A Climate Process Team focused on better representation of aerosol indirect effects in climate models through improved cloud macrophysical parameterization

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GFDL (SCM and GCM simulations: *Leo Donner, Chris Golaz, Yi Ming, Huan Guo*)

NCAR (SCM and GCM simulations: *Andrew Gettelman, Hugh Morrison, Pete Bogenschutz*)

NOAA ESRL (Process modeling: *Graham Feingold, Tak Yamaguchi, Seoung-Soo Lee*)

JPL (Satellite obs: *Graeme Stephens, Matt Lebsock, Terry Kubar*)

U. Washington (Field and satellite obs: *Rob Wood, Daniel Grosvenor*)

Supported by

State of play

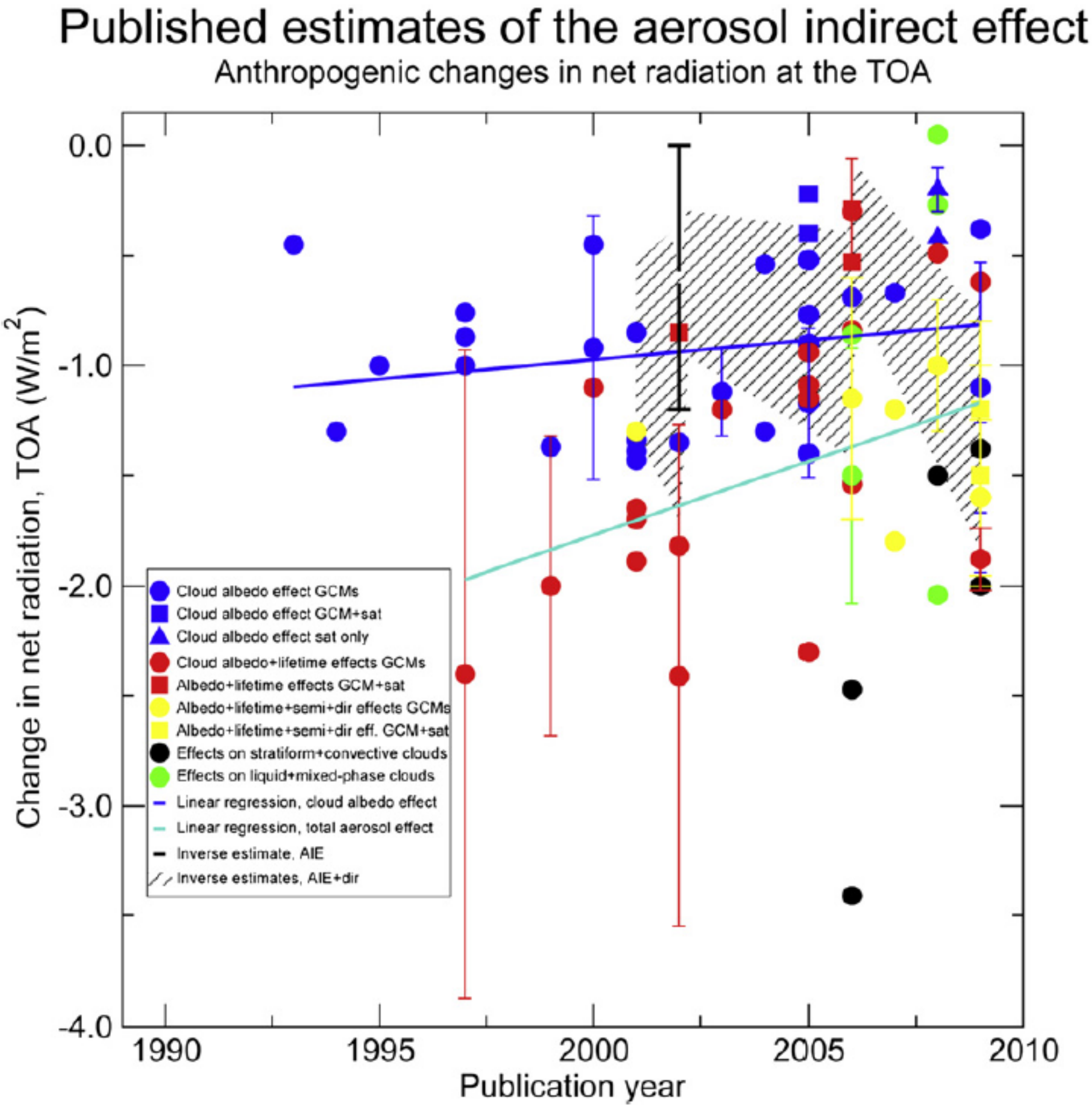
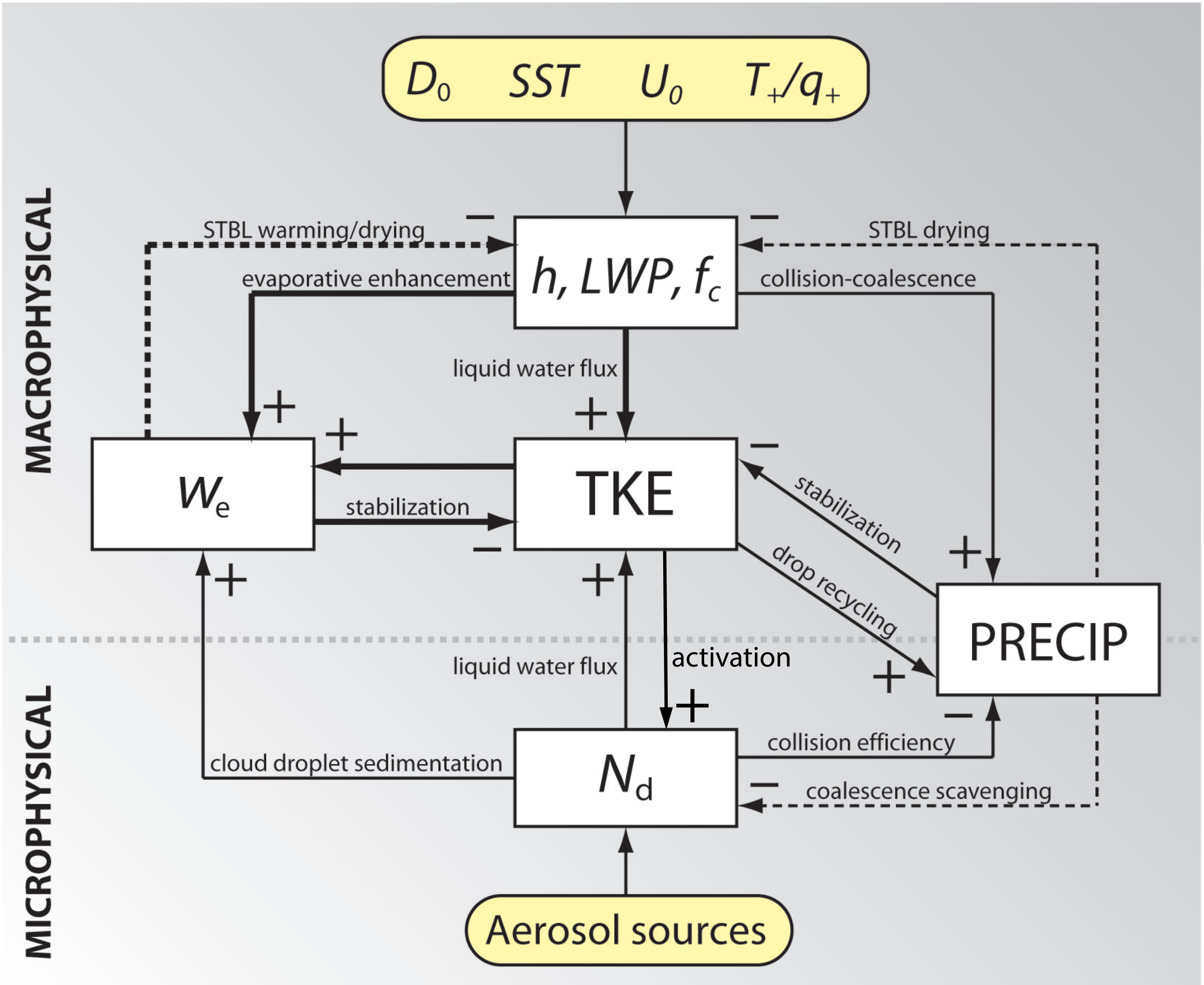


Figure from Trude Storelvmo, in Isaksen et al. (*Atmos. Env.*, 2009)

Critical interactions in low clouds



CPT Goals

- Chief deliverable: implementation of new parameterization (CLUBB) unifying turbulence, cloud and shallow convection schemes within NCAR and GFDL GCMs
- Couple CLUBB with model microphysics scheme
- Investigate aerosol indirect effects (AIEs) in sensitivity studies using large eddy simulation, aircraft/satellite data, and CLUBB => use to improve PDF scheme representation of AIEs
- Develop toolkit for testing GCM using relevant satellite datasets and metrics

Model physics in climate models

- ~~Boundary layer mixing~~
- ~~Shallow convection~~
- Deep convection
- ~~Large scale cloud~~
- **Microphysics**
- Radiation
- Aerosols

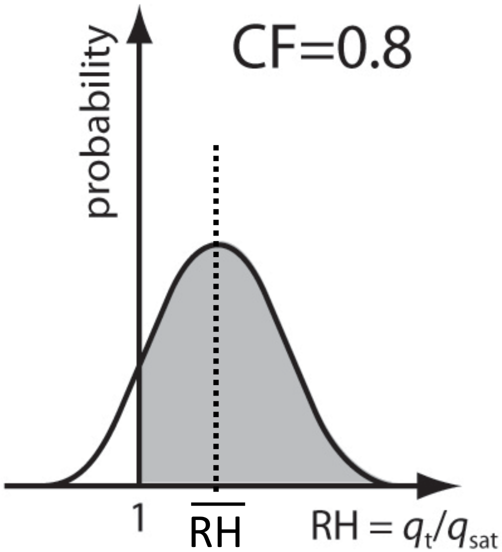
Replace with unified model physics

CLUBB = **C**loud **L**ayers **U**nified **B**y **B**inormals

Dynamics-Based PDFs for Cloud Parameterization: Motivation

- Moisture-based PDFs (widely used to represent cloud cover in GCMs) are not linked to dynamics of cloud formation and dissipation

- Key microphysical and macrophysical processes like drop activation, entrainment, and precip. formation are closely linked to vertical motions, i.e. need **joint distribution** of thermodynamics *and* vertical motion

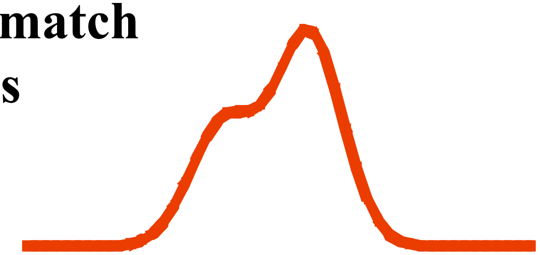


Building a PDF-based parameterization

Advance prognostic moment equations

$$\overline{w},\ \overline{\theta_l},\ \overline{q_t},\ \overline{w'^2},\ \overline{w'^3},\ \overline{q_t'^2},\ \overline{\theta_l'^2},\ \overline{q_t'\theta_l'},\ \overline{w'q_t'},\ \overline{w'\theta_l'}$$

Select PDF from functional form to match moments



Use PDF to close higher-order moments, buoyancy terms

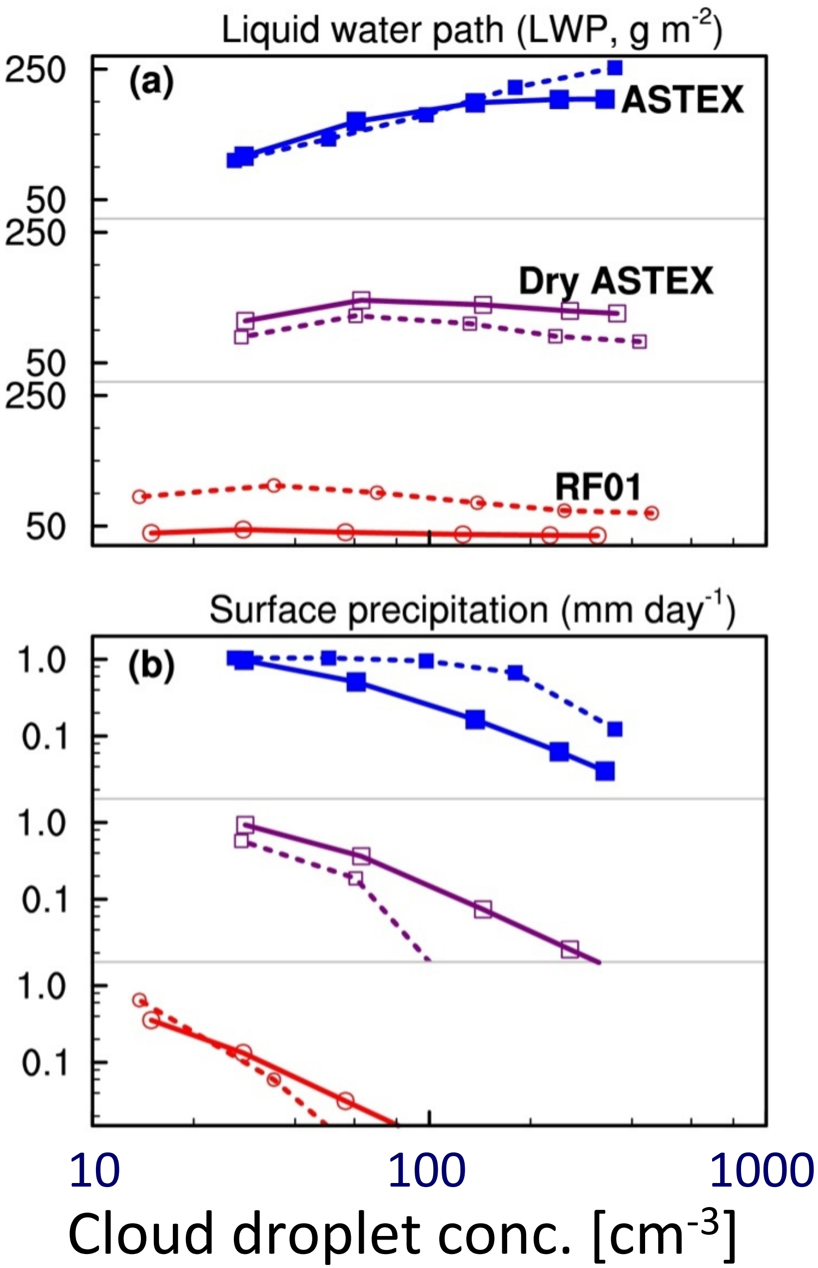
$$\overline{w'q_t'^2},\ \overline{w'\theta_l'^2},\ \overline{w'q_t'\theta_l'},\ \overline{w'^2q_t'},\ \overline{w'^2\theta_l'},\ \overline{w'^4},$$
$$\overline{q_t'\theta_v'},\ \overline{\theta_l'\theta_v'},\ \overline{w'\theta_v'},\ \overline{w'^2\theta_v'}$$

Δt

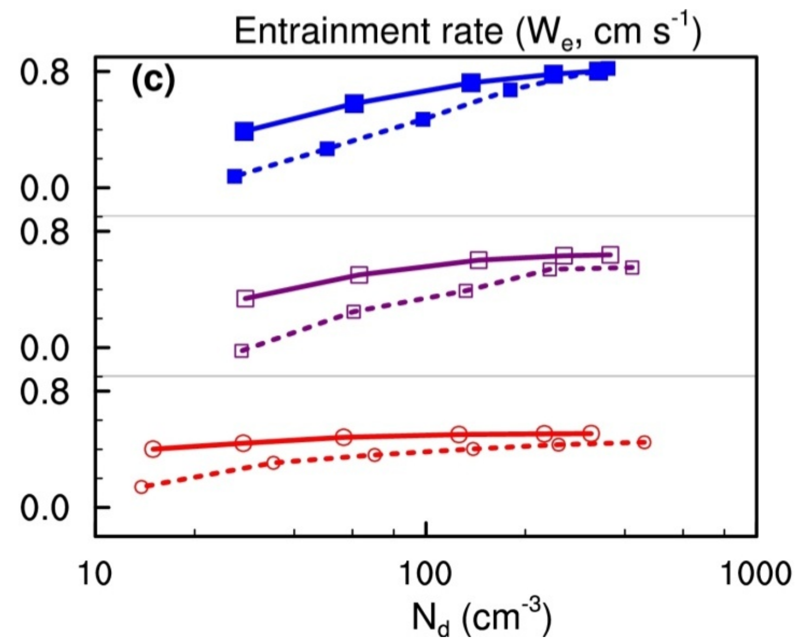
Diagnose cloud fraction, liquid water, droplet number from PDF

Adapted from Golaz et al. 2002a,b (JAS)

CLUBB SCM reproduces LES responses to aerosols



Solid: CLUBB (GFDL)
Dashed: LES based on Ackerman *et al.* (2004, *Nature*)

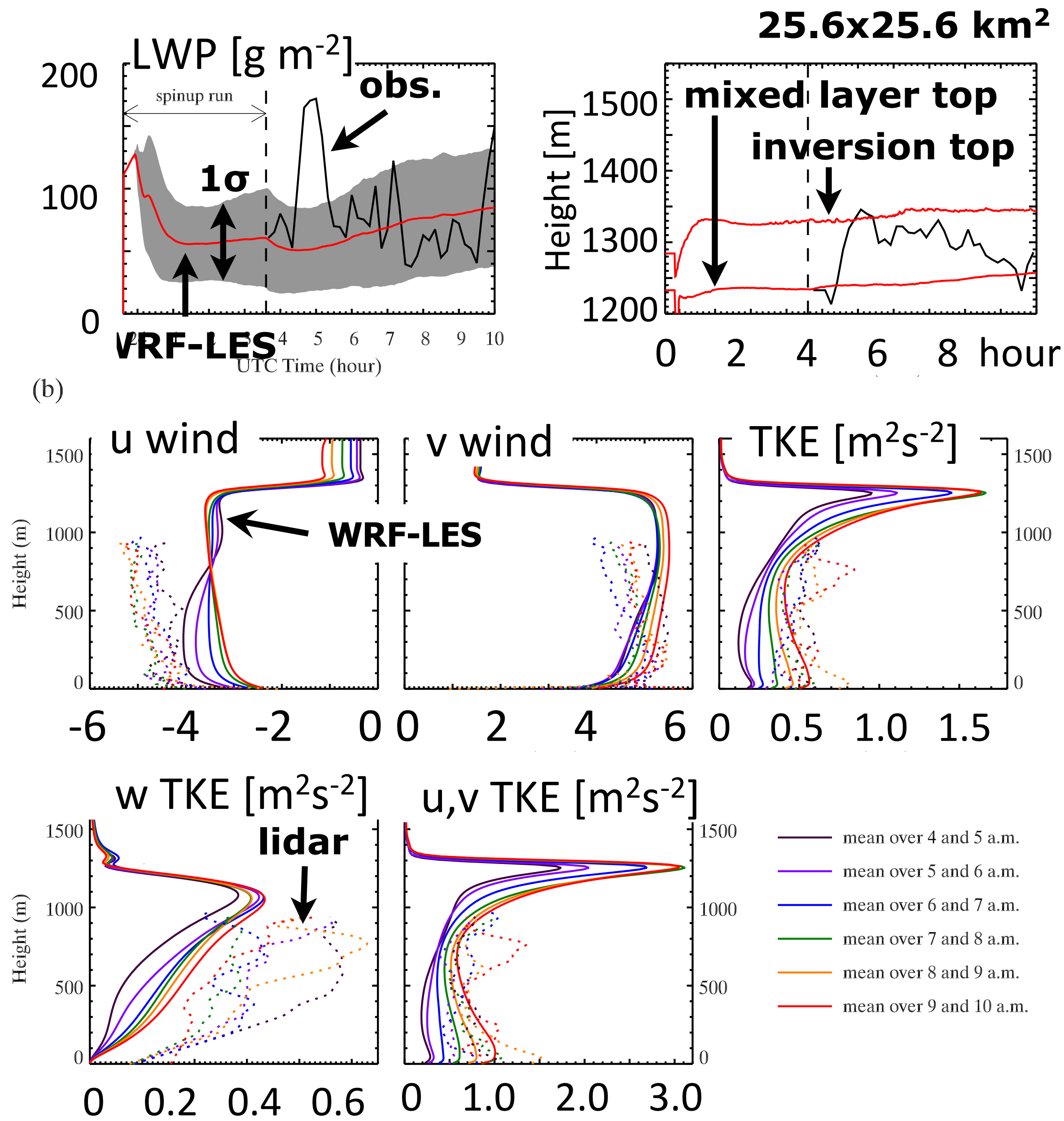


Guo *et al.* (*Geophys. Res. Lett., 2011*)

See also Guo *et al.* (2010, *GMD*)

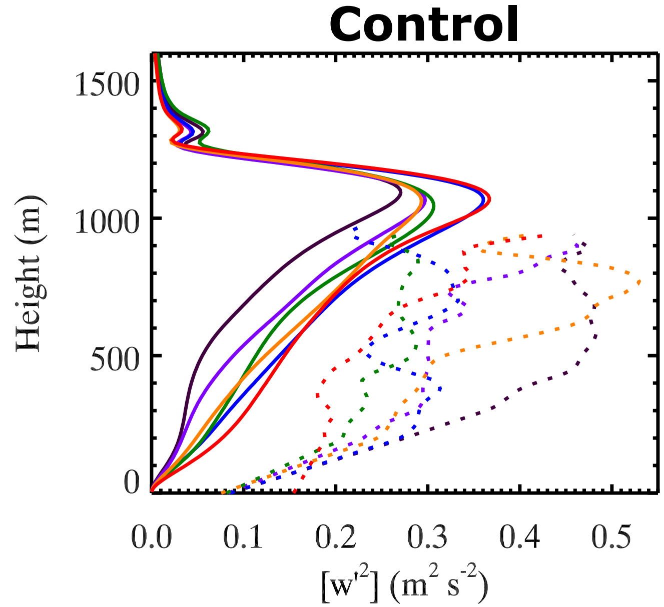
Comparison of LES turbulence with lidar

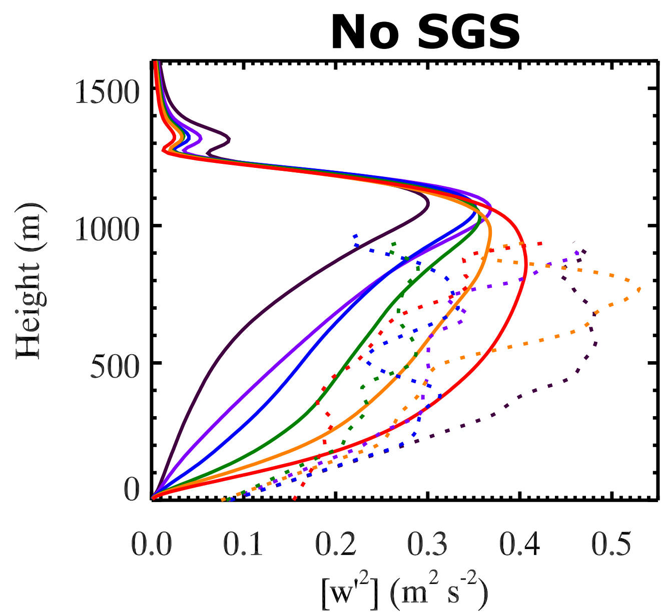
- Turbulence measurement with a high resolution Doppler lidar on board the R/V Brown during VOCALS
- New case based on the shipborne data
- LES with WRF
- Disagreement between WRF and obs.
  - Simulated [u] is weak.
  - Simulated turbulence, e.g., $[w'^2]$, is weak.
  - **Ultimate goal: simulate same case with CLUBB, identify defects to drive improvements**



Sensitivity tests

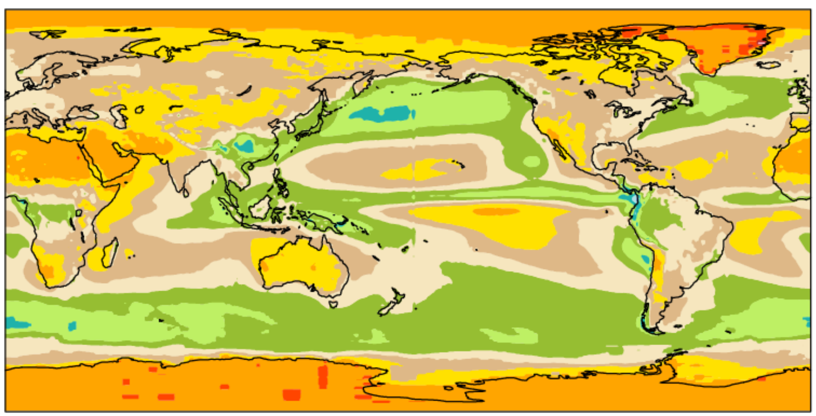
- $[w'^2]$ *is not* improved with
  - High resolution (from Δx=100 m & Δz~10 m to Δx=50 m & Δz~5m for 6.4x6.4 km^2)
  - Various domain sizes (6.4, 12.8, 25.6 km)
- $[w'^2]$ *is* improved with
  - No SGS (i.e., physical diffusion is turned off)
- Implicit model numerical diffusion is too strong?



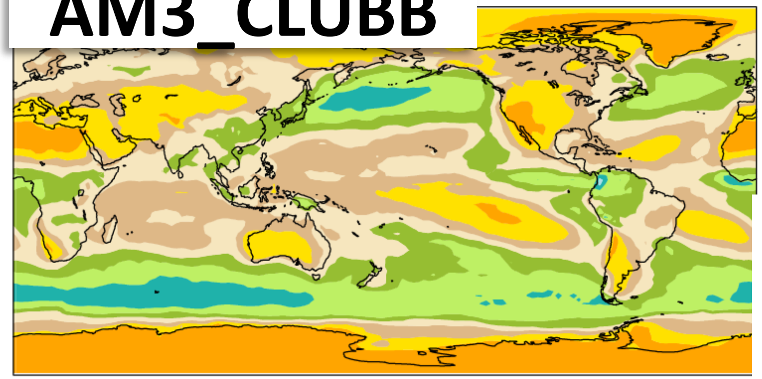


Simulations at 0.5º resolution (GFDL)

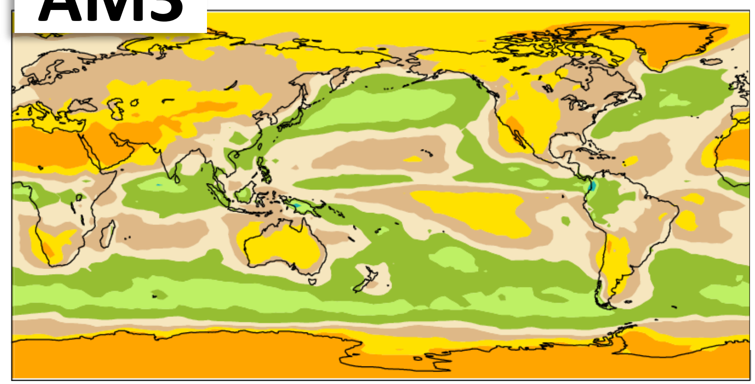
OBS (CERES) SW Cloud Radiative Effect at TOA

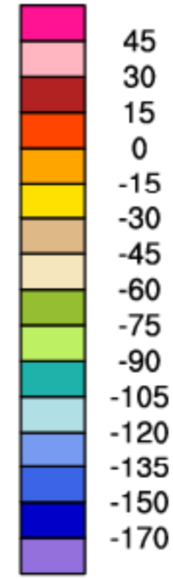


AM3_CLUBB

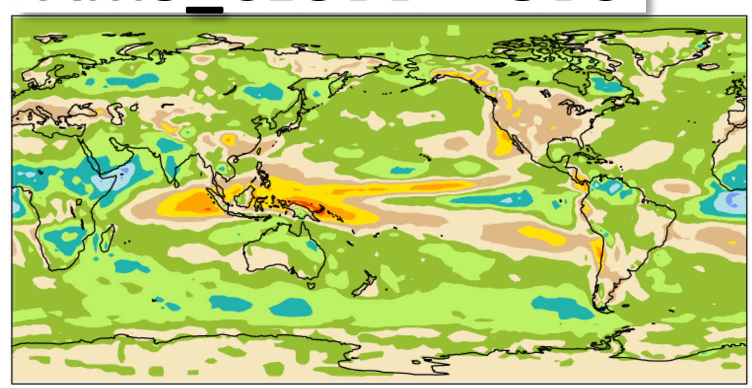


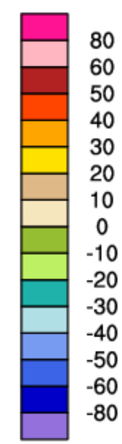
AM3



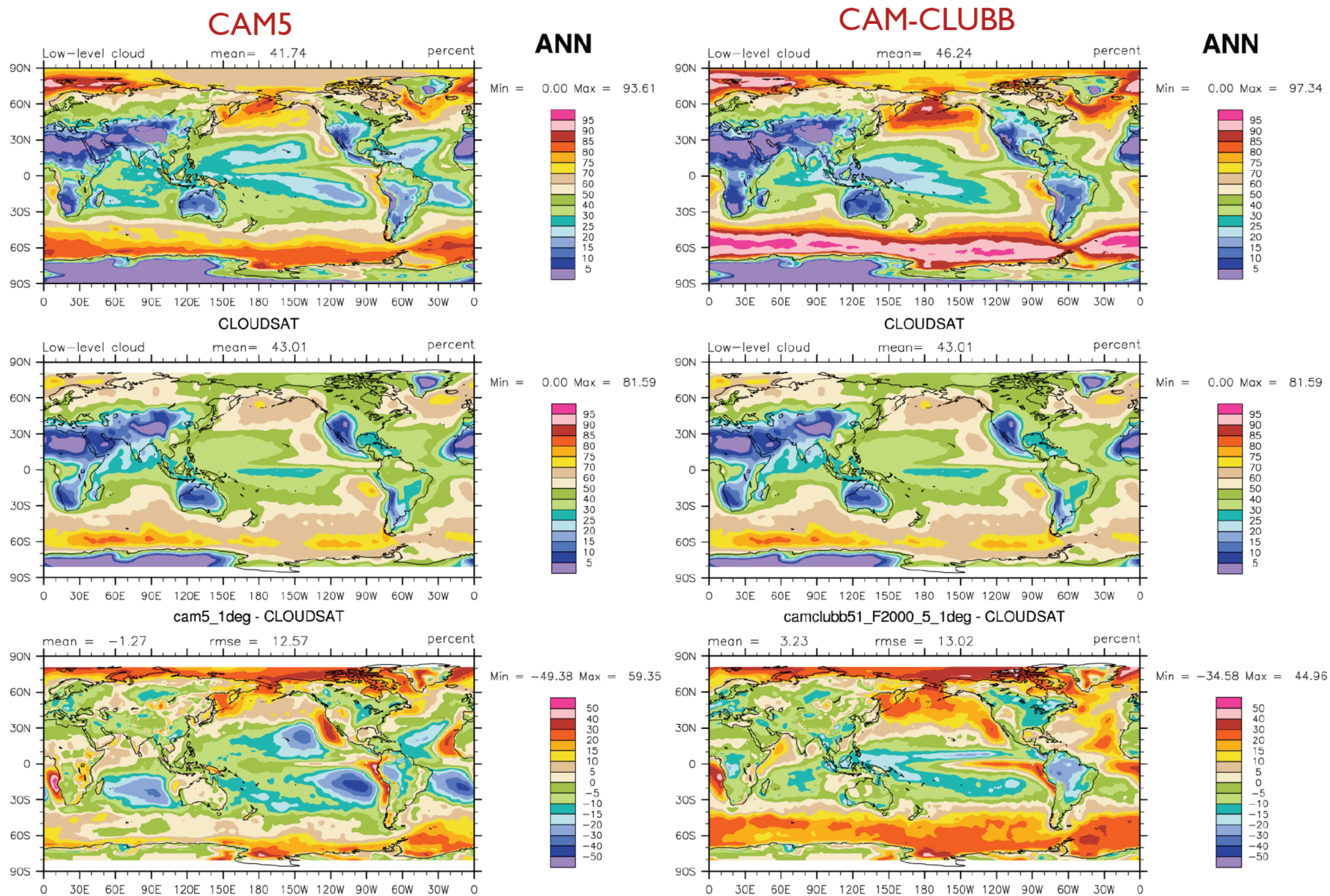


AM3_CLUBB – OBS





Low Cloud Amounts



A first look at aerosol indirect effects in CAM-CLUBB

- Preliminary AIE experiment performed with CAM-CLUBB
- Ran CAM5 and CAM-CLUBB for two years at 1 degree for both present day (PD) and preindustrial (PI) emissions

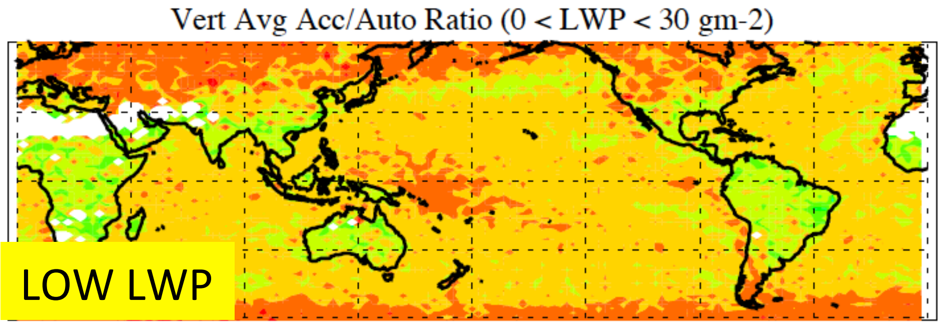
	CAM5	CAM-CLUBB
Δ SWCF	-1.6 W/m^2	- 1.8 W/m^2
Δ LWCF	0.5 W/m^2	0.4 W/m^2
Δ(SWCF + LWCF)	-1.1 W/m^2	- 1.4 W/m^2
RFP	-1.4 W/m^2	- 1.6 W/m^2

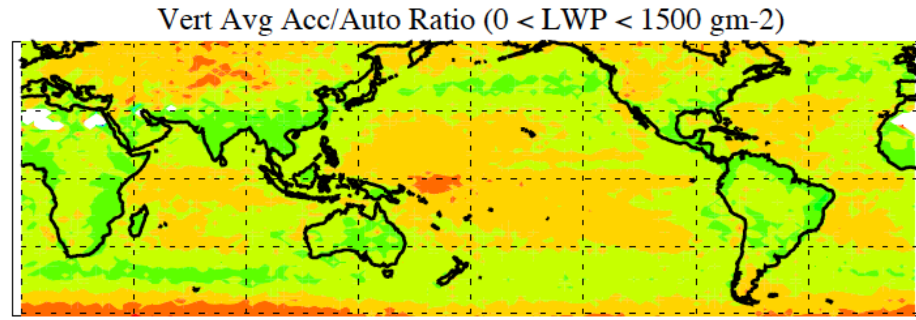
- Reasonable results for a preliminary investigation. Detailed analysis is needed

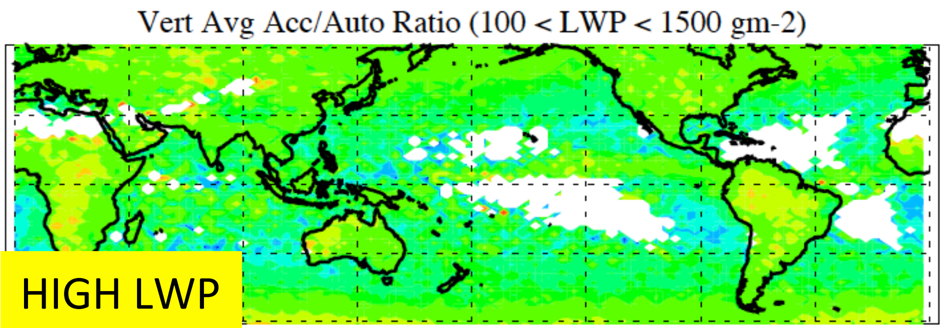
Challenge: microphysics unification

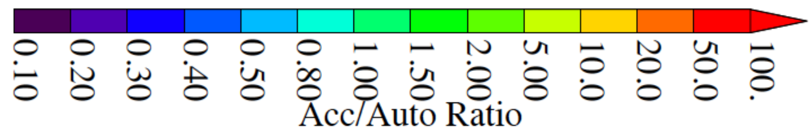
- Conceptually difficult to unify CLUBB (which predicts subgrid macrophysical variability) with microphysics schemes to produce precipitation
- CLUBB generates subgrid variability in condensate, but how to use this to generate realistic precipitation variability
  - Current workaround is to invoke model subcolumns, whereby the subgrid distribution of precipitation is generated by a number of distinct realizations drawn from the CLUBB-predicted pdf
  - May need to introduce prognostic precipitation (can be computationally expensive) to obtain correct balance of processes creating precipitation
  - Current microphysics scheme in CAM may need upgrades to deal with shallow cumulus

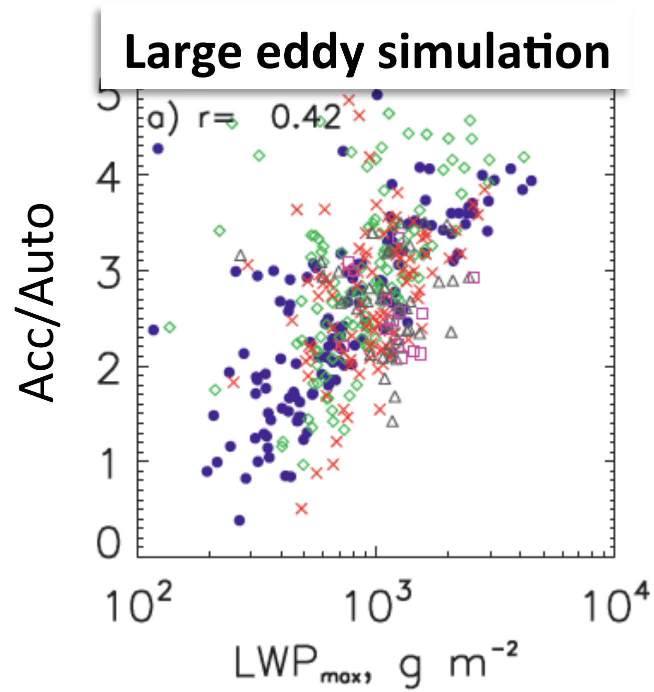
How model rain is produced: <u>Accretion</u> (raindrops collecting cloud drops) vs <u>Autoconversion</u> (cloud drops coalescing with each other)











Process models: Ratio of accretion to autoconversion *increases* with cloud condensate (liquid water path)

CAM5: Ratio *decreases* with condensate

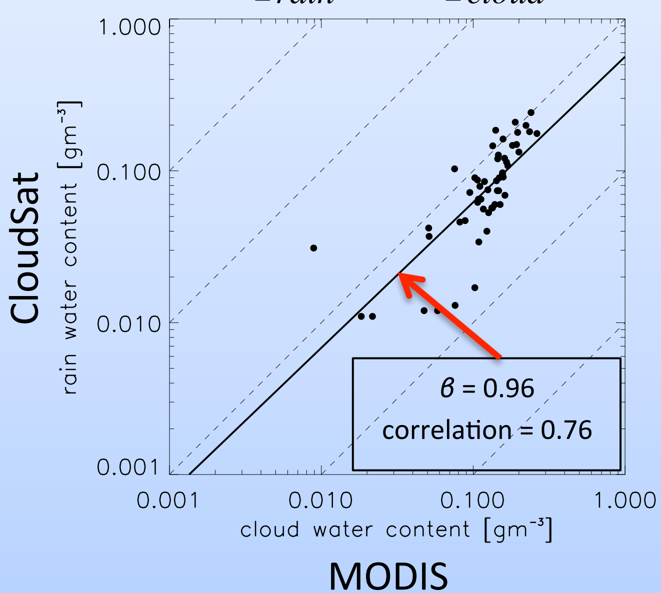
Too much autoconversion => precipitation likely too sensitive to aerosols

Using Satellite Data to Improve Climate Models

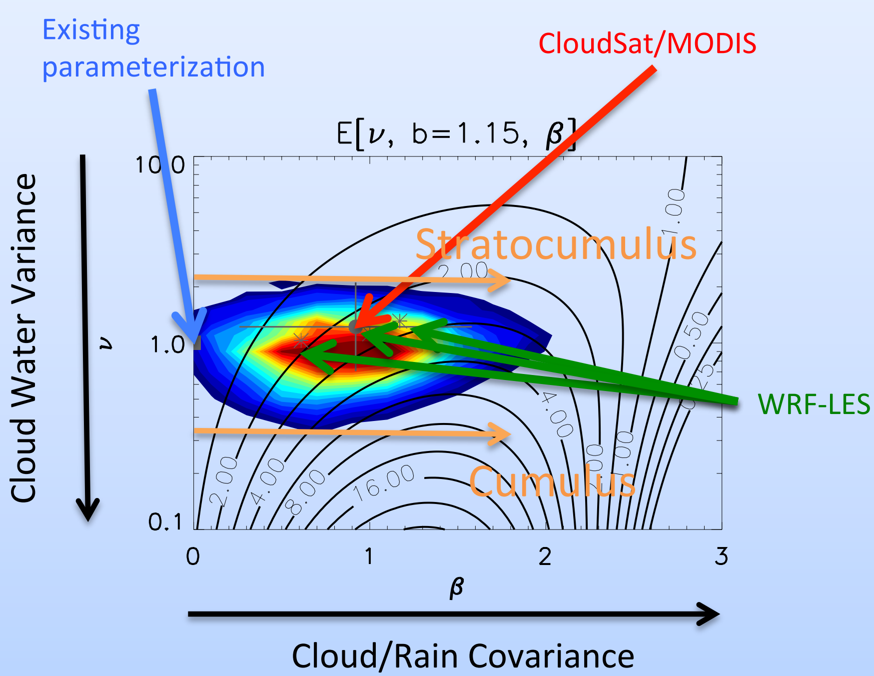
- Cloud microphysical processes occur at small scales and are non-linear
  - Calculation of these processes in coarse resolution global models requires knowledge of the sub-grid variability.
  - CloudSat (rain water) and MODIS (cloud water) provide an estimate of the sub-grid variability that can be used to improve the simulation of microphysical processes (e.g. accretion) in models

Estimating Cloud/Rain Covariance

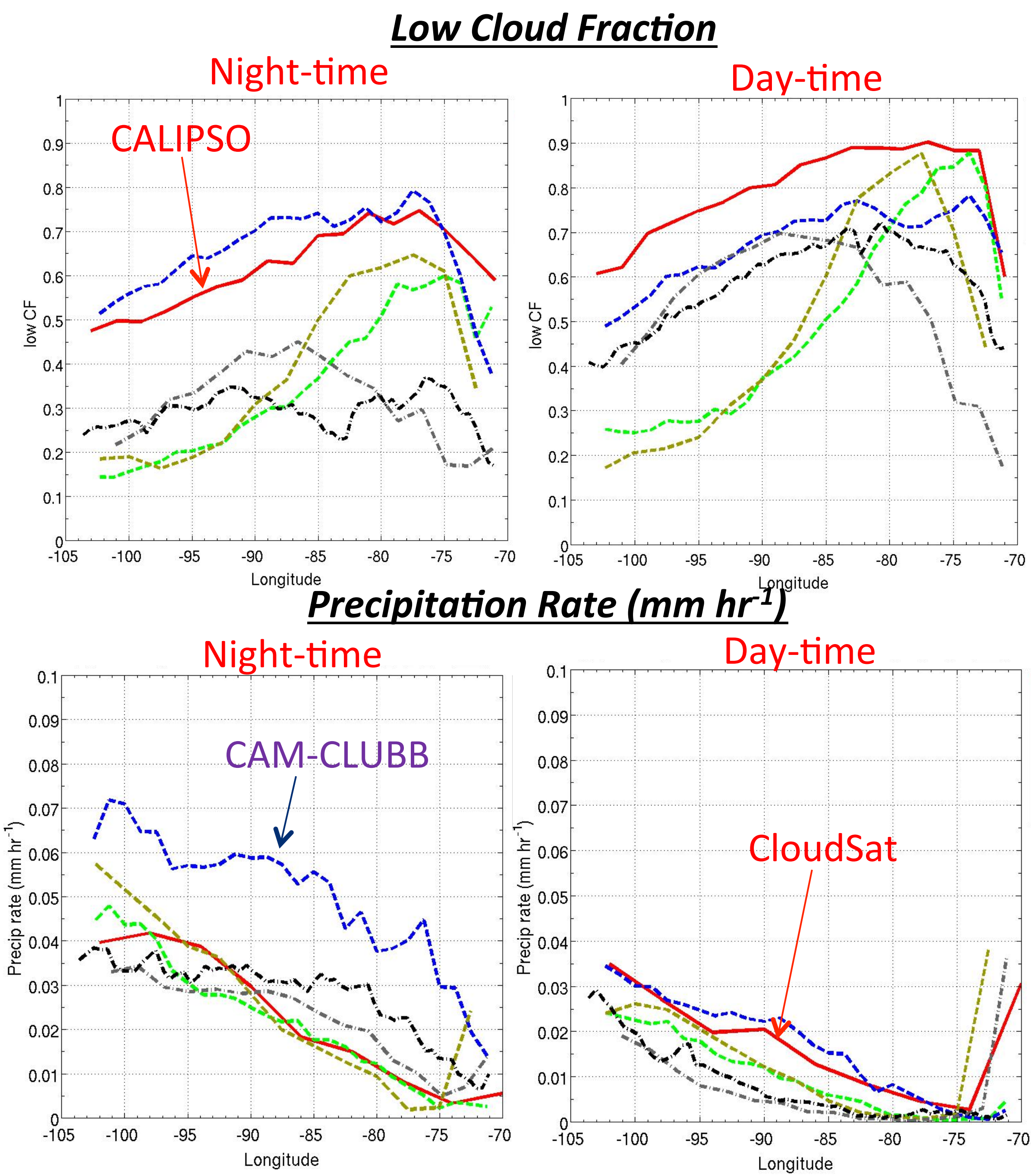
$$q_{rain} = \alpha q_{cloud}^{\beta}$$



Comparing Observations to Theory

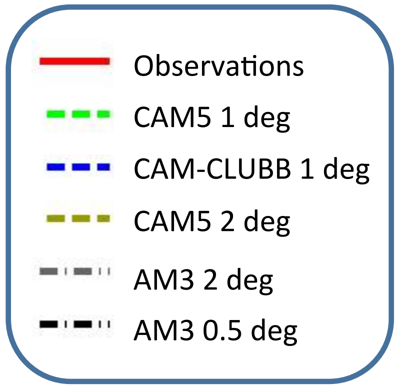


Contours show the enhancement of accretion rates by including sub-grid variability.



- **CAM-CLUBB shows a more realistic low cloud fraction than CAM5 throughout the stratocumulus deck**

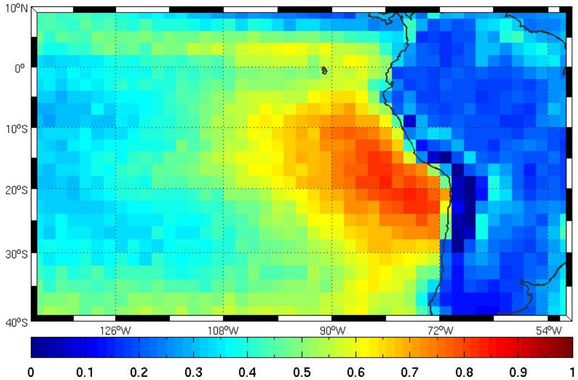
Longitude transects along 20°S (VOCALS region)



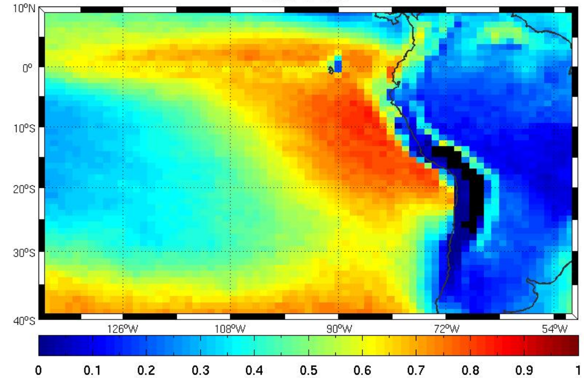
- CAM-CLUBB shows a larger diurnal cycle in precip. rate compared to obs and other models
- However, this precipitation is achieved with little LWP

Low Cloud Fraction (all day, annual averages)

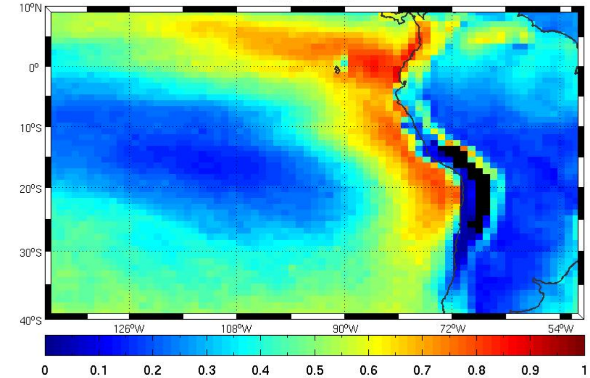
CALIPSO obs



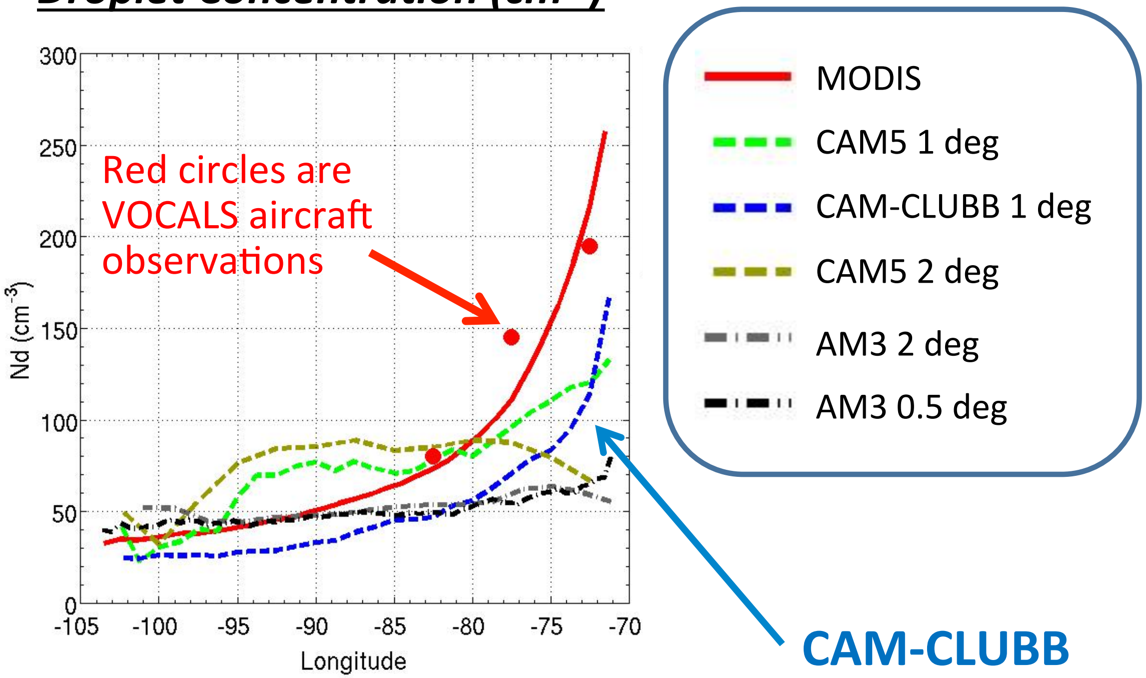
CAM-CLUBB 1 degree



CAM5 1 degree



Droplet Concentration (cm^{-3})



- The CLUBB stratocumulus deck extent is much more realistic than CAM5
- CAM-CLUBB removes the high Nd values in the stratocumulus to cumulus transition regions

Longitude transects along 20S (VOCALS stratocumulus region)

Future work

1. Implement subcolumn framework to drive microphysics in CAM-CLUBB.
2. Implement analytic coupling between CLUBB and key microphysical processes in AM3-CLUBB.
3. Compare approaches 1 and 2.
4. Continue to improve understanding of model errors using satellite observations and LES.
5. Quantify and explore aerosol indirect effects in CAM-CLUBB and AM3-CLUBB.