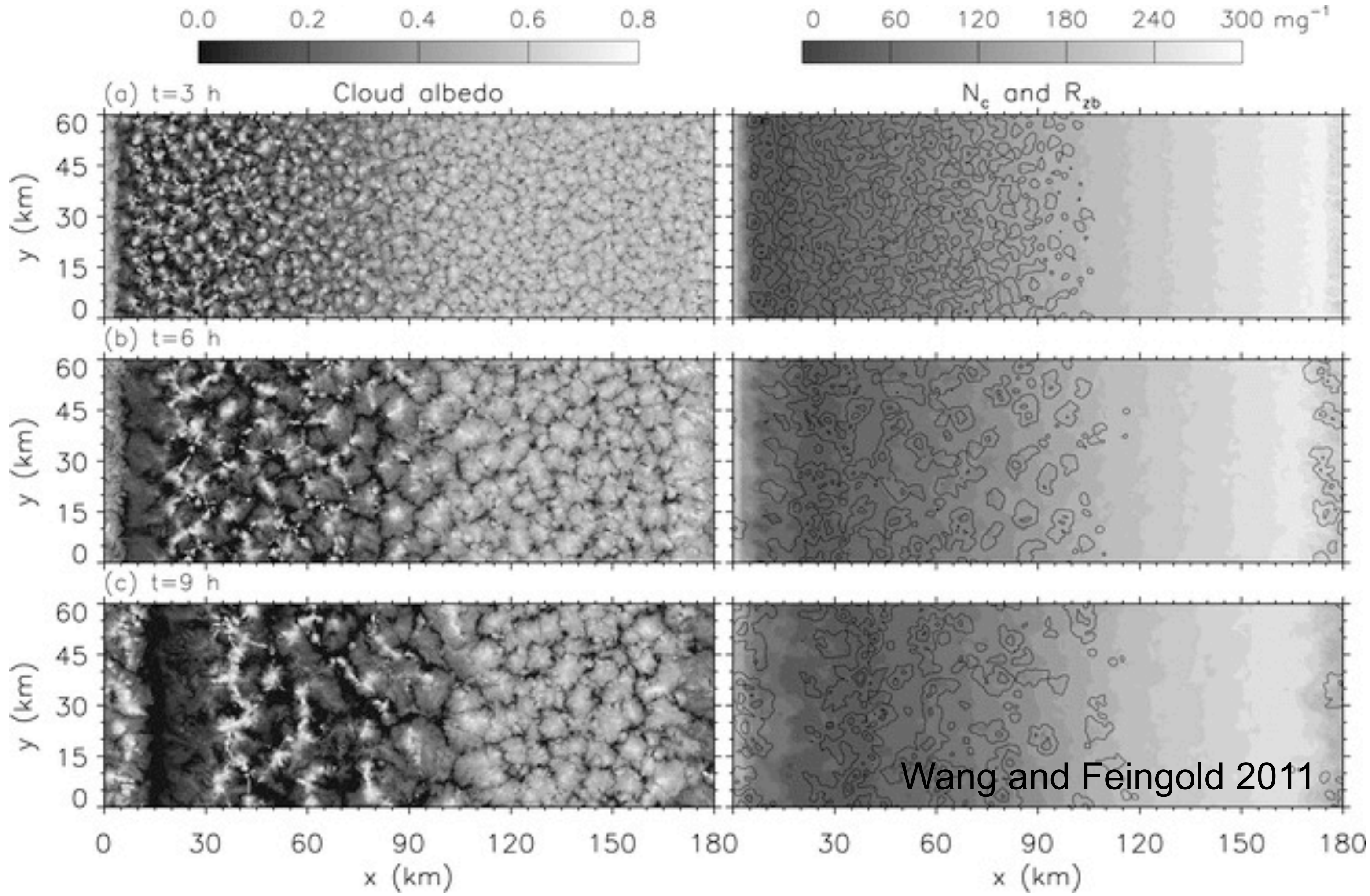


Bretherton et al. 2010

POC is less cloudy & turbulent, entrains less – but ‘propped up’ by OVC through mesoscale circulations that diverge descending air away from the POC and into the entraining OVC cloud to keep the inversion nearly flat.

Is this an abrupt regime transition?

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

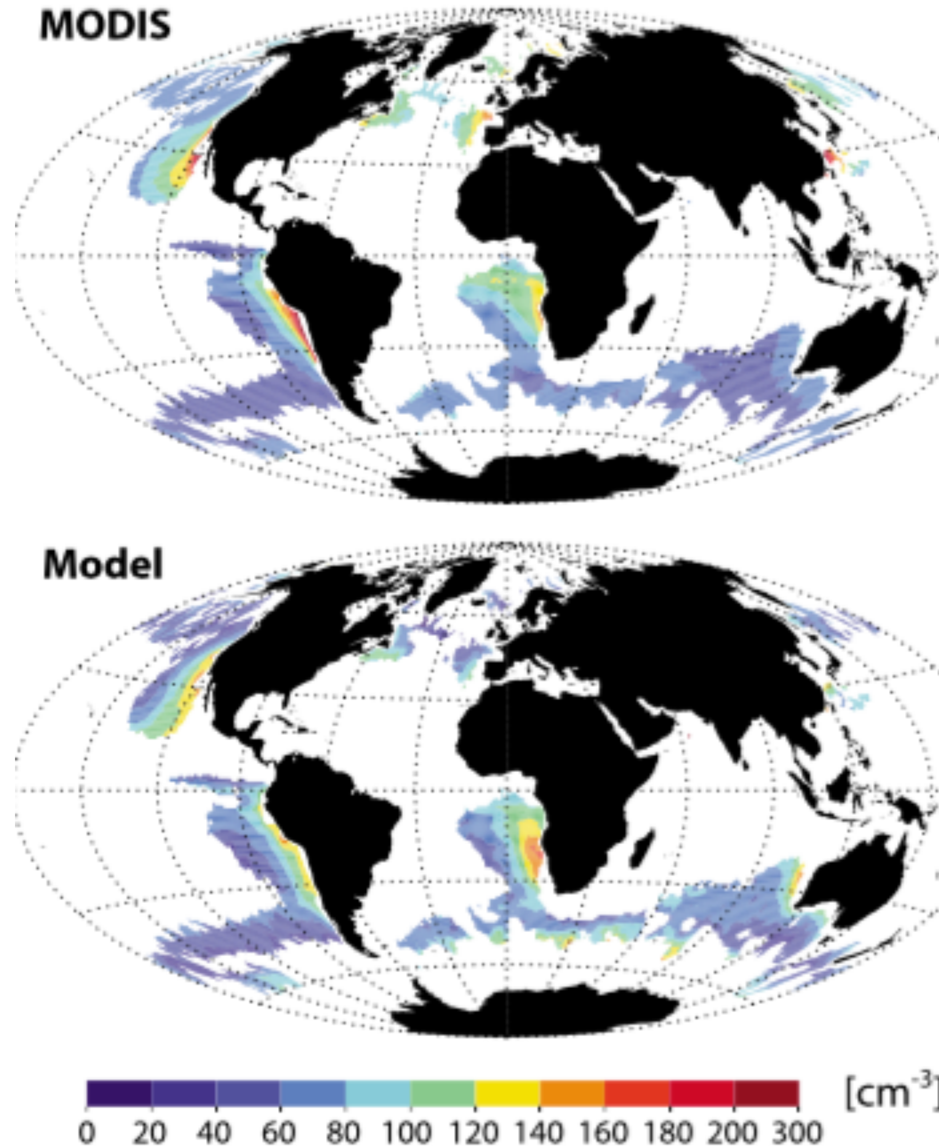


But clouds affect aerosols too!

Drizzle affects stratocumulus cloud droplet concentration and albedo on global scales

Wood et al. 2012

$$N_{eq} = \frac{\left(N_{FT} + \frac{F(\sigma)U_{10}^{3.41}}{Dz_i}\right)}{\left(1 + \frac{hKP_{CB}}{Dz_i}\right)}$$



Cloud-precipitation-aerosol feedback

- We think the aerosol concentration is low in POCs because rain from the clouds is scavenging it.
- That is, there is a positive feedback:

Less aerosol → Fewer, bigger cloud droplets

More rain

More cumuliform cloud

Bistability of CCN concentrations and thermodynamics in the cloud-topped boundary layer

Marcia B. Baker* & Robert J. Charlson†

NATURE · VOL 345 · 10 MAY 1990

Finally, it is interesting to note that, *a priori*, the existence of two stable regimes in the marine stratus clouds of the globe could also correspond to two different climate regimes. At present the marine stratiform clouds seem to be in a low-N_M state, and their albedo is relatively low (0.3–0.7). A shift to the high-N_M state could cause a substantial decrease in the solar energy absorbed by the system because the global heat balance is sensitive to the albedo of these clouds and because they cover ~25% of the Earth's surface[17]. The calculations discussed here suggest that this shift may come about through elevated source strengths or if atmospheric conditions suppress precipitation

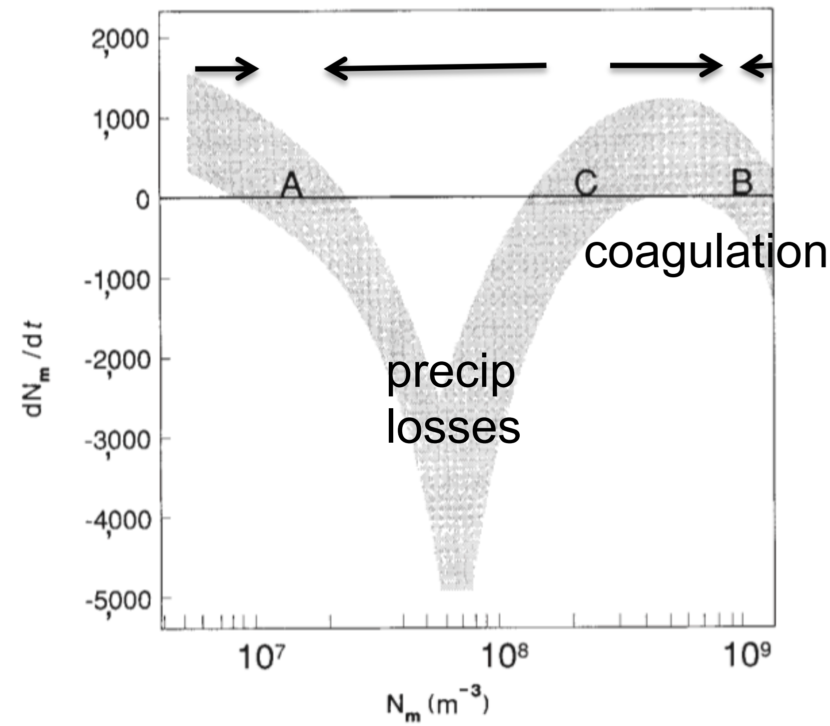


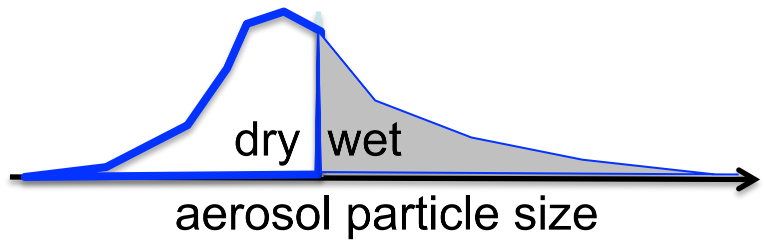
FIG. 1 Variation of N_M according to equation (1), with fixed boundary conditions. The envelope comprises variations in S_0 from 800 to 2,000 $(m^3\ s)^{-1}$, in boundary-layer thickness from 800 to 1,000 m, and in cloud thickness from 250 to 300 m. See text for definition of points A, B and C.

Idealizations: Specified cloud, no entrainment source/sink, simplified aerosol-cloud-drizzle interaction etc.

Much LES-based modeling work since then (e. g Feingold group), but not for the multiday timescales necessary to properly evaluate this bistability idea.

Add interactive aerosol to LES (Berner et al. 2013)

- Broadly inspired by Ivanova & Leighton (2008)
- Aerosol has a single log-normal size distribution with predicted number and mass concentration.

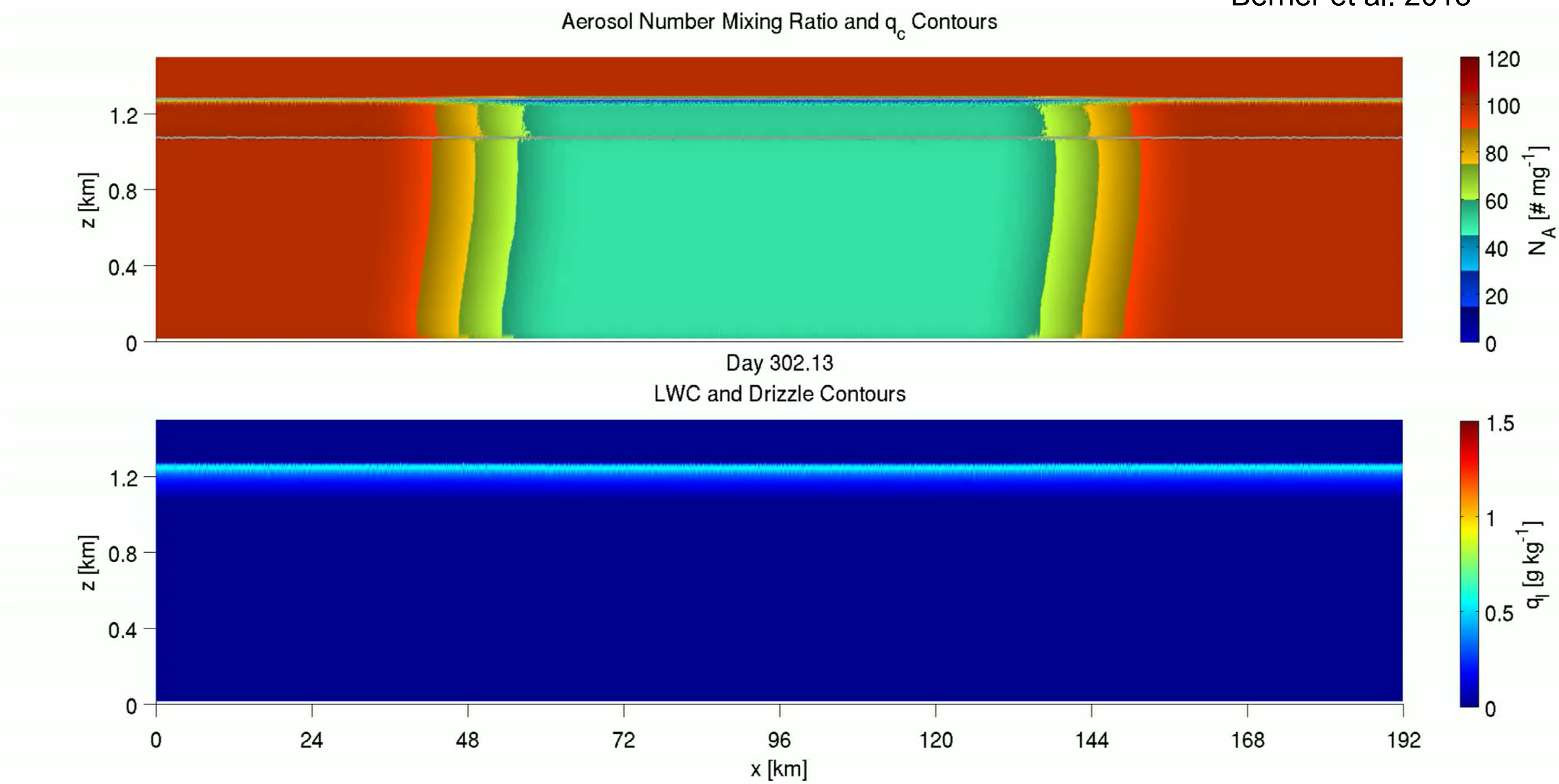


- The largest particles activate in saturated air to nucleate cloud droplets. The activated fraction increases with the updraft velocity at cloud base.
- Aerosol sources: surface ($wind^3$), overlying atmosphere
- Aerosol sinks: coagulation, scavenging of dry aerosol and cloud droplets due to cloud and rain, tightly coupled to LES 2-moment microphysics scheme.
- Numerically closed budgets of aerosol mass and number.

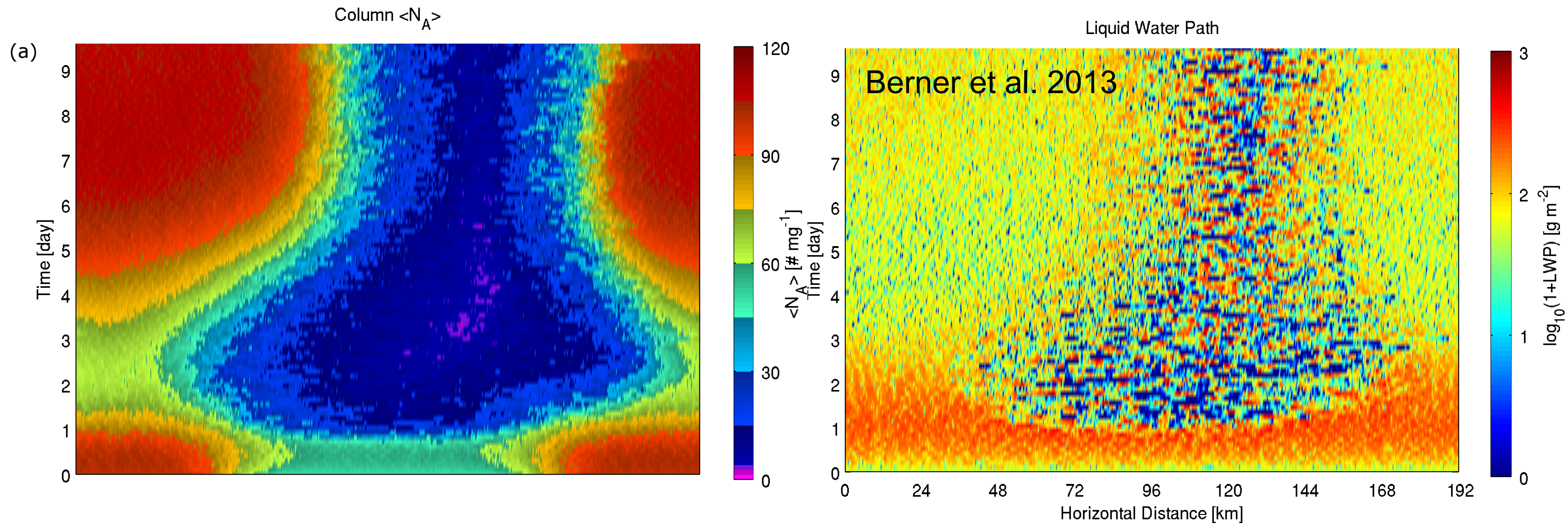
POC development in aerosol-coupled LES

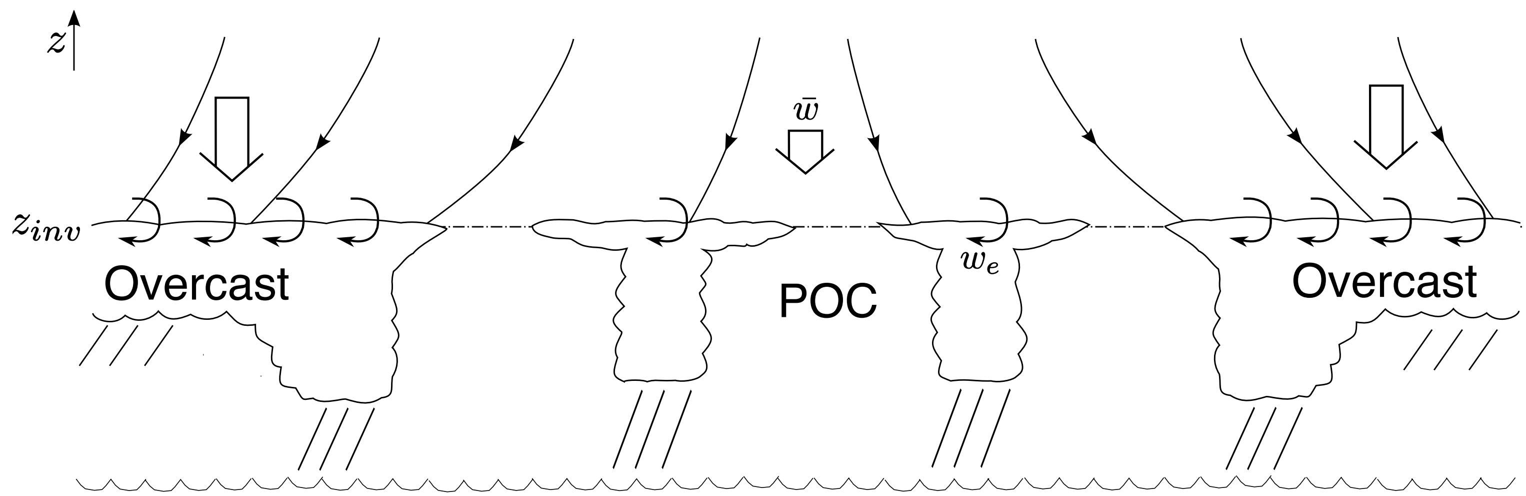
Model setup: Initial RF06 case with uniform initial thermodynamic sounding but with PBL aerosol concentration varying from 100 to 50 mg^{-1} across a 192 km domain. 6-day animation below…

Berner et al. 2013



POCs: Mutually supporting cloud-aerosol regimes





Inversion height locked between 'bistable' overcast and open-cell regions
Strong entrainment in overcast region keeps inversion up, prevents POC collapse
Weak entrainment in open-cell region keeps inversion down and overcast Sc thin.

Conclusions

- Aerosol-low cloud interaction favors two long-lived regimes:
  Nondrizzling, thick Sc with high aerosol conc., entrainment
  Drizzling open-cell (or thin) Sc with low aerosol conc.

  LES is a good tool for simulating these regimes.
- Thick Sc transition to a low-aerosol, open-cell structure with weaker entrainment if precipitation gets strong enough.
- In POCs, the open-cell low-aerosol regime is propped up by an adjacent overcast high-aerosol cloud layer, a configuration that can stably persist for days, in reality and in LES.
- These behaviors are due to strong feedbacks between clouds, precipitation, aerosol, turbulence, radiation that challenge GCMs but may be important to cloud microphysics and aerosol indirect effects over much of the oceans.