A CPT for Cloud Parameterization and Aerosol Indirect Effects

Supported by

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GFDL and NCAR are both implementing a parameterization for clouds and boundary layers, based on multi-variate PDFs, into atmospheric general circulation models, through a CLIVAR NOAA/NSF Climate Process Team.

GFDL AM3:	NCAR CAM5:
Huan Guo	Pete Bogenschutz
Chris Golaz	Andrew Gettelman
Leo Donner	Hugh Morrison

University of Wisconsin, Milwaukee:
Vince Larson ("CLUBB" Parameterization)

Dynamics-Based PDFs for Cloud Parameterization: Motivation

- Moisture-based PDFs are not linked to dynamics of cloud formation and dissipation.
- Key microphysical processes like droplet activation are linked to vertical motions.
- Aerosol-cloud interaction: An example.

Observed dependence of cloud droplets on aerosols

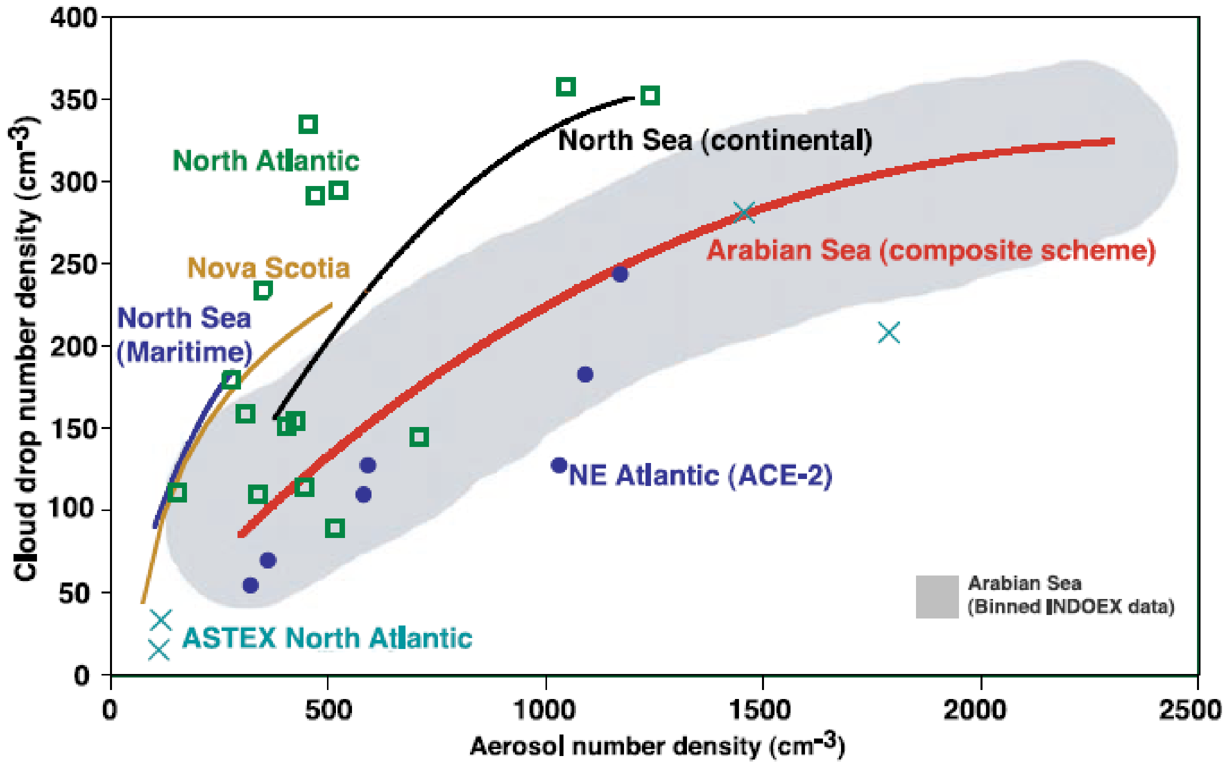
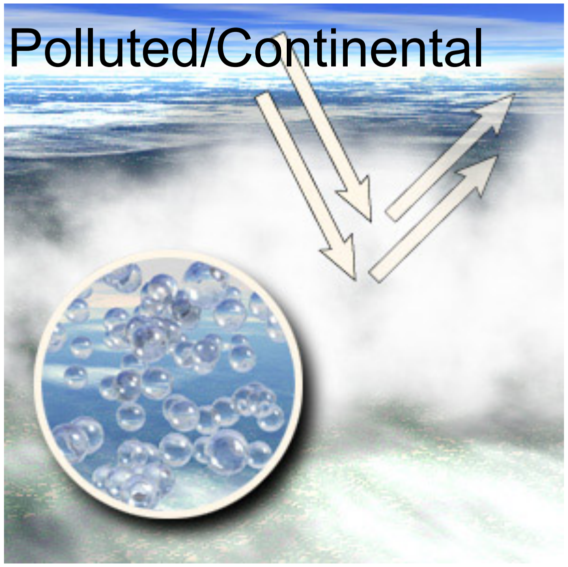
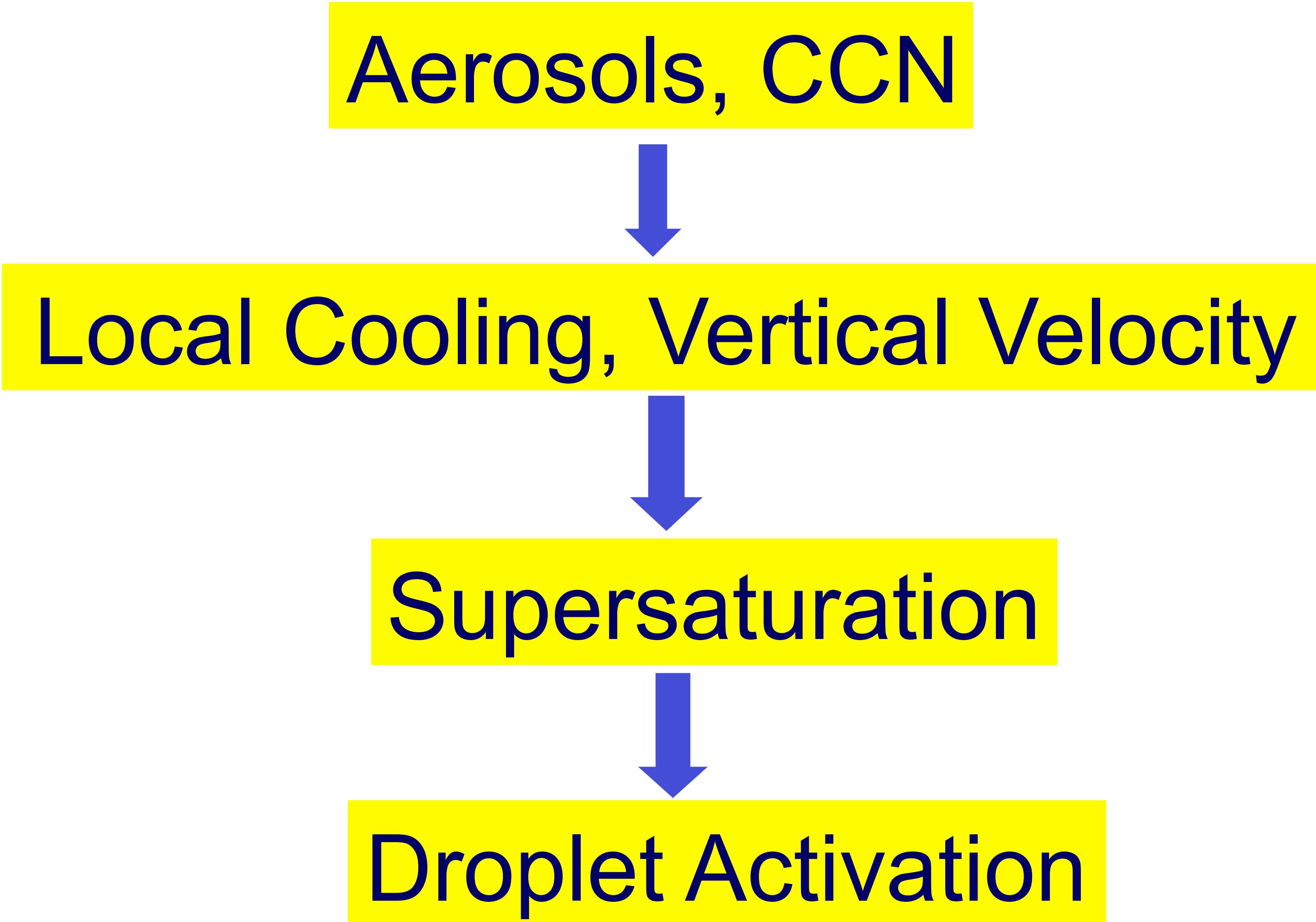


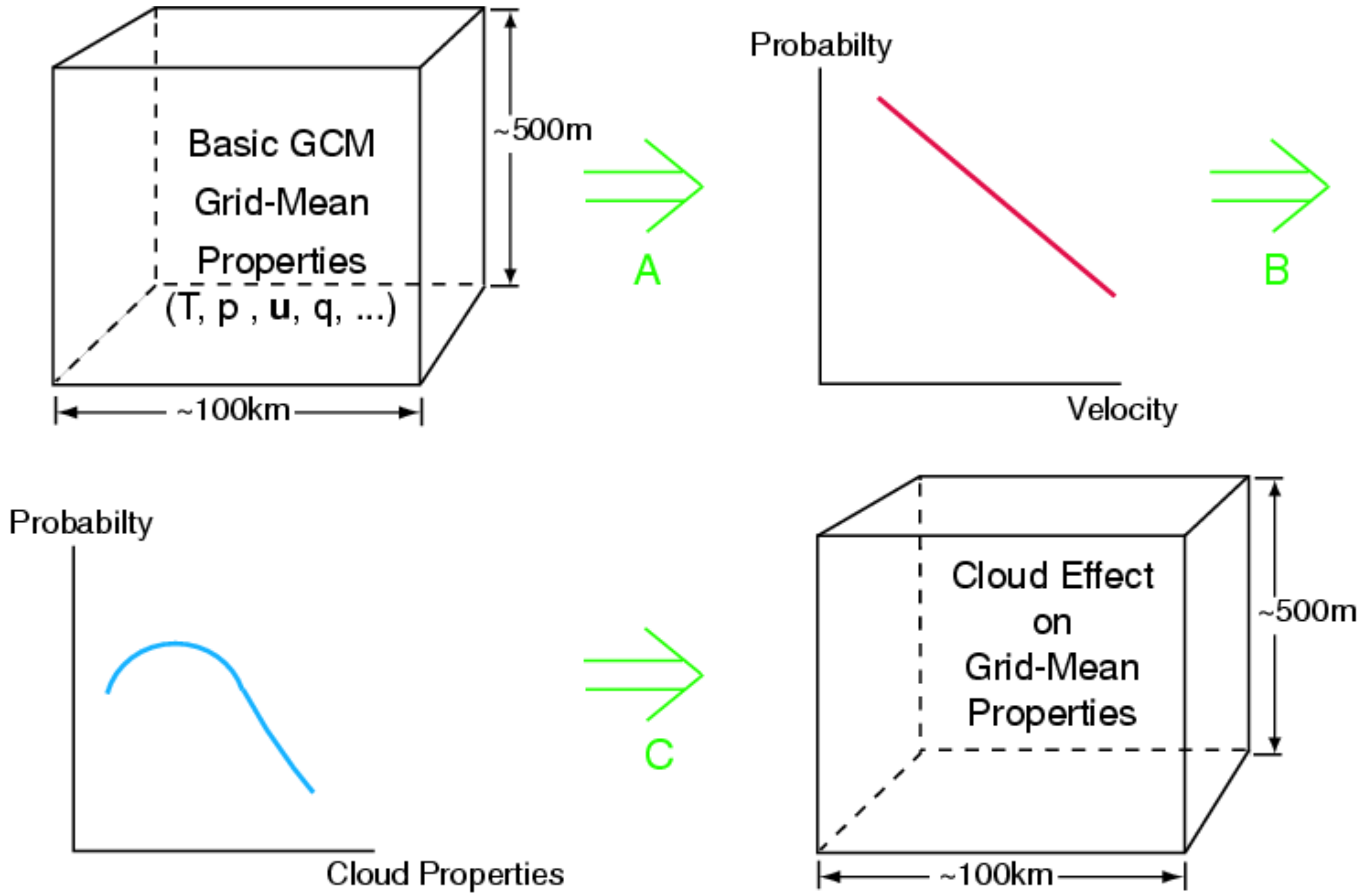
Fig. 5. Aircraft data illustrating the increase in cloud drops with aerosol number concentration. References for the data are as follows: North Sea (*28*), Nova Scotia and North Atlantic (*29*), ACE-2 (*30*), Astex (*31*), the thick red line is obtained from a composite theoretical parameterization that fits the INDOEX aircraft data for the Arabian Sea (*23*). The gray-shaded region is the INDOEX aircraft data for the Arabian Sea (*32*).

Source: Ramanathan et al. (*Science*, 2001)




Aerosols, CCN
Local Cooling, Vertical Velocity
Supersaturation
Droplet Activation

Linking Cloud Microphysics and Macrophysics

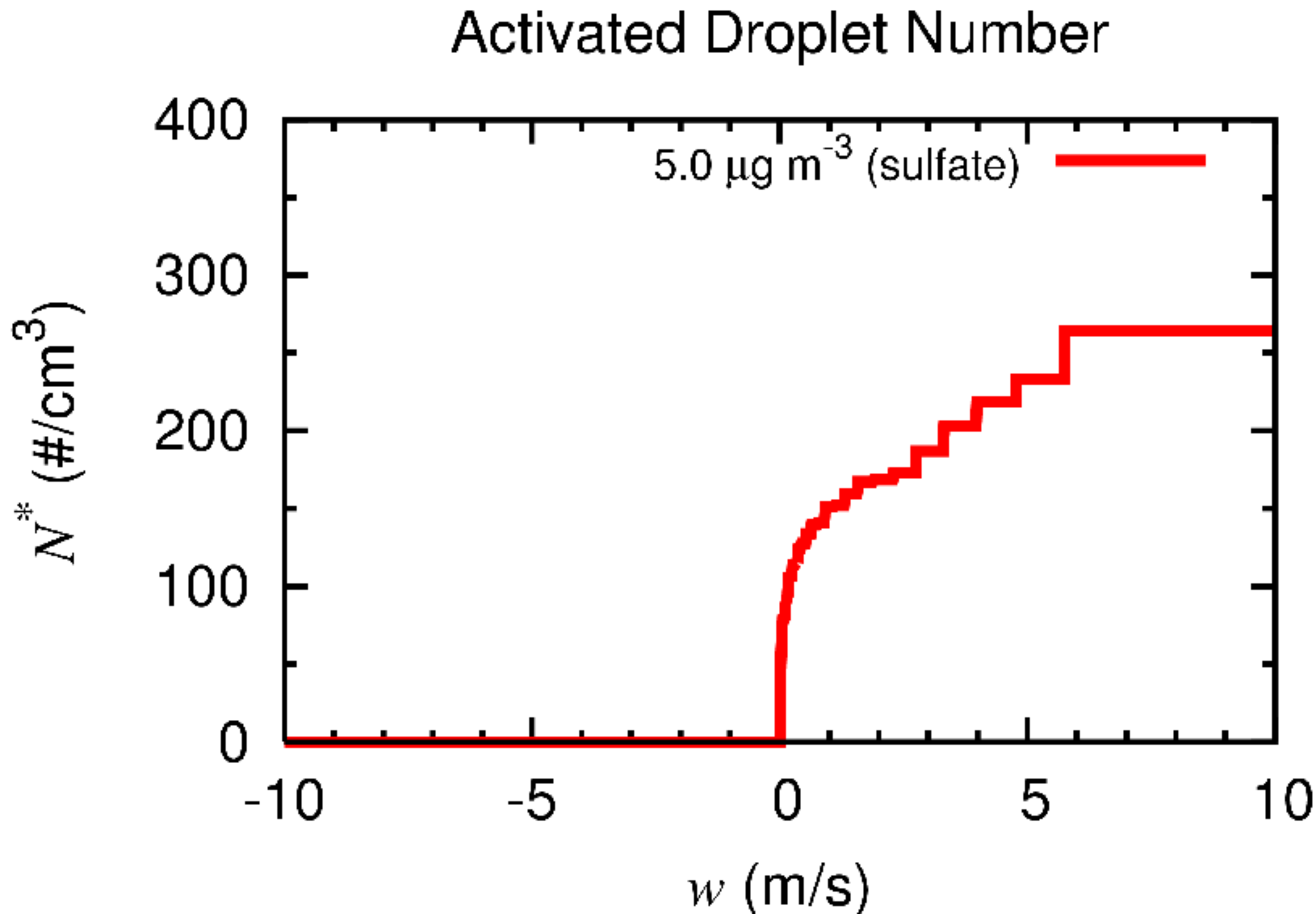


A: "Statistical" Parameterizations, e.g.
Donner (1993, *J. Atmos. Sci.*), Golaz et al. (2002, *J. Atmos. Sci.*)

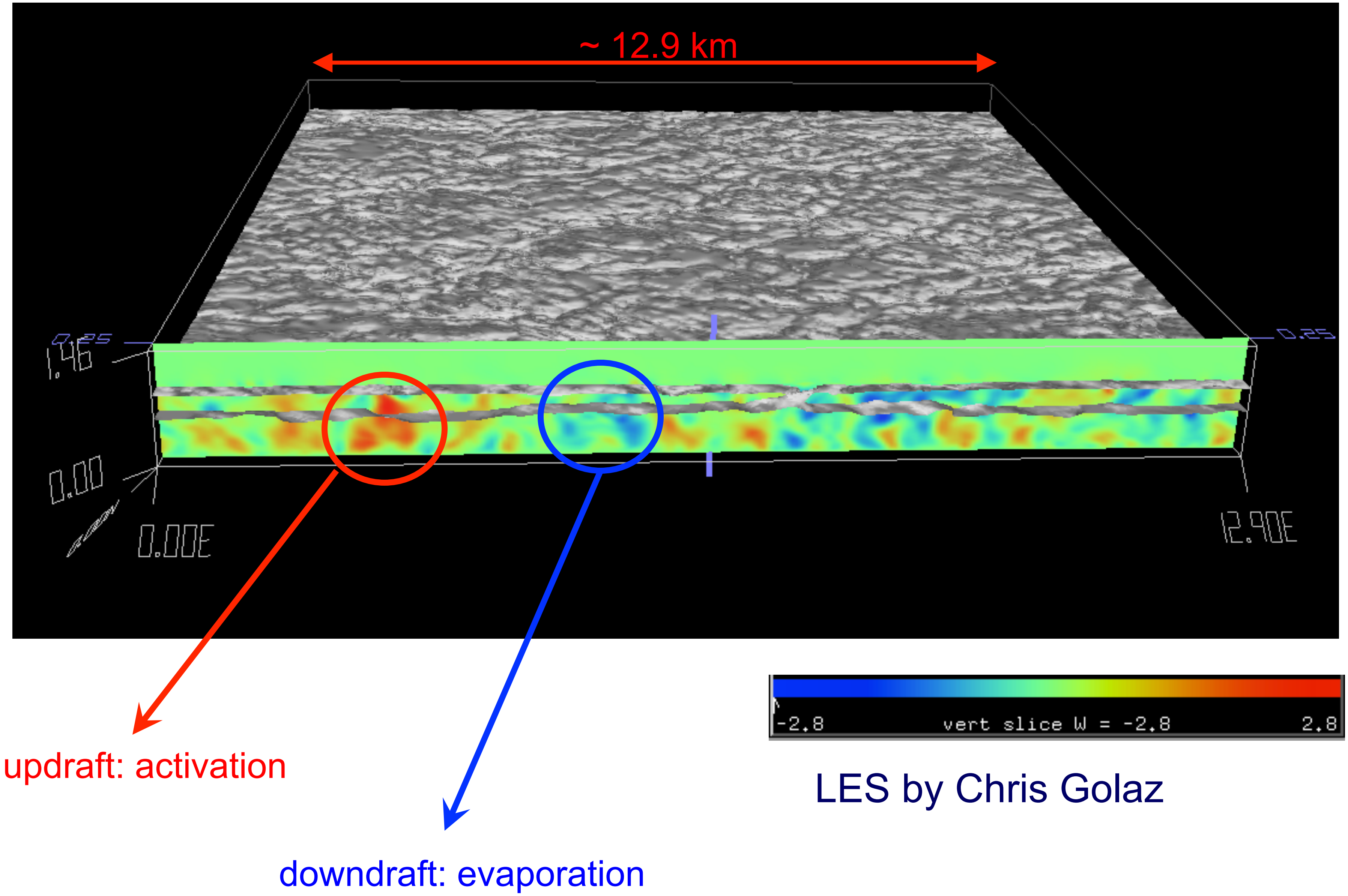
B: "Classical" Process Studies, e.g., CPT, GCSS

C: Averaging

Linking Cloud Macrophysics and Microphysics in Stratiform Clouds

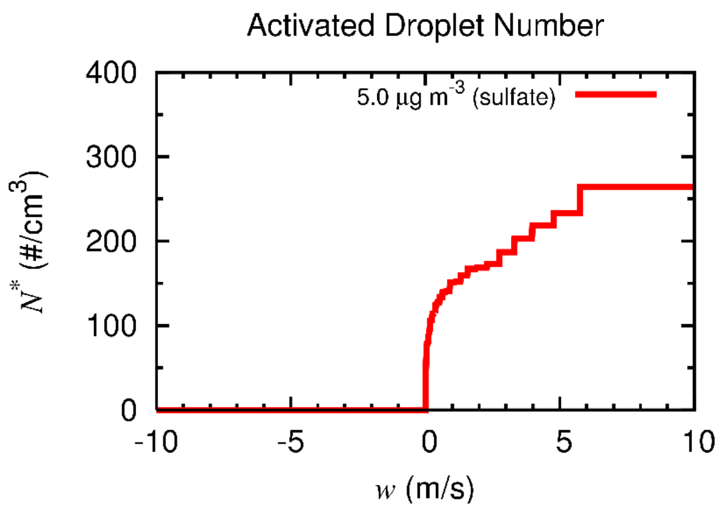


cf., Ming *et al.* (*J. Atmos. Sci.*, 2006)



LES by Chris Golaz

Large-scale CCN activation



Layer-averaged activation:

$$\overline{N}_{\text{activation}} = \int N^*\left(w, p, T\right)\, dx\, dy$$

Because *N** is non-linear

$$\overline{N}_{\text{activation}} \neq N^*\left(\bar{w}, \bar{p}, \bar{T}\right)$$

However,

$$\overline{N}_{\text{activation}} \cong \int N^*\left(w, \bar{p}, \bar{T}\right) pdf\left(w\right) dw$$

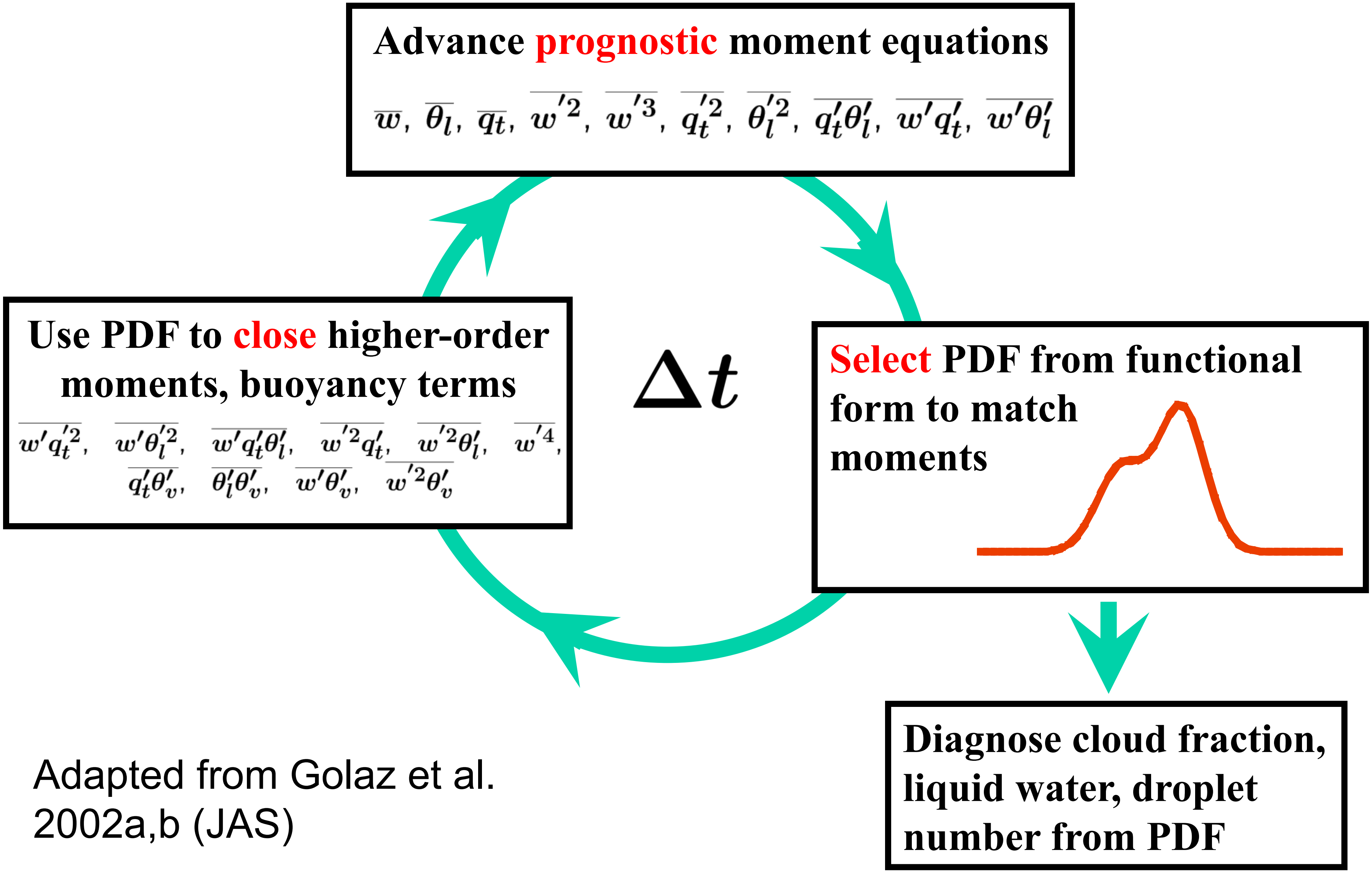
Dynamics-PDF Cloud Parameterization: Overview

- Based on Golaz et al. (2002, *J. Atmos. Sci.*): "CLUBB" (Cumulus Layers Unified by Bi-Normals)
- Joint PDFs for vertical velocity, liquid potential temperature, and total water mixing ratio

Dynamics PDF Parameterization for Stratiform Clouds and Turbulence

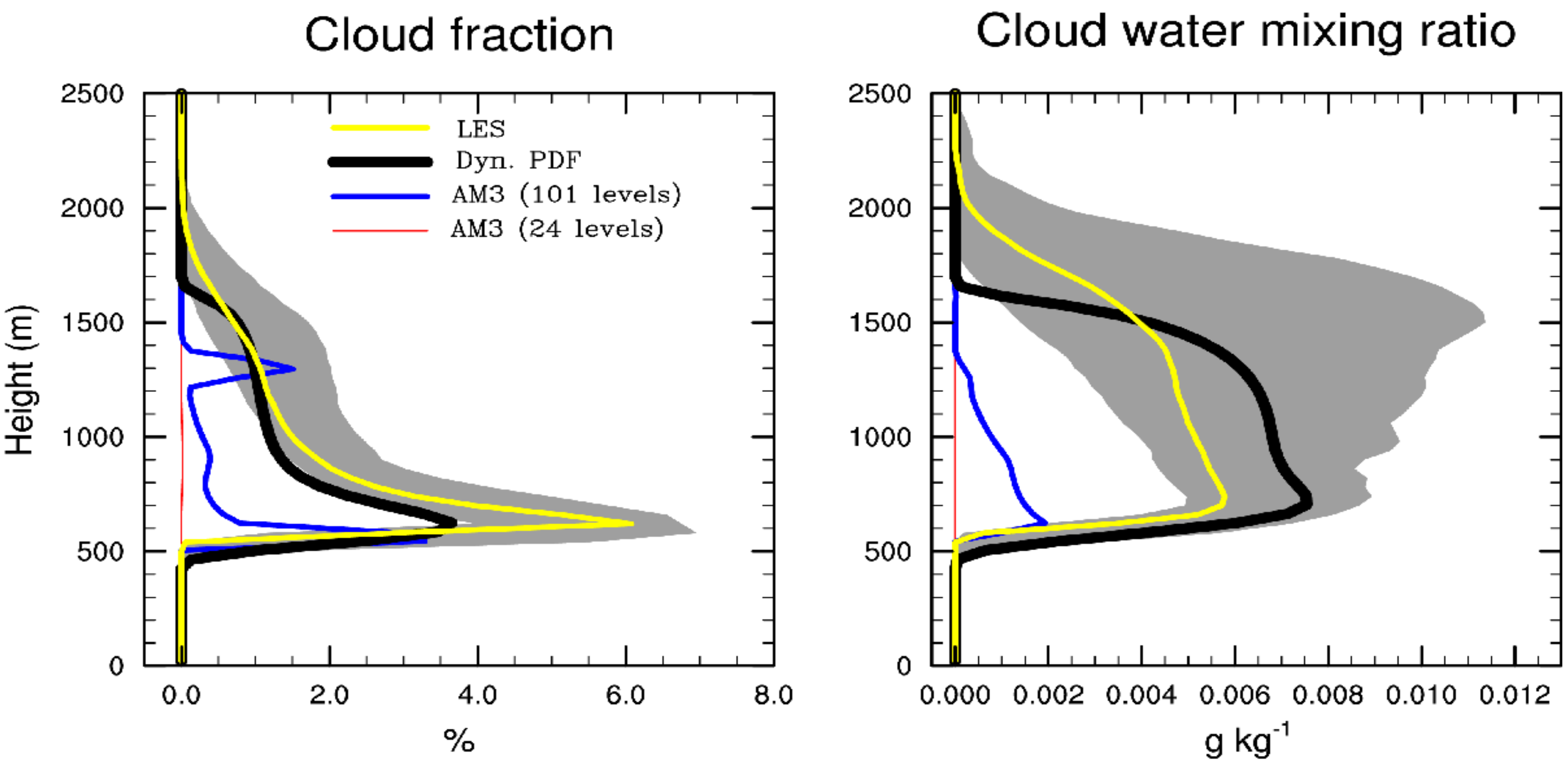
- Fit liquid potential temperature, total water, vertical velocity PDFs for range of Cu and Sc PBLs to LES simulations
- LES evaluated using GCSS WG 1 cases (ARM, ATEX, BOMEX, DYCOMS-II RF01 & RF02, FIRE, RICO)
- Prognostic equations for higher-order moments
- Select PDFs based on evolution of higher-order moments
- Extract cloud macrophysics (fraction, liquid content, etc.) from PDFs

Building a PDF-based parameterization



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

BOMEX (cumulus)

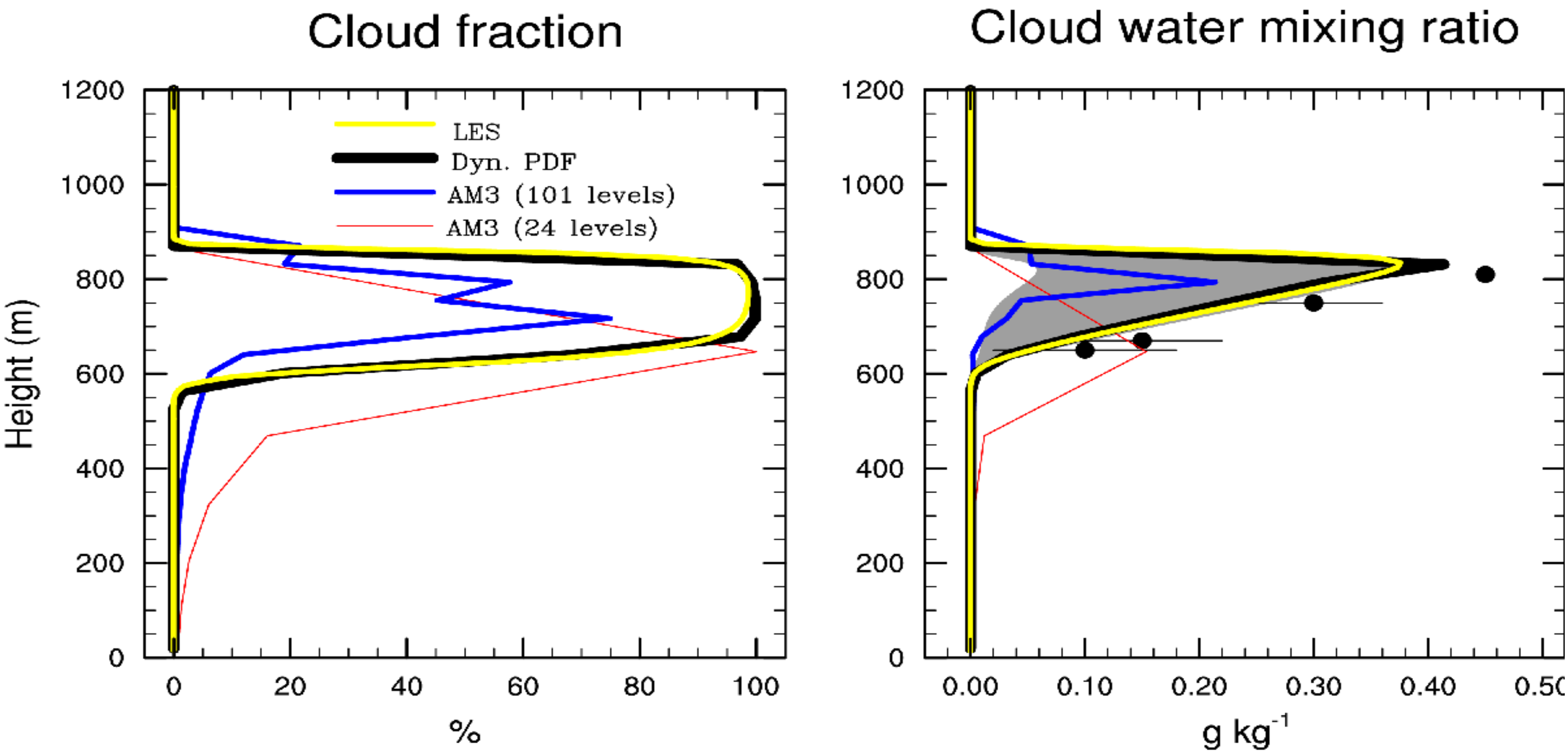


Note: 1. shaded areas indicate the range (Min. and Max. bounds) of GCSS LES intercomparisons

AM3 uses Tiedtke (1993, *Mon. Wea. Rev.*)

(Source: Huan Guo, GFDL)

DYCOMS-II Research Flight 1 (stratocumulus)



Note: 1. shaded areas indicate the range (Min. and Max. bounds) of GCSS LES intercomparisons

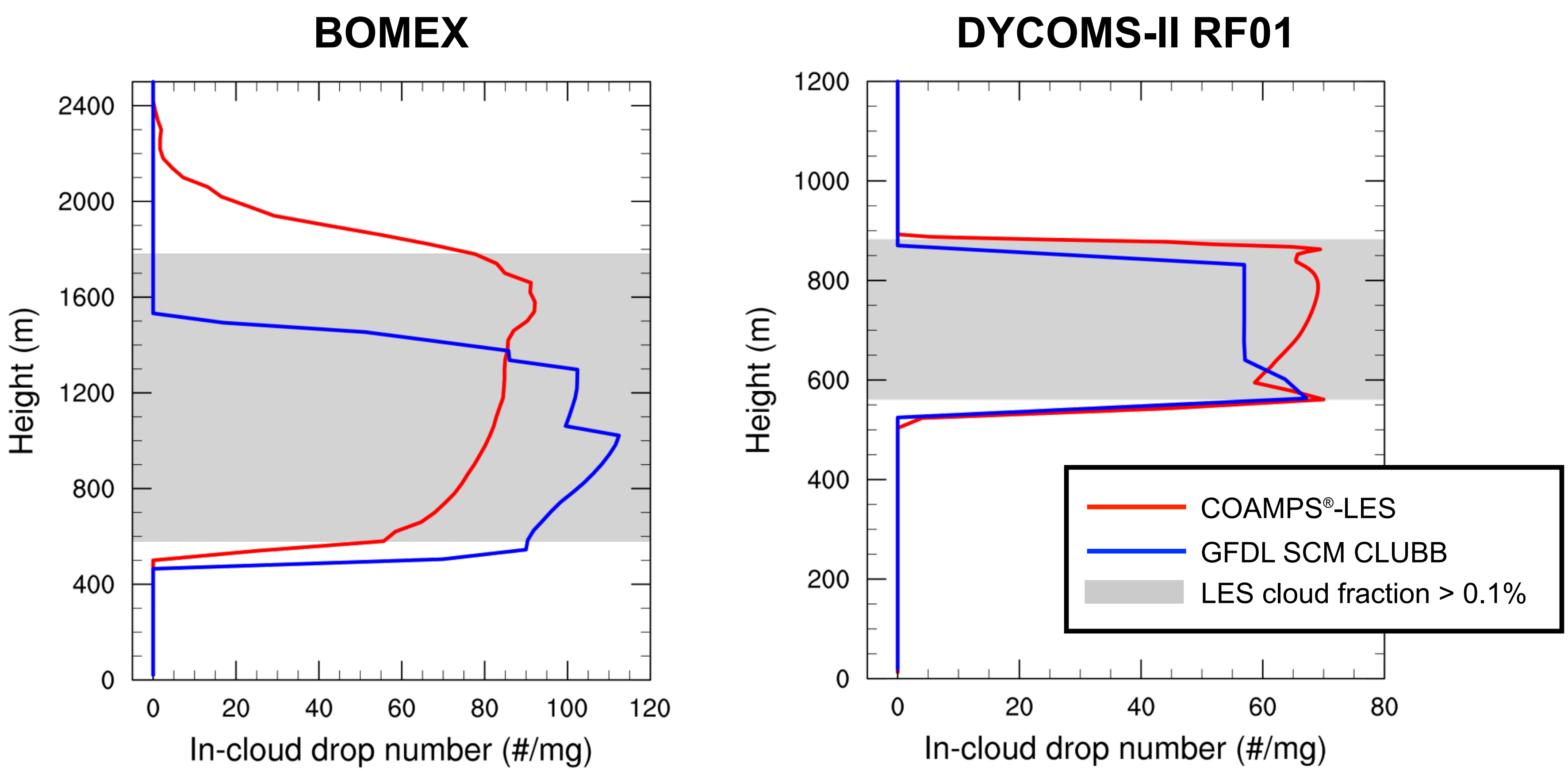
2. dots and horizontal bars indicate the obs. (Stevens et al., 2005 MWR)

AM3 uses Tiedkte (1993, *Mon. Wea. Rev.*)

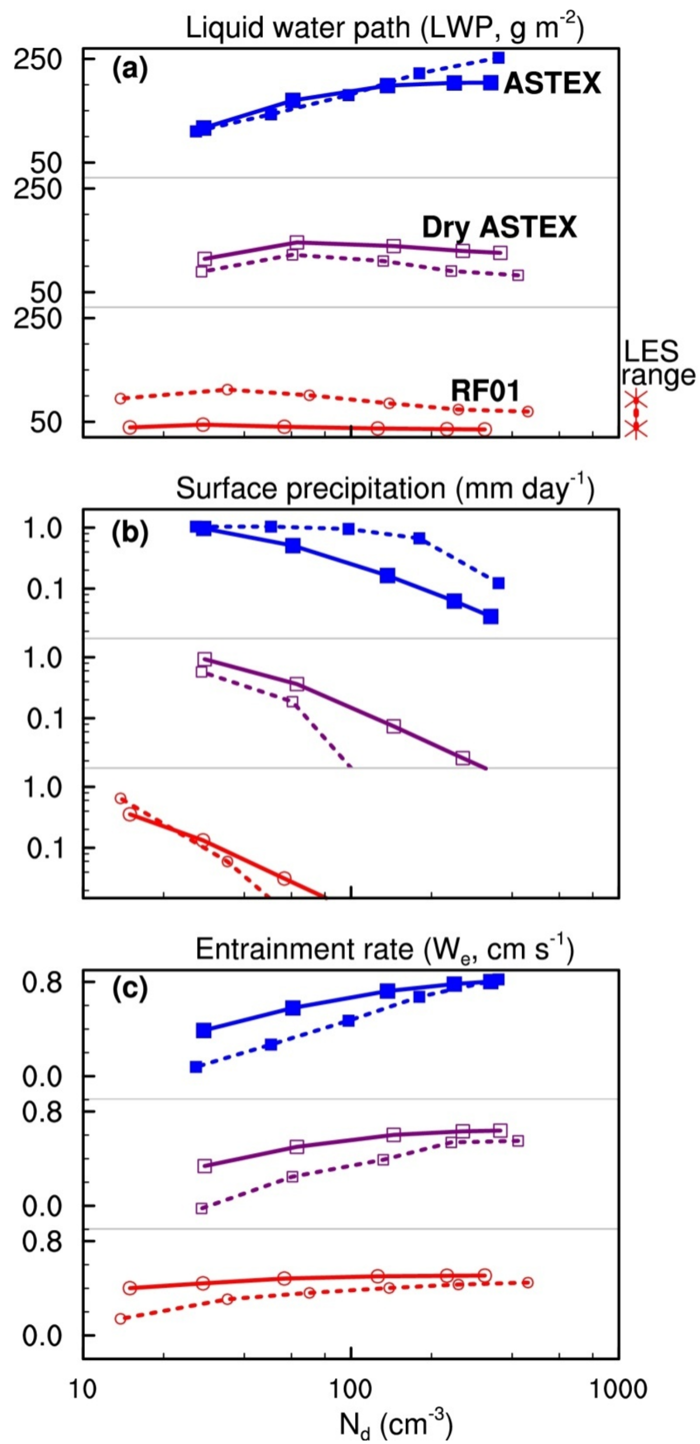
(Source: Huan Guo, GFDL)

Prediction of cloud drop number (Guo et al., 2010, *Geoscientific Model Development)*

- Added predictive equation for cloud drop number:
  activation, evaporation and turbulence transport.
- Uniform background aerosol mass concentration.



Physics of entrainment-aerosol interaction similar in CLUBB and LES

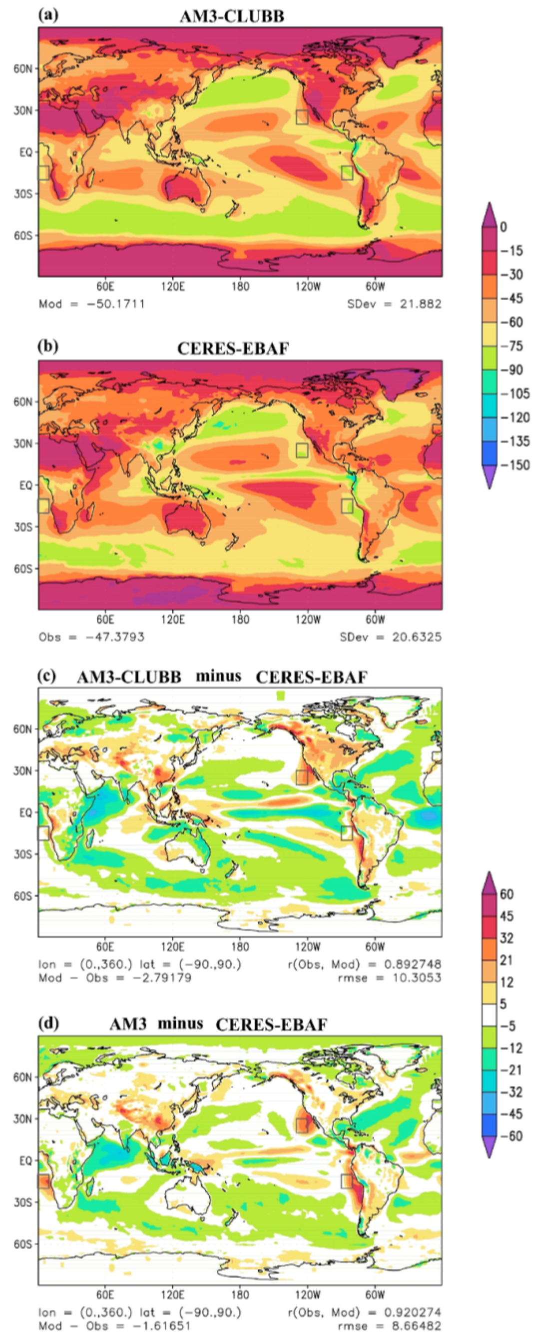


LES range from Guo *et al.* (2010, *GMD*)

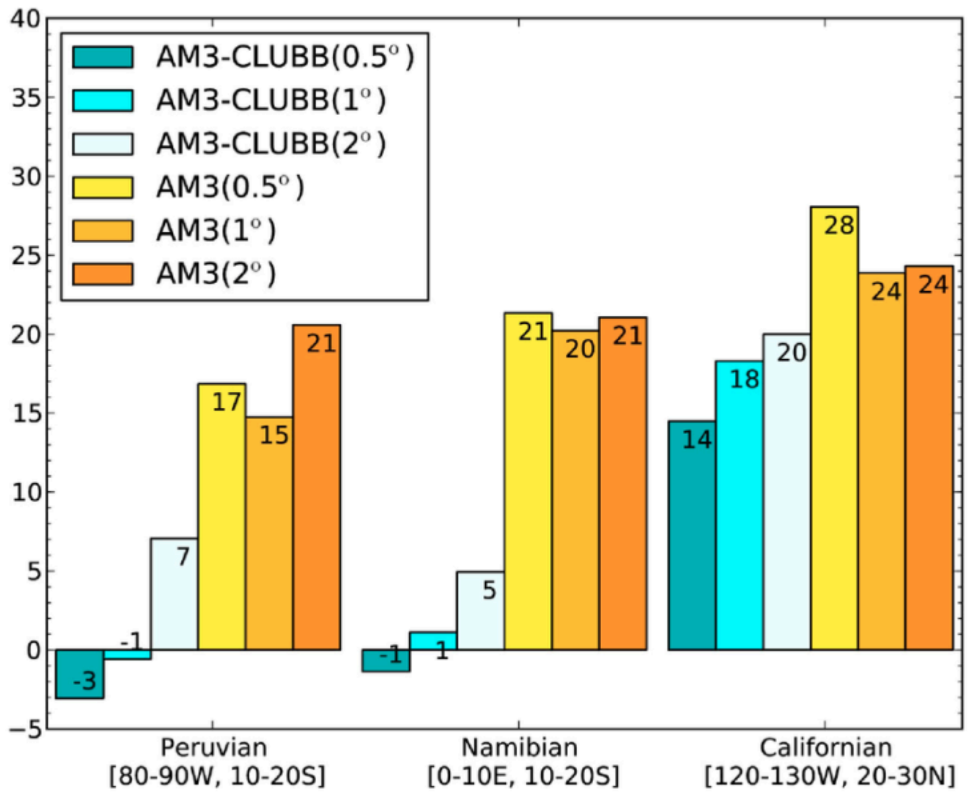
Solid: MVD PDFs

Dashed: LES from Ackerman *et al.* (2004, *Nature*)

cf., Guo *et al.* (2011, *GRL*)



Parameterization ("CLUBB") in GFDL AM3 (Guo *et al.*, 2013, *J. Climate*, submitted) substantially reduces errors in shortwave cloud forcing off west coasts of South America and Africa, a long-standing bias in marine stratocumulus in GFDL climate models.



Improved simulation of marine stratocumulus in AM3 holds at horizontal resolutions from about 50 km to 200 km (Guo *et al.*, 2013, *J. Climate,* submitted).

Figure 8: Annual-mean bias of shortwave cloud forcing (W m^{-2}) for AM3-CLUBB and AM3 at different horizontal resolutions of 0.5°, 1°, and 2° over the Peruvian, Namibian, and Californian subtropical stratocumulus regions analyzed by Klein and Hartmann (1993).

GFDL AM3 and NCAR CAM5 perform similarly with respect to key cloud-related global metrics when both use CLUBB (Bogenschutz *et al.*, 2013, *J. Climate,* in revision; Guo *et al.*, 2013, *J. Climate,* submitted).

	AM3-CLUBB	CAM5-CLUBB
Shortwave Cloud Forcing Bias	-2.8 W m^{-2}	-1.8 W m^{-2}
Shortwave Cloud Forcing RMSE	10.3 W m^{-2}	12.4 W m^{-2}
Longwave Cloud Forcing Bias	-3.6 W m^{-2}	-4.7 W m^{-2}
Longwave Cloud Forcing RMSE	7.2 W m^{-2}	7.6 W m^{-2}

Bias and RMSE relative to CERES-EBAF (Loeb *et al.*, 2009, *J. Climate*).

Summary

- Most current state-of-science cloud parameterizations built around moisture PDFs.
- Cloud microphysical and aerosol processes "see" dynamics, suggesting next-generation cloud parameterizations should also include dynamics PDFs.
- Cloud and boundary-layer parameterization using multi-variate PDFs with dynamics ("CLUBB") realistically simulates multiple-cloud regimes and aerosol-cloud interactions in single-column tests with high spatial and temporal resolution.
- GFDL AM3 and NCAR CAM5 have both incorporated CLUBB with comparable results for global metrics related to boundary-layer clouds. GFDL AM3 simulations of marine stratocumulus clouds are more realistic than in earlier GFDL models.