Cloud-Aerosol Interactions in Boundary-Layer Clouds: Perspectives from Macrophysics based on Multi-Variate Probability Distribution Functions with Dynamics

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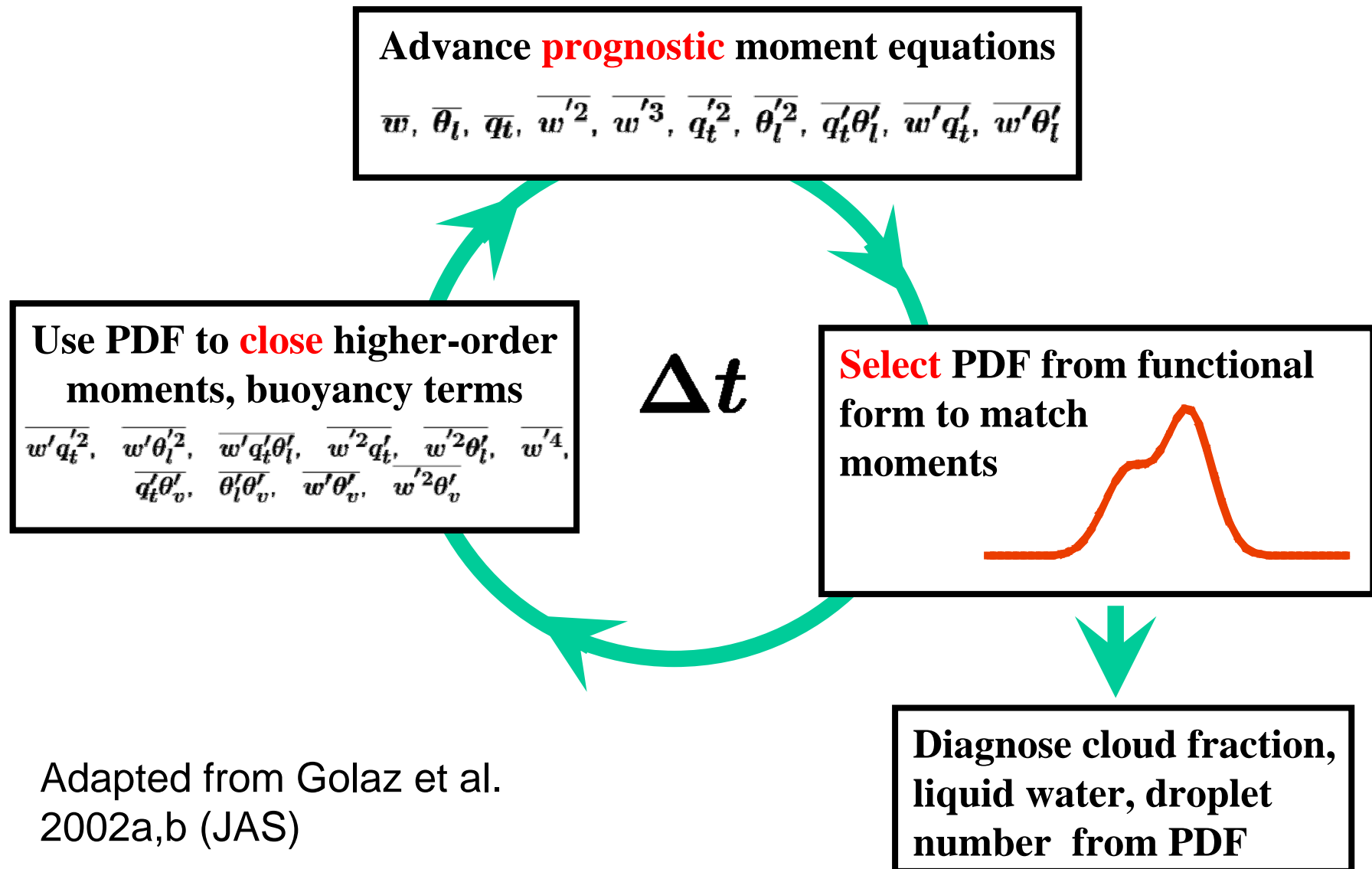CFMIP/GCSS/EUCLIPSE Meeting on Cloud Processes
and Climate Feedbacks

Overview

- Using multi-variate probability density functions with dynamics to parameterize boundary layers and clouds

- Application to warm and mixed phase clouds

- Aerosol interactions

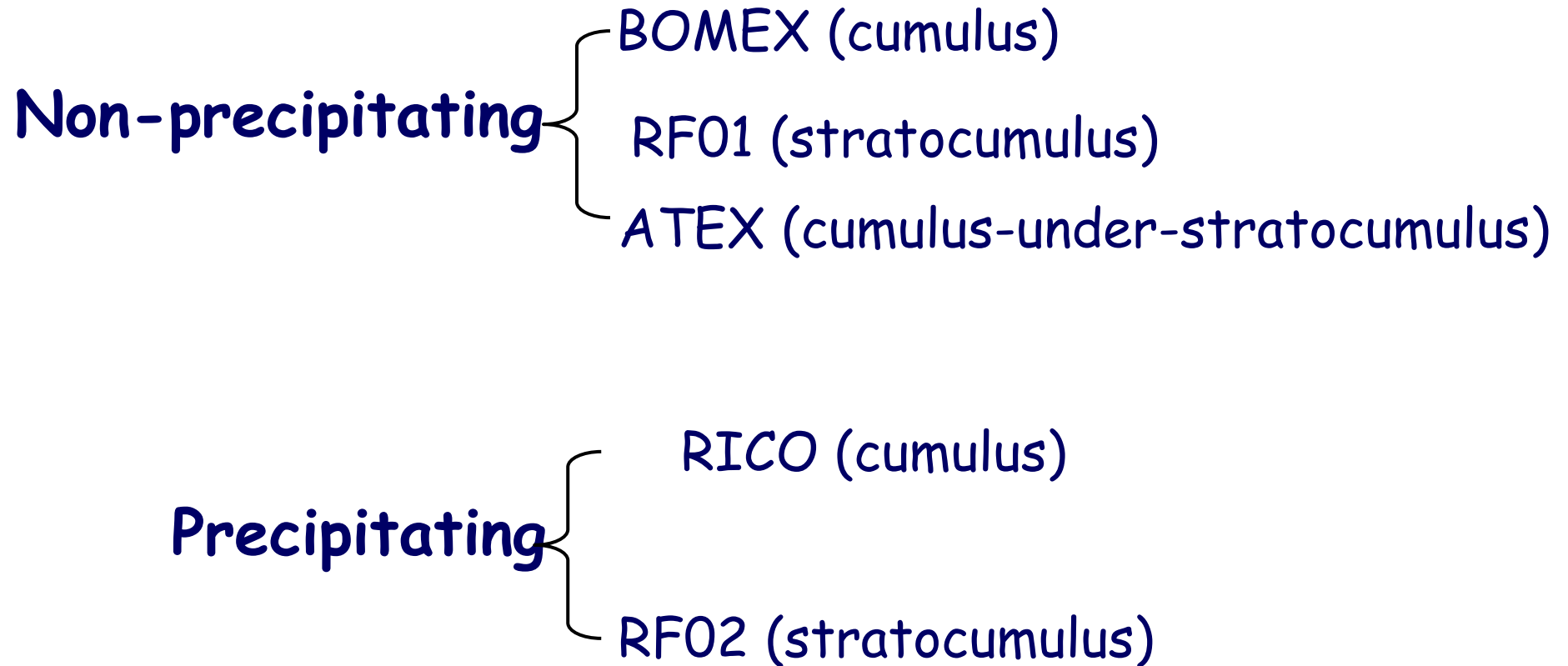- Concerns regarding observations for SCM evaluation
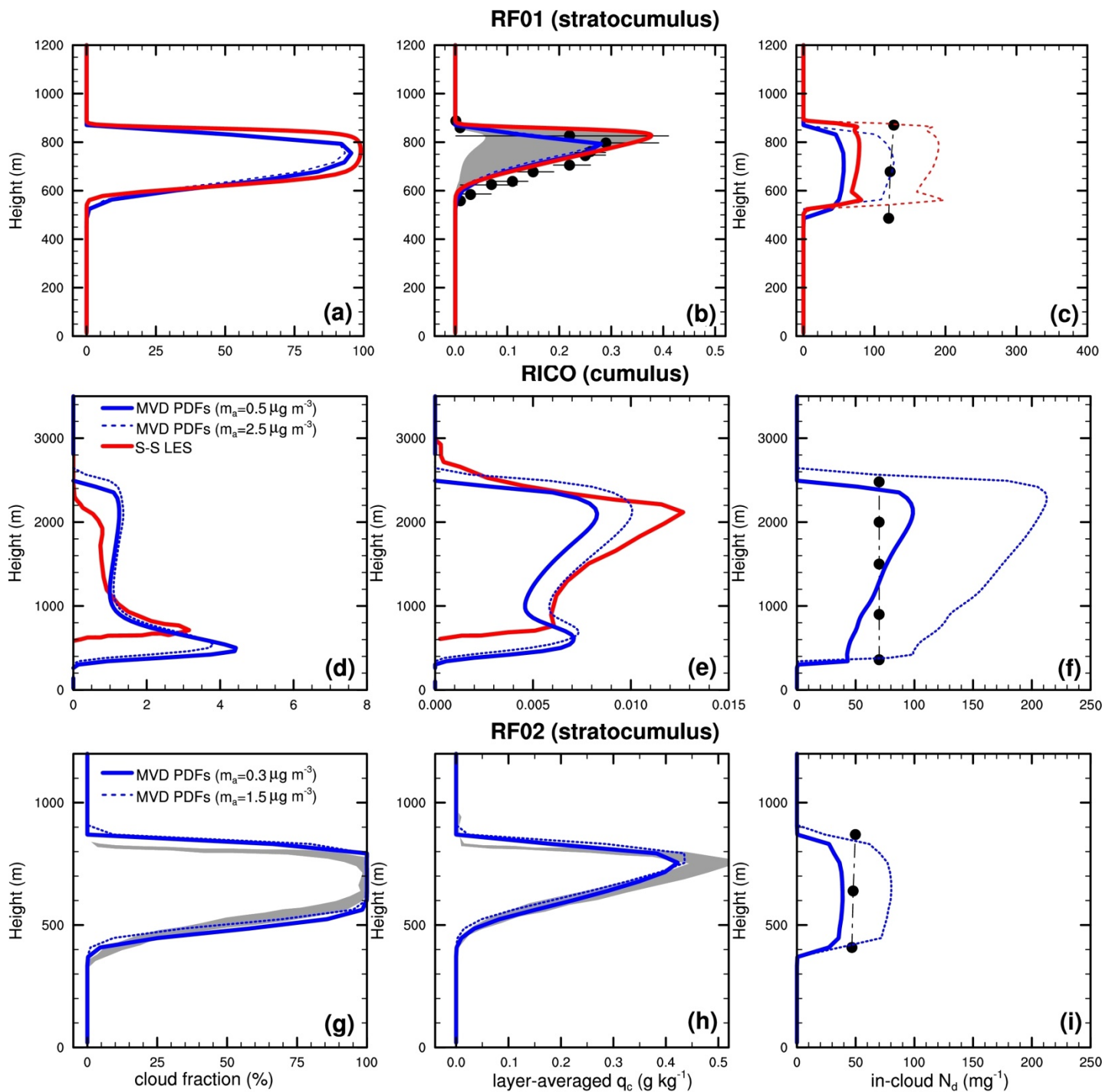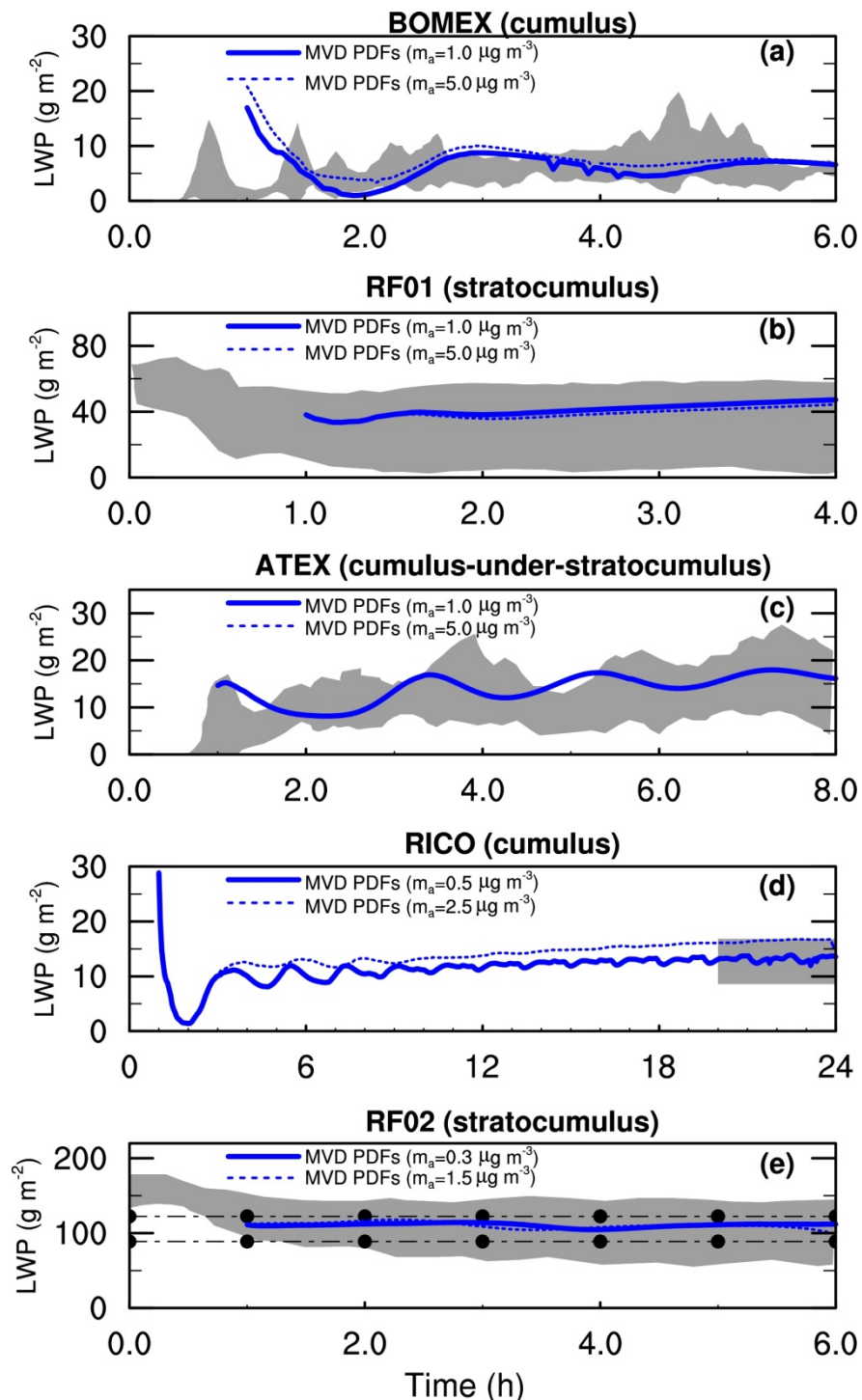
Building a PDF-based parameterization

Advance prognostic moment equations

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

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

Select PDF from functional form to match moments

Diagnose cloud fraction, liquid water, droplet number from PDF

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

Five warm cloud cases

Non-precipitating
- BOMEX (cumulus)
- RF01 (stratocumulus)
- ATEX (cumulus-under-stratocumulus)

Precipitating
- RICO (cumulus)
- RF02 (stratocumulus)

RF01 (stratocumulus)

RICO (cumulus)

RF02 (stratocumulus)

MVD PDFs (m_a=0.5 μg m^{-3})
MVD PDFs (m_a=2.5 μg m^{-3})
S-S LES

MVD PDFs (m_a=0.3 μg m^{-3})
MVD PDFs (m_a=1.5 μg m^{-3})

cloud fraction (%)

layer-averaged q_c (g kg^{-1})

in-cloud N_d (mg^{-1})

Height (m)

From Guo *et al.* (2010, *Geosci. Model Dev.*)

AM3 Single Column Model using Multi-Variate Probability Density Function with Dynamics, Aerosol Activation, and Double-Moment Microphysics

from *Guo et al.* (2010, *Geosci. Model Dev.*)

Liquid water path (LWP, g m^{-2})

(a)

ASTEX

Dry ASTEX

LES range

RF01

Surface precipitation (mm day^{-1})

(b)

Entrainment rate (W$_e$, cm s^{-1})

(c)

N$_d$ (cm^{-3})

Solid: MVD PDFs

Dashed: LES from Ackerman *et al.* (2004, *Nature*)
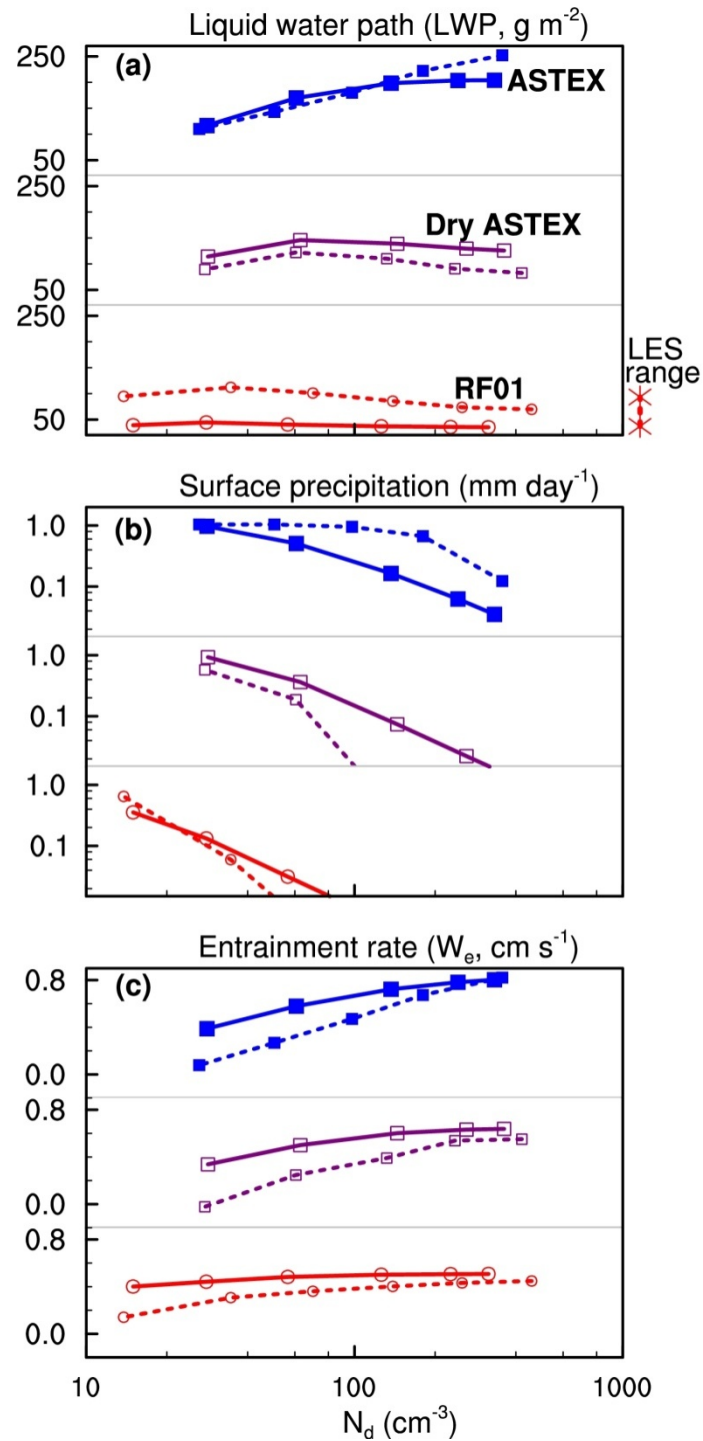
LES range from Guo *et al.* (2010, *GMD*)

from Huan Guo, GFDL

Two mixed-phase cases

Precipitating
- MPACE-B (pristine, warmer)
- SHEBA (polluted, colder)

MPACE-B: profiles

MPACE-B (Mixed-phase Arctic cloud)

ice nuclei (0.16/L)

ice number (2/L)

ice multiplication
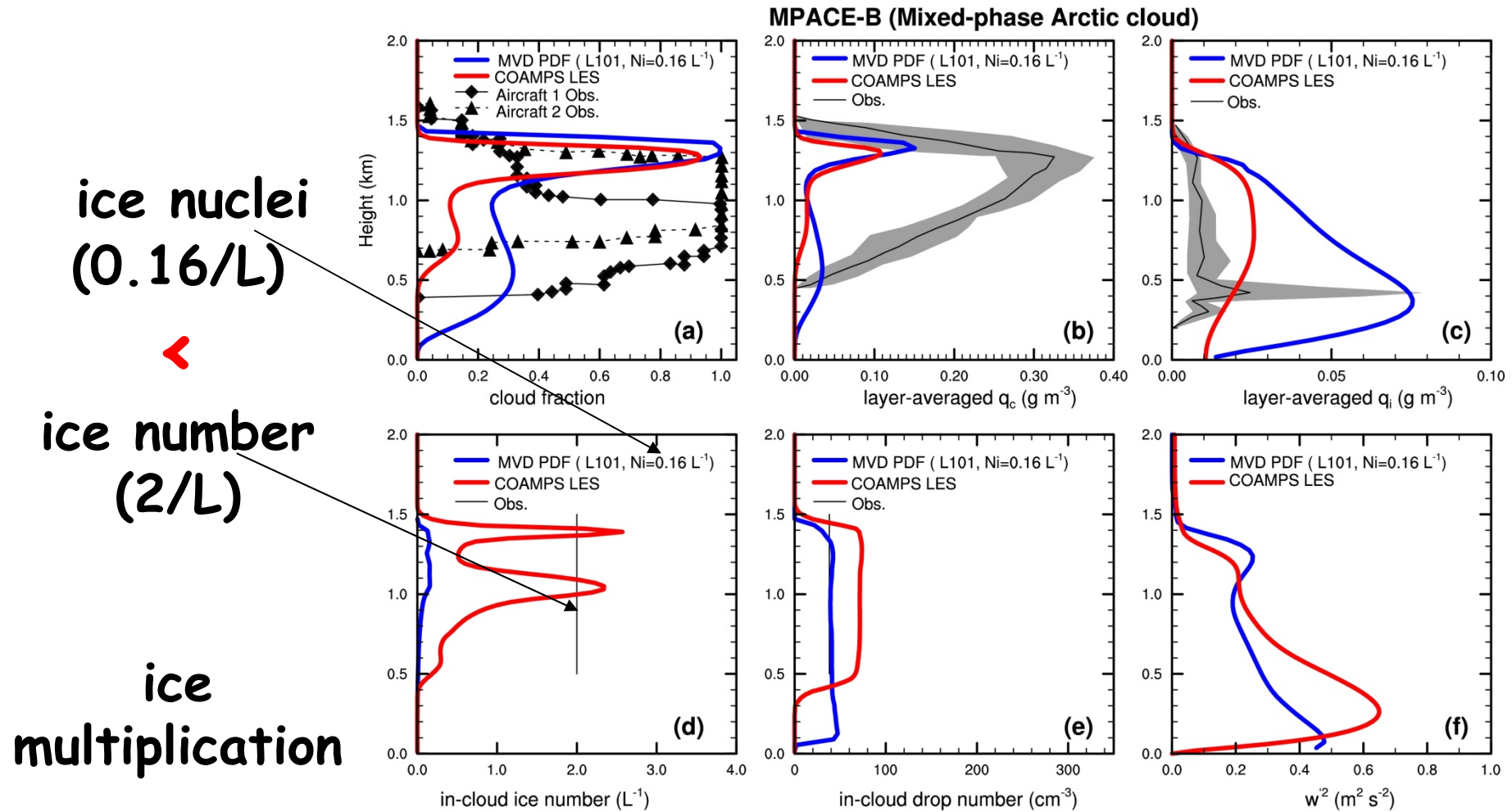
June 2011   GCSS/CFMIP/EUCLIPS   Aircraft obs, cf. Klein *et al.* (2009, *QJRMS*)

from Huan Guo. GFDL

MPACE-B: time series

MPACE-B (Mixed-phase Arctic cloud)

(a) MVD PDF (L101, Ni=0.16 L^{-1}), COAMPS LES, Obs.

(b) MVD PDF (L101, Ni=0.16 L^{-1}), COAMPS LES, Obs.

(c) MVD PDF (L101, Ni=0.16 L^{-1}), COAMPS LES
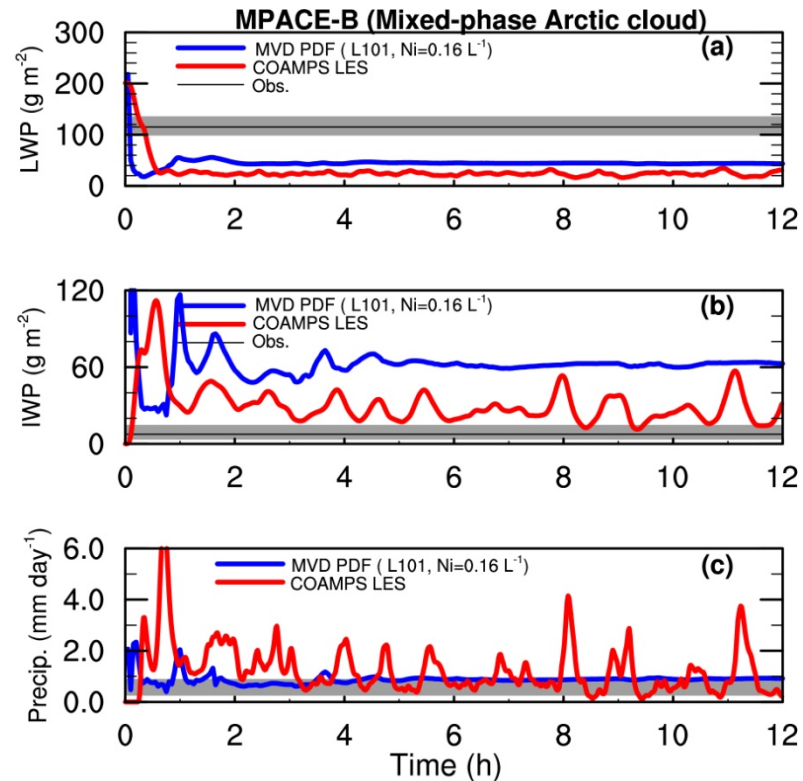
avg. over 4-12 hour

	LWP (g/m2)	IWP (g/m2)	Precip. (mm/day)
MVD PDF	44.2546	61.9714	0.8779
COAMPS LES	23.8739	26.2158	1.0155
Obs. Esti.	115.3000	7.6000	0.9000

SHEBA (Time series)

overestimate

LWP

SHEBA (Mixed-phase Arctic cloud)

(a) LWP (g m^{-2}) — MVD PDF (L101, Ni=1.7 L^{-1}), Radar Retrieval

(b) IWP (g m^{-2}) — MVD PDF (L101, Ni=1.7 L^{-1}), Radar Retrieval

(c) Precip. (mm day^{-1}) — MVD PDF (L101, Ni=1.7 L^{-1})

Time (h)

avg. over 4-12 hour

	LWP (g/m2)	IWP (g/m2)	Precip. (mm/day)
MVD PDF	35.6580	2.1440	0.3530

GCSS/CFMIP/EUCLIPSE

SHEBA: sensitivity to IN

LWP

decreases

with IN

SHEBA (Mixed-phase Arctic cloud)
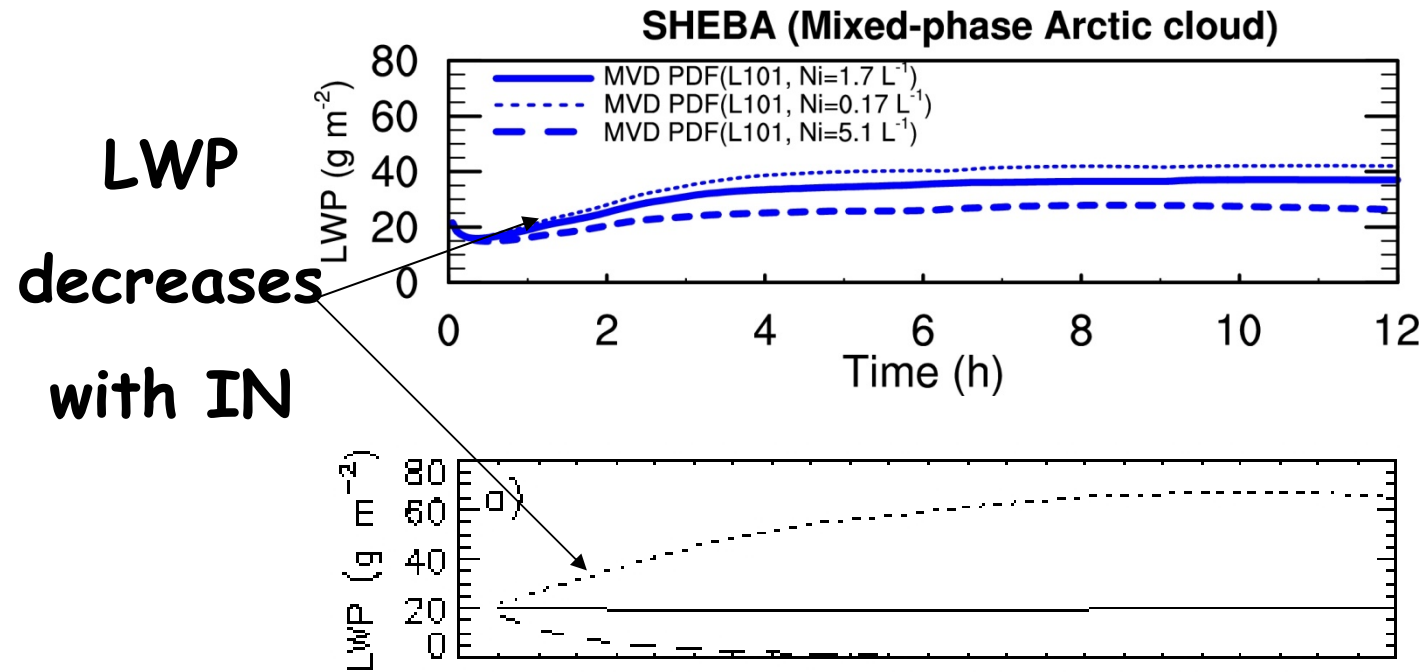
Morrison et al., 2011

Observations for SCM Evaluation

GCSS ARM case

AM3

Cloud fraction

MVD PDFs

OBS
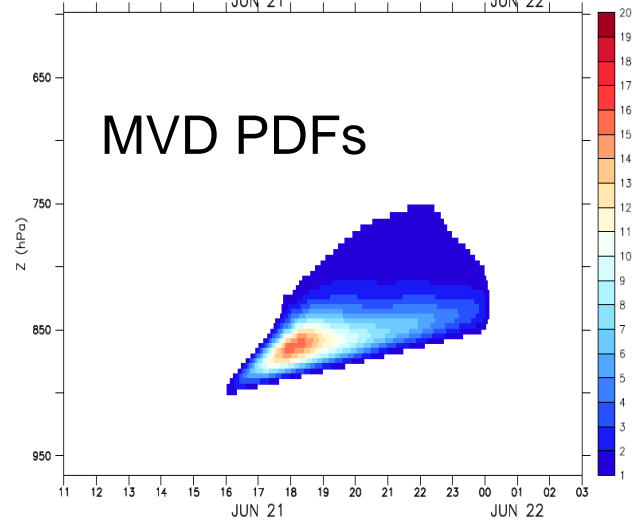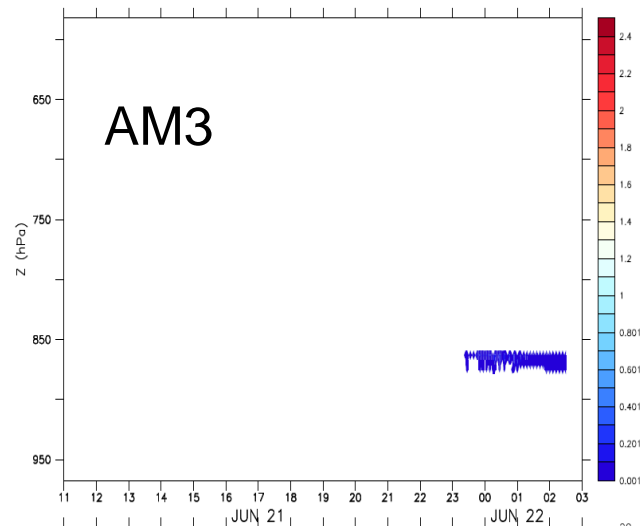
Vertical motion PDF comparison

ARM GCSS
21 June 97
Brown *et al.*
(*QJRMS,*
2002)
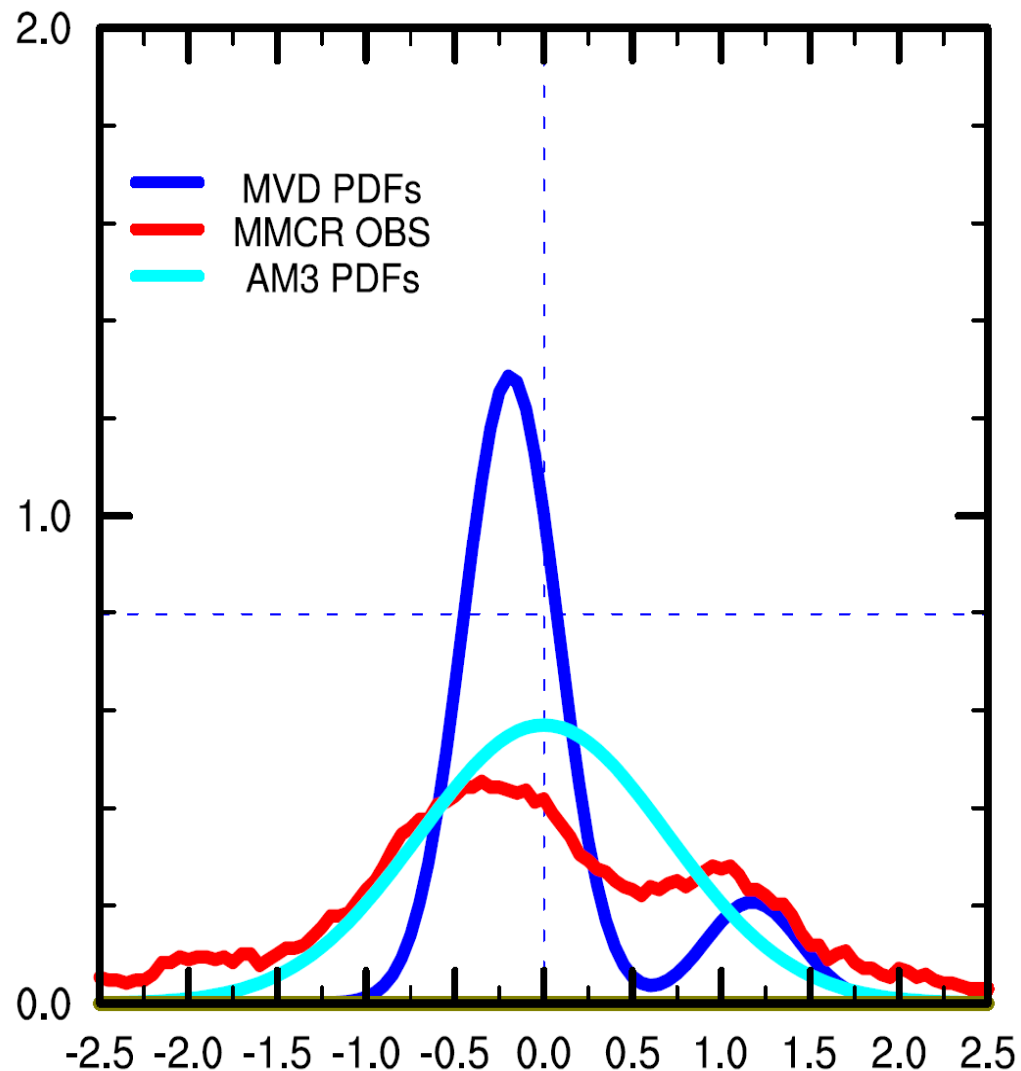
Surface latent and sensible heat flux from ARM variational analysis and GCSS forcing
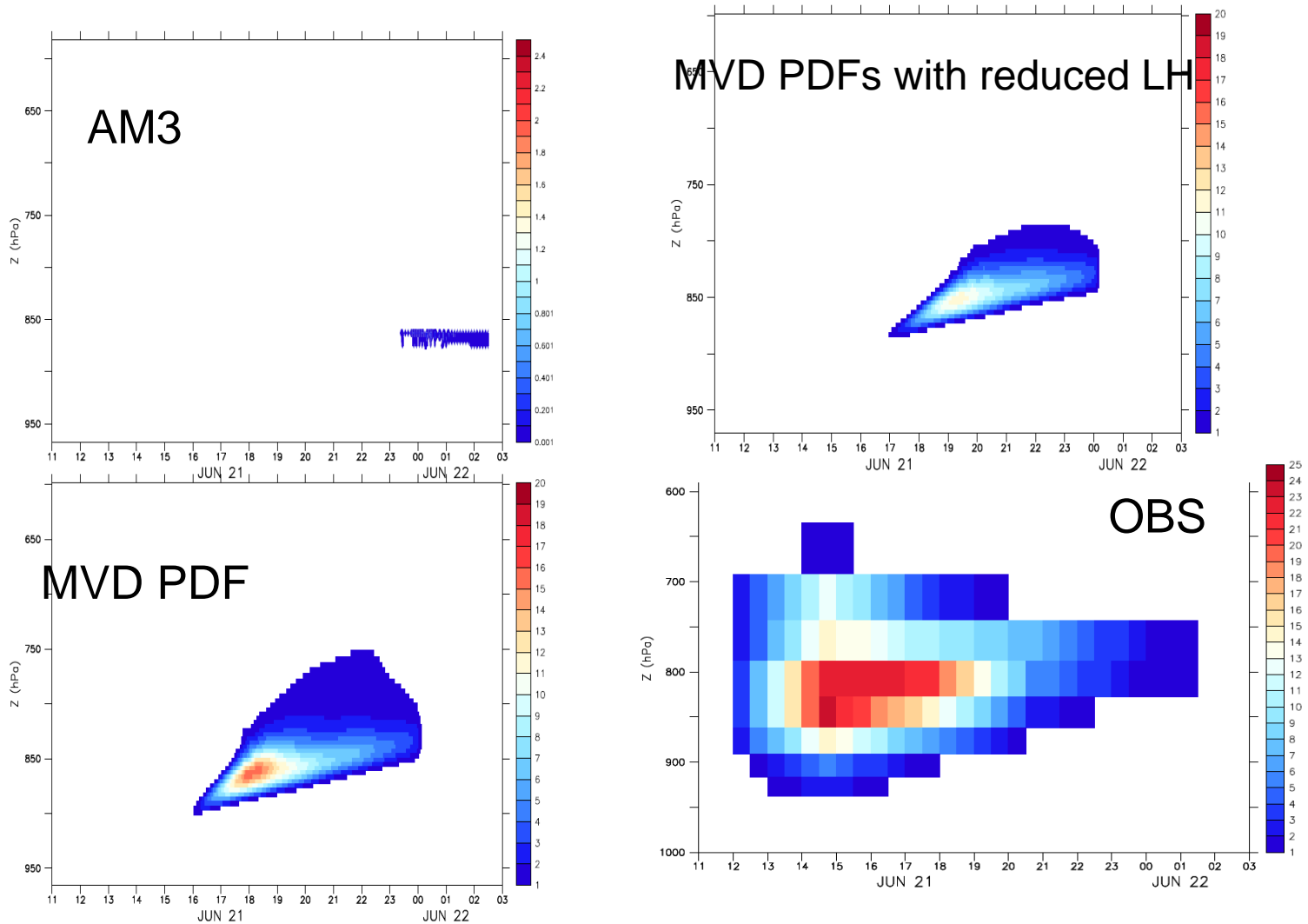
LH: solid line
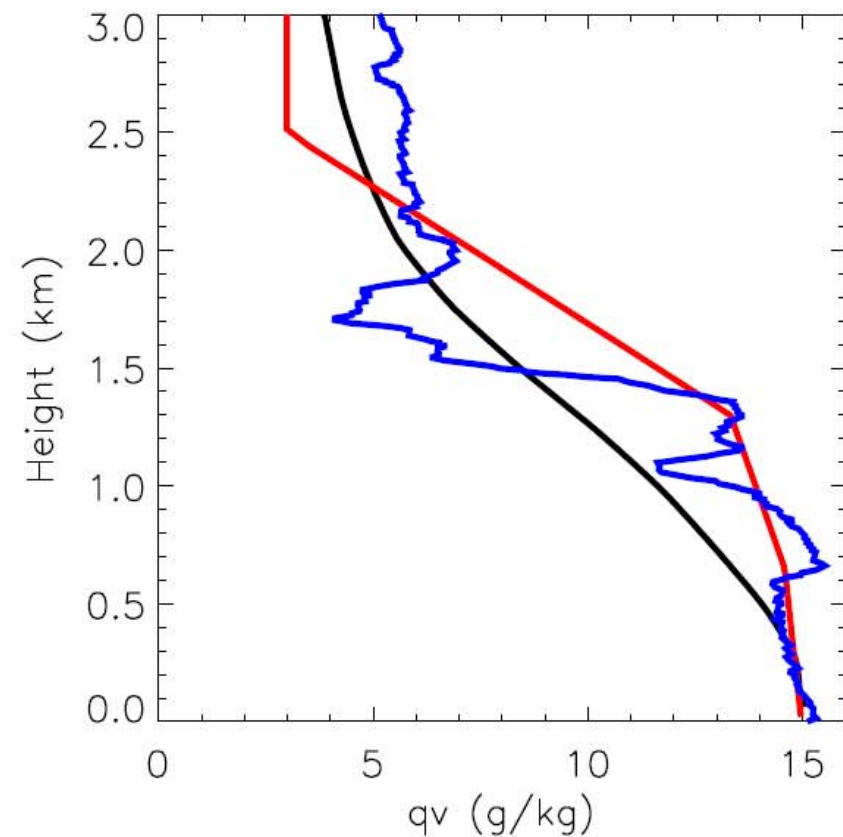SH: dashed lines

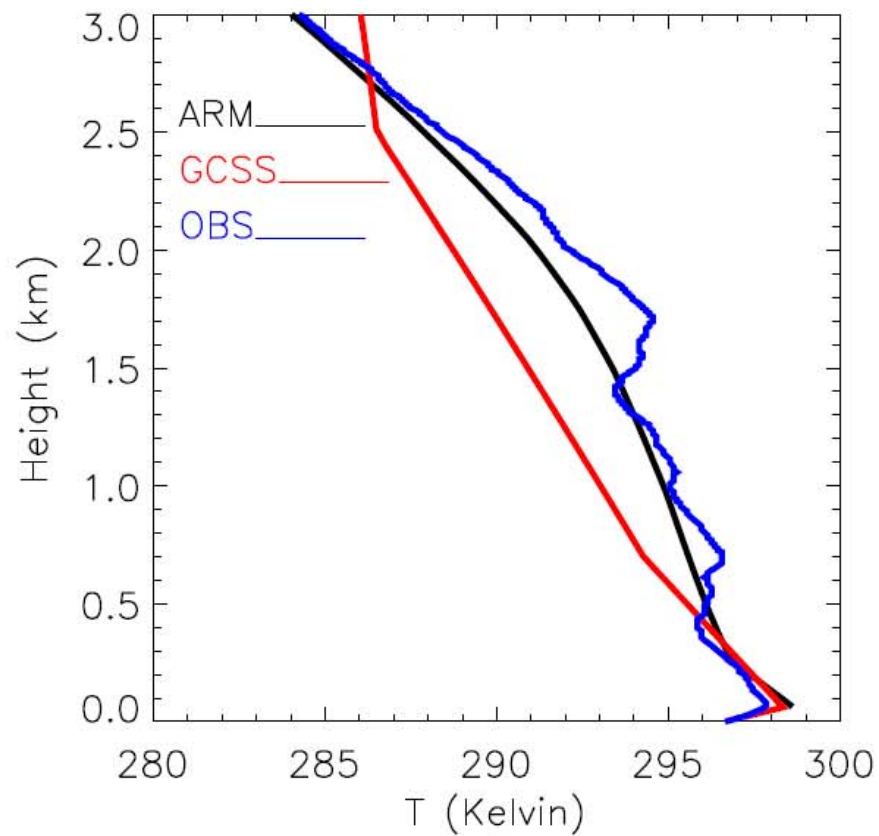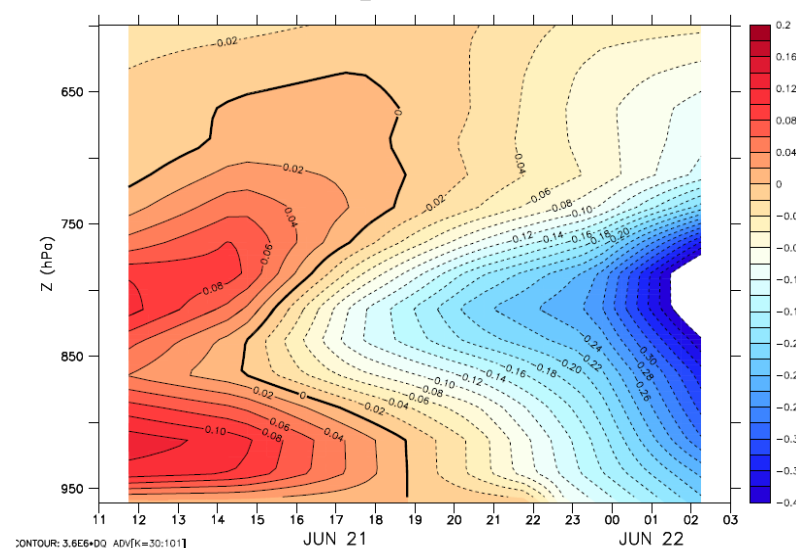Symbols are fluxes at the central facility.
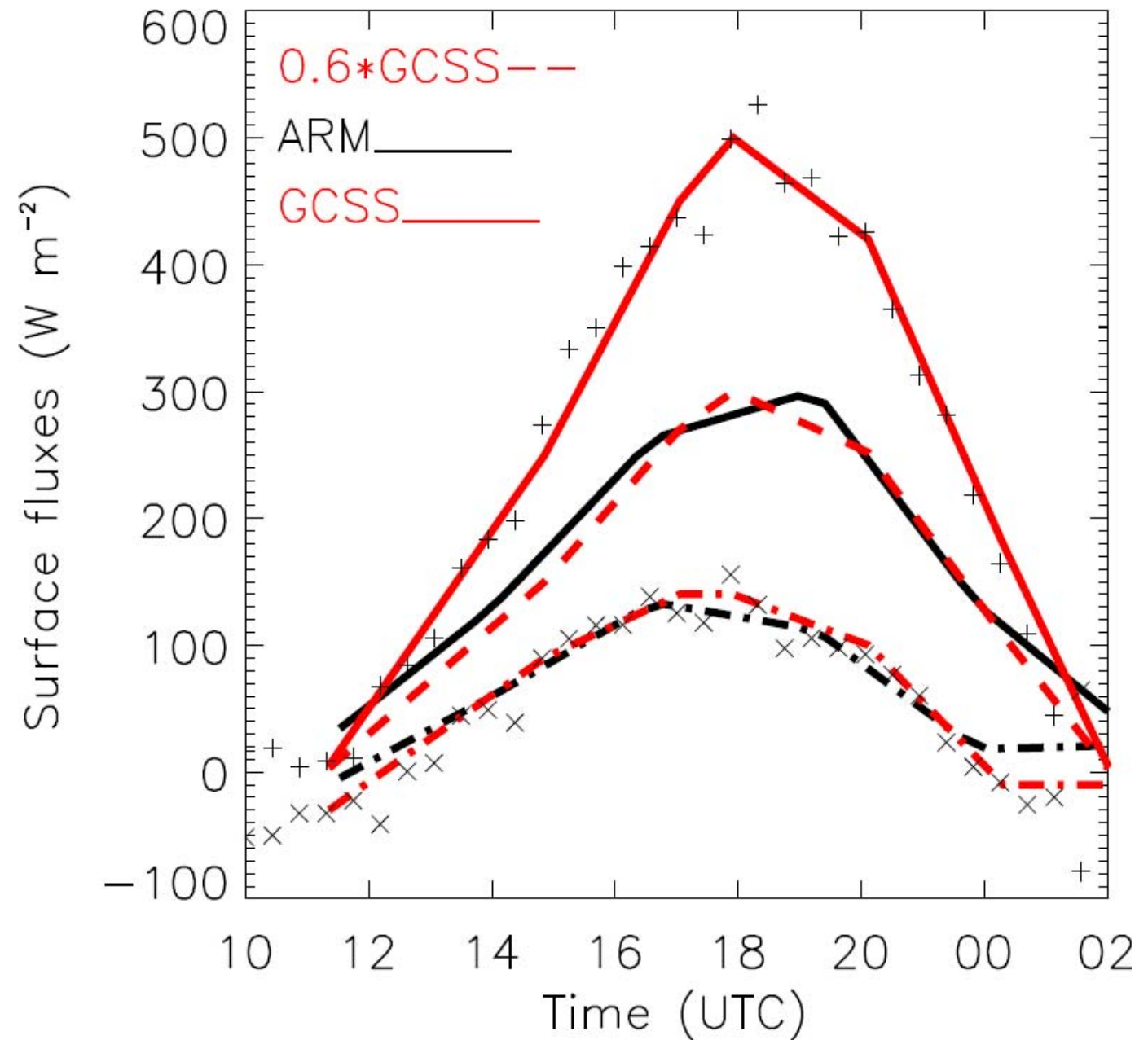
GCSS ARM case

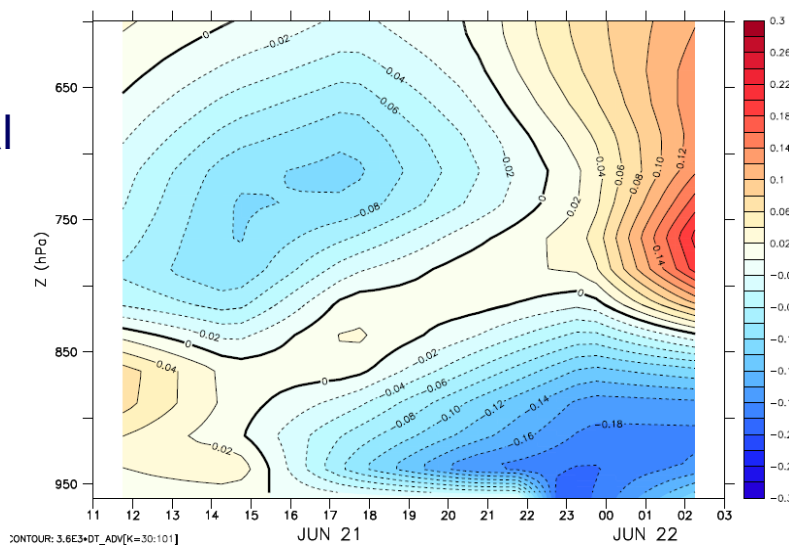Cloud fraction

AM3
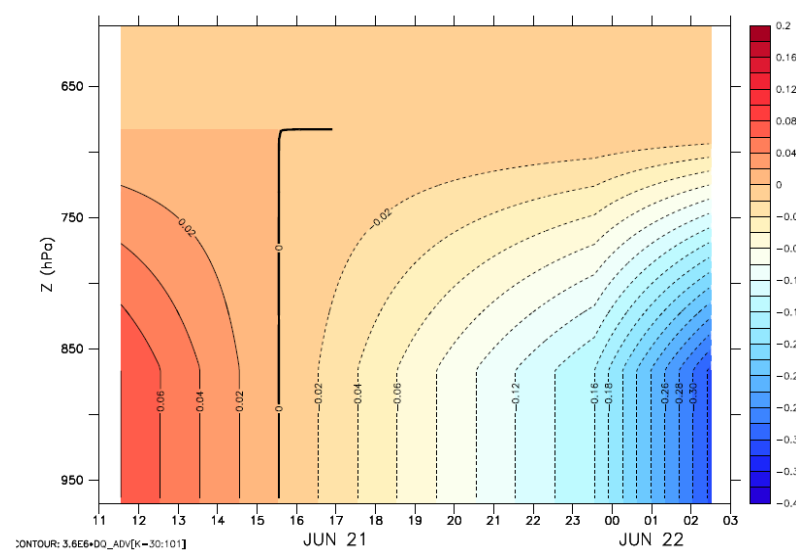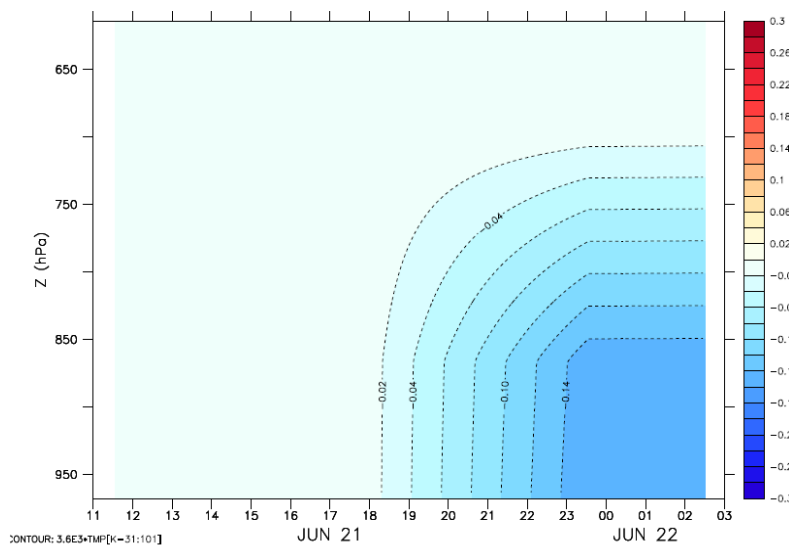
MVD PDFs with reduced LH

MVD PDF

OBS

Initial T and Qv

T adv

qv adv

GATE
Variational

GCSS

MVD PDF fails to produce cloud using ARM variational analysis

Summary

- MVD PDFs successfully simulate cloud fraction, water path, and droplet numbers for Sc and shallow Cu GCSS cases

- MVD PDFs simulation of mixed-phase clouds raises ice microphysics issues

- MVD PDFs indicate both positive and negative indirect effects on LWP

- Entrainment change as control on LWP change with aerosol loading consistent between LES and MVD PDFs

- Critical issues regarding observations…strong difference in MVD PDFs using ARM variational analysis and GCSS forcing for same case