A CPT for Cloud Parameterization and Aerosol Indirect Effects

Supported by
Our CPT’s participating institutions:

- U. Wisconsin --- Milwaukee (Cloud parameterization: V. Larson, Lead PI)
- GFDL (GCM simulations: L. Donner, J.-C. Golaz, Y. Ming)
- NCAR (GCM simulations: A. Gettelman, H. Morrison)
- JPL (Satellite obs: G. Stephens)
- U. Washington (Aircraft obs: R. Wood)
- NOAA ESRL (LES: G. Feingold)
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

![Graph showing the observed dependence of cloud droplet number density on aerosol number density for different regions: North Atlantic (Maritime), North Sea (continental), Nova Scotia, North Sea (Maritime), NE Atlantic (ACE-2), and Arabian Sea (composite scheme). The gray-shaded region represents the INDOEX aircraft data for the Arabian Sea. The thick red line is obtained from a composite theoretical parameterization that fits the INDOEX aircraft data for the Arabian Sea.

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

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

C: Averaging
Linking Cloud Macrophysics and Microphysics in Stratiform Clouds
Activated Droplet Number

$N^* \text{ (#/cm}^3\text{)}$

$w \text{ (m/s)}$

5.0 μg m$^{-3}$ (sulfate)

cf., Ming et al. (J. Atmos. Sci., 2006)
updraft: activation

downdraft: evaporation

LES by Chris Golaz
Large-scale CCN activation

Layer-averaged activation:

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

Because \( N^* \) is non-linear

\[
\overline{N}_{\text{activation}} \neq N^* (\overline{w}, \overline{p}, \overline{T})
\]

However,

\[
\overline{N}_{\text{activation}} \approx \int N^* (w, \overline{p}, \overline{T}) \, \text{pdf}(w) \, dw
\]
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

• Single-column model tests for BOMEX and DYCOMS-II field programs
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
Observed cumulus case from ASTEX

Aircraft transect through a cumulus layer during ASTEX

Adapted from Larson et al. 2002 (JAS)
Observed cumulus case from ASTEX

Joint distribution of $q_t$ and $w$

Met Office C-130 Flight a215r6.4 data
Adapted from Larson et al. 2002 (JAS)
Observed cumulus case from ASTEX

Distribution of $w$

Met Office C-130 Flight a215r6.4 data
Adapted from Larson et al. 2002 (JAS)
ASTEX
Example of PDF fits to the data

Distribution of $w$

- Aircraft data
- Double delta
- Single Gaussian
- LGC Double Gauss.
- LY Double Gauss.

Met Office C-130 Flight a215r6.4 data
Adapted from Larson et al. 2002 (JAS)
Building a PDF-based parameterization

Advance **prognostic** moment equations

$w, \bar{\theta}_l, q_t, \bar{w}'^2, \bar{w}'^3, \bar{q}'_l^2, \bar{q}'_l \bar{\theta}'_l, \bar{w}' q'_t, \bar{w}' \bar{\theta}'_l$

Use PDF to **close** higher-order moments, buoyancy terms

$w' q'_t, w' \bar{\theta}'_l^2, \bar{w}' q'_l \bar{\theta}'_l, \bar{w}'^2 d'_t, \bar{w}'^2 \bar{\theta}'_l, \bar{w}'^4, q'_t \bar{\theta}'_v, \bar{\theta}'_l \bar{\theta}'_v, \bar{w}' \bar{\theta}'_v, w'^2 \theta'_v$

Select PDF from functional form to match moments

$\Delta t$

Diagnose cloud fraction, liquid water, droplet number from PDF

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

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

(Source: Huan Guo, GFDL)
DYCOMS-II Research Flight 1 (stratocumulus)

Cloud fraction

Cloud water mixing ratio

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)


(Source: Huan Guo, GFDL)
Prediction of cloud drop number:
Preliminary results (Guo et al., 2010, GMDD)

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

• Most current state-of-science cloud parameterizations built around moisture PDFs.
• Cloud microphysical processes “see” dynamics, suggesting next-generation cloud parameterizations should also include dynamics PDFs.
• Cloud macrophysics and microphysics have been simulated using proto-application with dynamics PDFs.
Our CPT project: “Cloud macrophysical parameterization and its application to aerosol indirect effects”

- We will implement CLUBB in GFDL’s GCM (AM) and NCAR’s GCM (CAM).

- We will test the models versus LES, aircraft observations, and satellite observations.

- The goal is to improve low clouds in the GCMs.

- A particular focus is the effects of aerosols on clouds.