Progress on CAM5 microphysics using self-consistent ice particle mass- and area-dimension expressions

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Photo by Ehsan Erfani

Contents

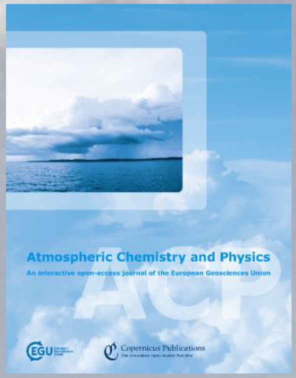
Part 1:

Erfani, E., and D. Mitchell, 2015:

Developing and Bounding Ice Particle Mass- and Area-dimension Expressions for Use in Atmospheric Models and Remote Sensing,

Atmos. Chem. Phys. Discuss., 15, 28517-28573,

doi:10.5194/acpd-15-28517-2015.



Part 2:

Eidhammer, T., H. Morrison, D. Mitchell, A. Gettelman, E. Erfani, 2016:

Improvements in the Community Atmosphere Model (CAM5) microphysics using a new, consistent representation of ice particle properties,

submitted to *J. Clim*.

Contents

- **Part 1:**
  Ice Particle Mass- and Area-dimension Expressions

- **Part 2:**
  Improvements in CAM5 Microphysics

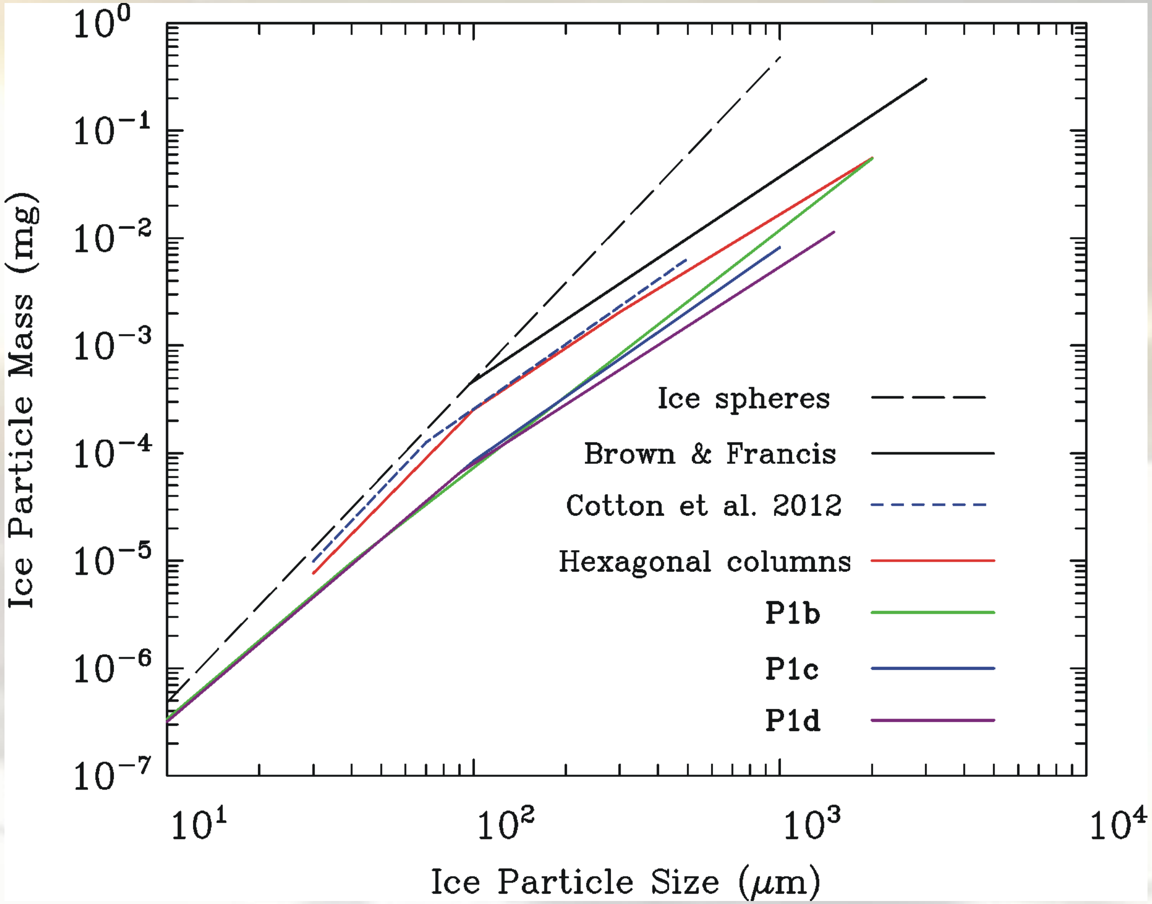
Common Power Laws

Projected Area-Dimension: $A = \gamma D^{\delta}$

Mass-Dimension: $m = \alpha D^{\beta}$

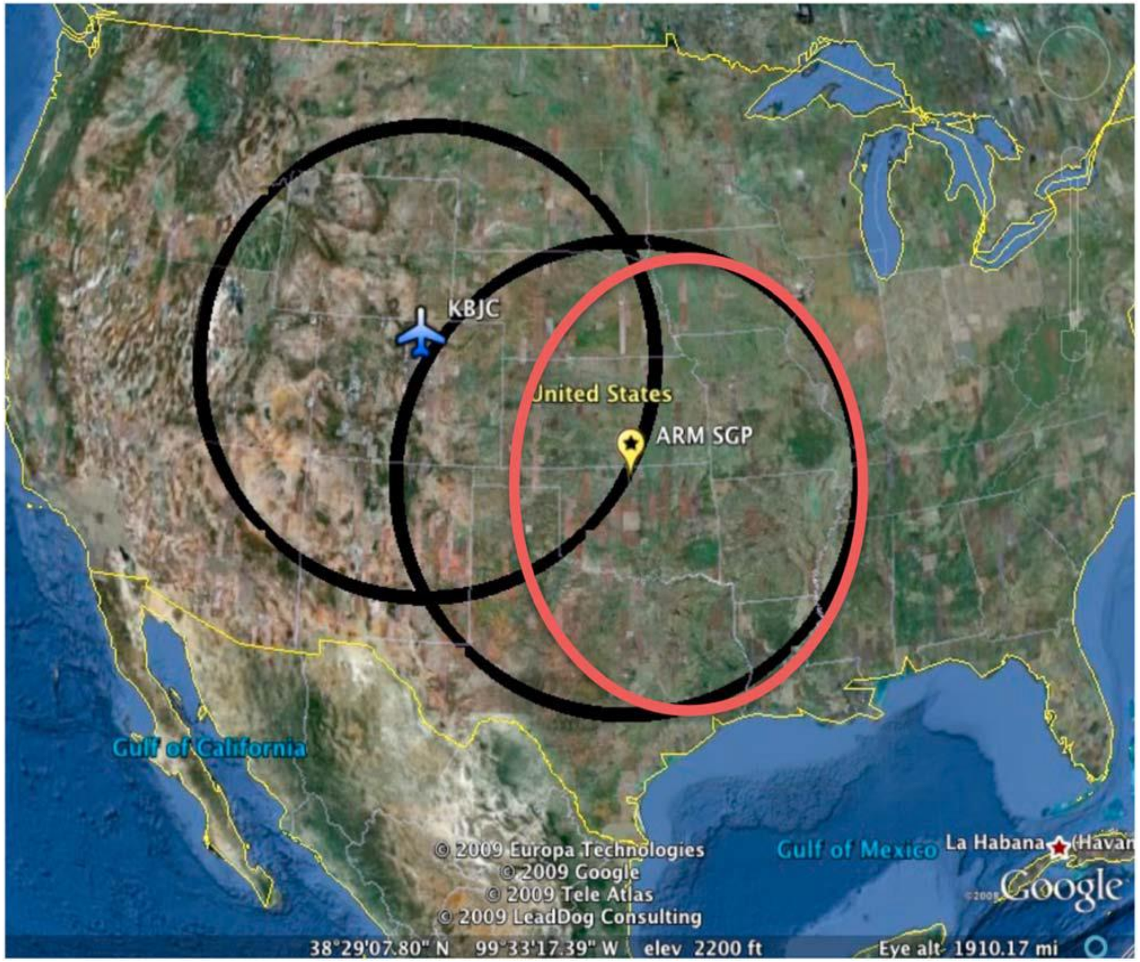
Challenge:

- A single power law is not valid for the whole range of particle size distribution (PSD).
- So, it produces uncertainty in modeling the ice cloud microphysics.



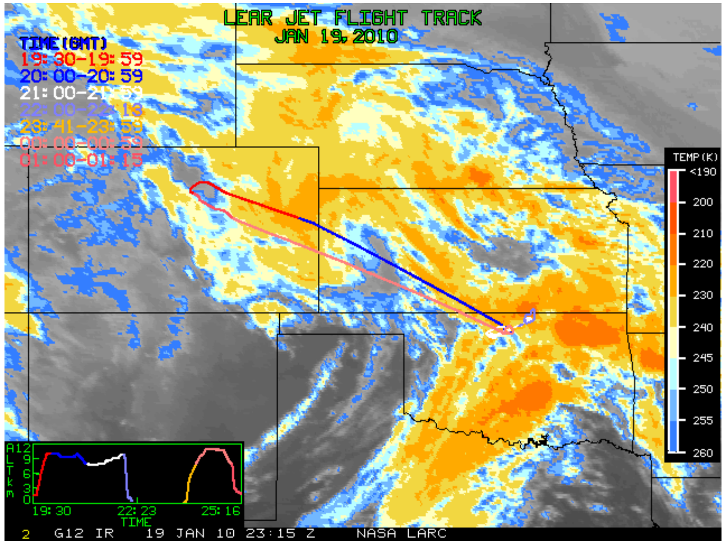
SPARTICUS field campaign

(Small Particles In Cirrus)

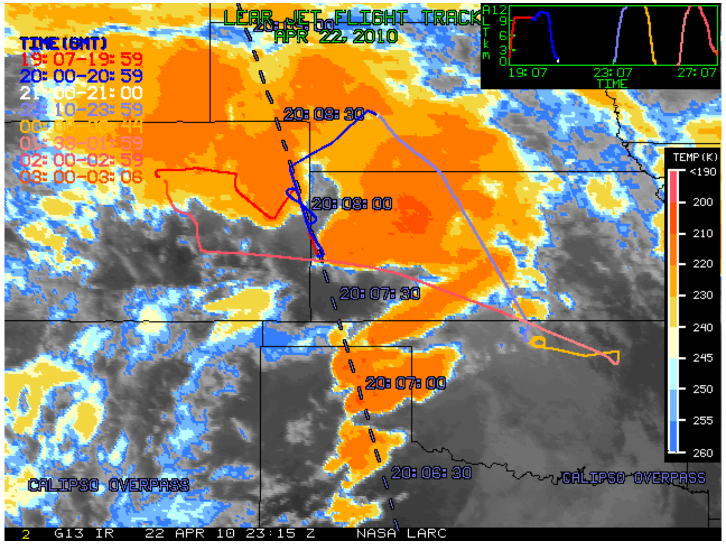


Mace et al. (2009)

Synoptic Clouds

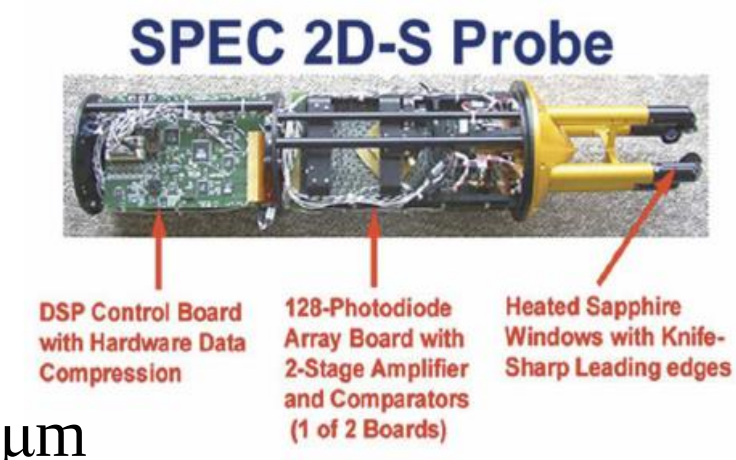


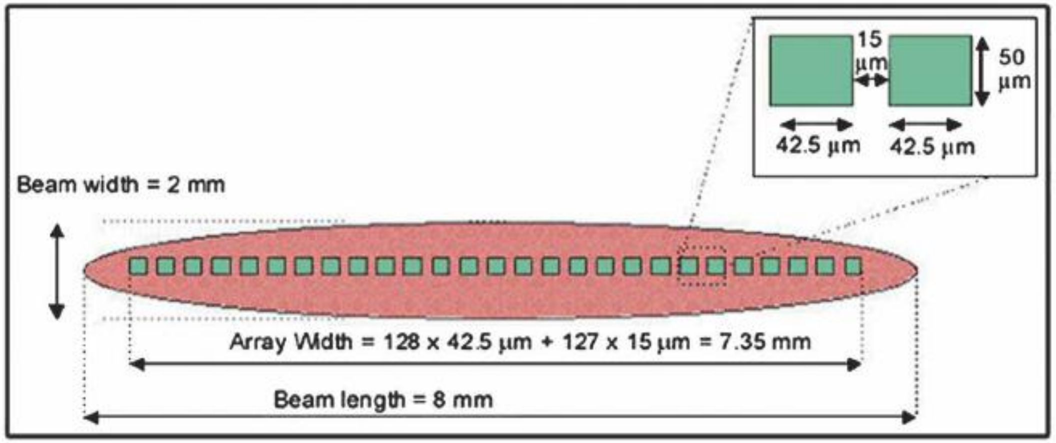
Anvil Clouds



SPARTICUS

- **2D-S** (2D-Stereo): $D > 200$ μm
- **CPI** (cloud particle imager): $D < 100$ μm





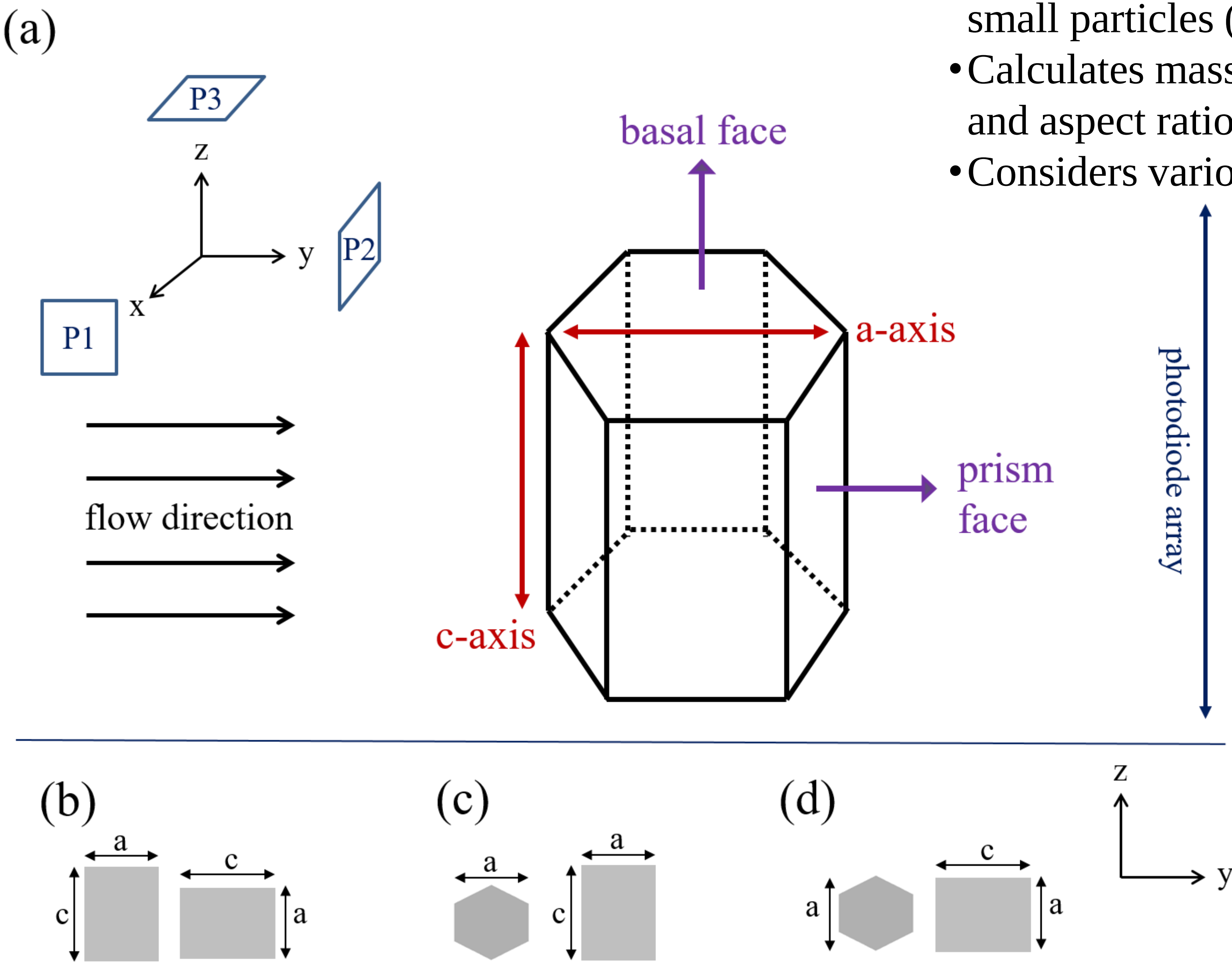
Measures:
- Particle size
- Particle concentration
- Projected area

- Estimates mass
  2D-S: from Baker-Lawson (2006) mass-area power law
- CPI: from area based on hexagonal column assumption

Lawson et al. 2006

Assumption for Small Ice Particles

- Hexagonal columns seen in images of small particles (Lawson et al., 2006)
- Calculates mass from projected area and aspect ratio of hexagonal columns.
- Considers various orientations



a) 3-d Geometry of hexagonal prism, representative of small ice crystals, and the projection of hexagonal prism for two extremes, when its c-axis is parallel to b) P1, c) P2, and d) P3.

SCPP (Sierra Cooperative Pilot Project)

- 3-year field study of cloud seeding experiment (1986-88)
- determine ice particle length, mass and shape.
- temperature between -20 °C and -40 °C

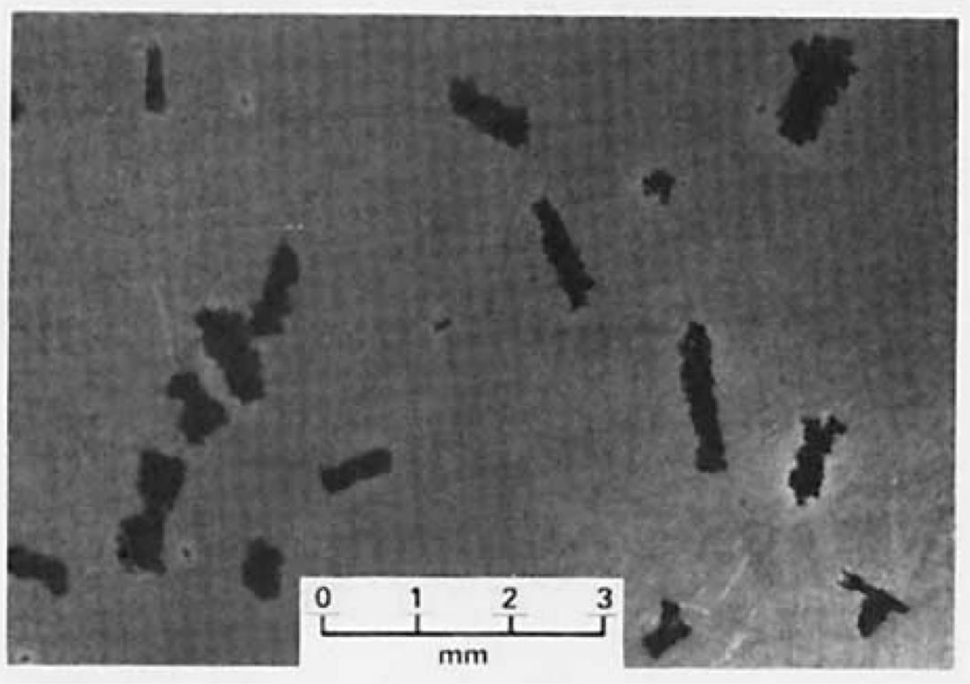


FIG. 3. Primarily rimed long columns from the 1986–87 field season, showing a diversity of aspect ratios.

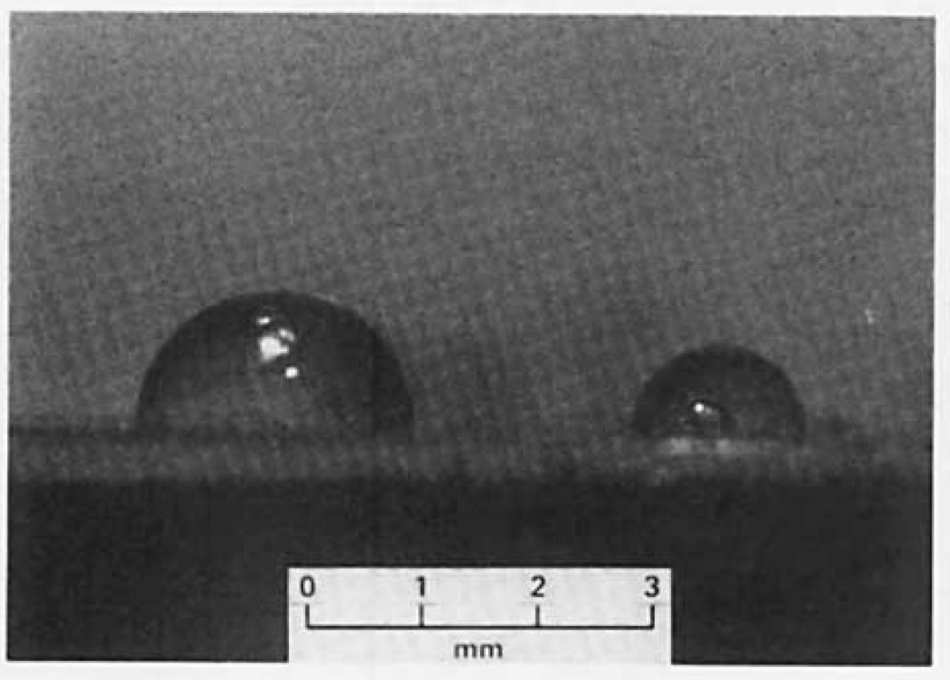


FIG. 4. Melted ice particles on a plastic petri dish, photographed in the horizontal to reveal their hemispherical shape.

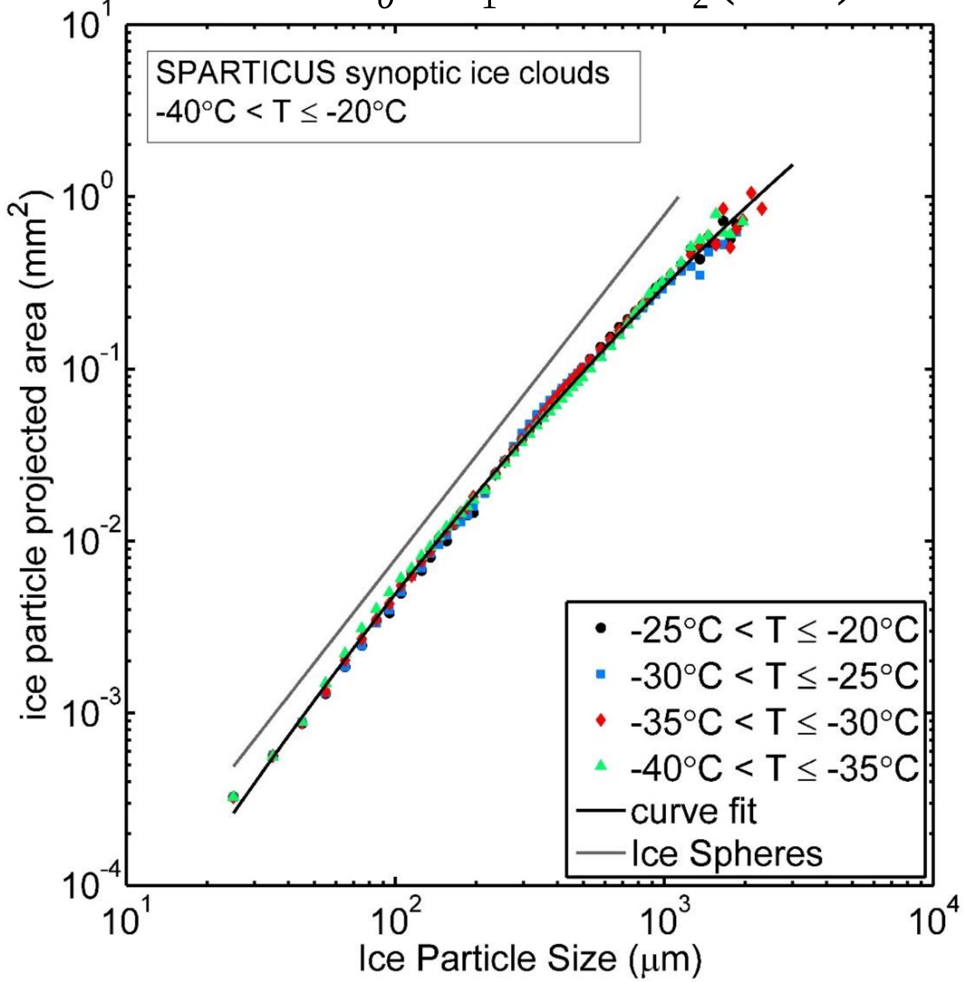
Mitchell et al. (1990)

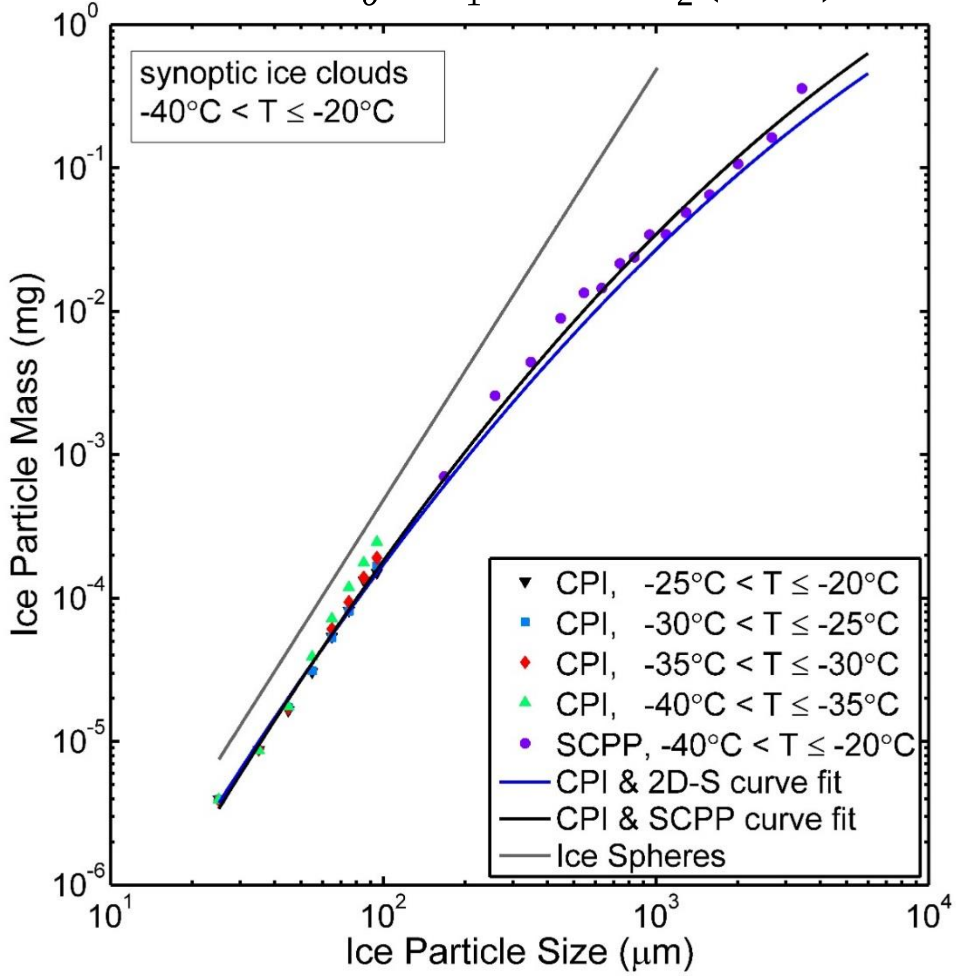
m-D and A-D Polynomial Curve Fits

2nd-order polynomial fit in log-log space:

$$\ln A = a_o + a_1 \ln D + a_2 (\ln D)^2$$

$$\ln m = a_o + a_1 \ln D + a_2 (\ln D)^2$$





m-*D* and *A*-*D* curves are fitted well to the broad range of PSD (small and large sizes).

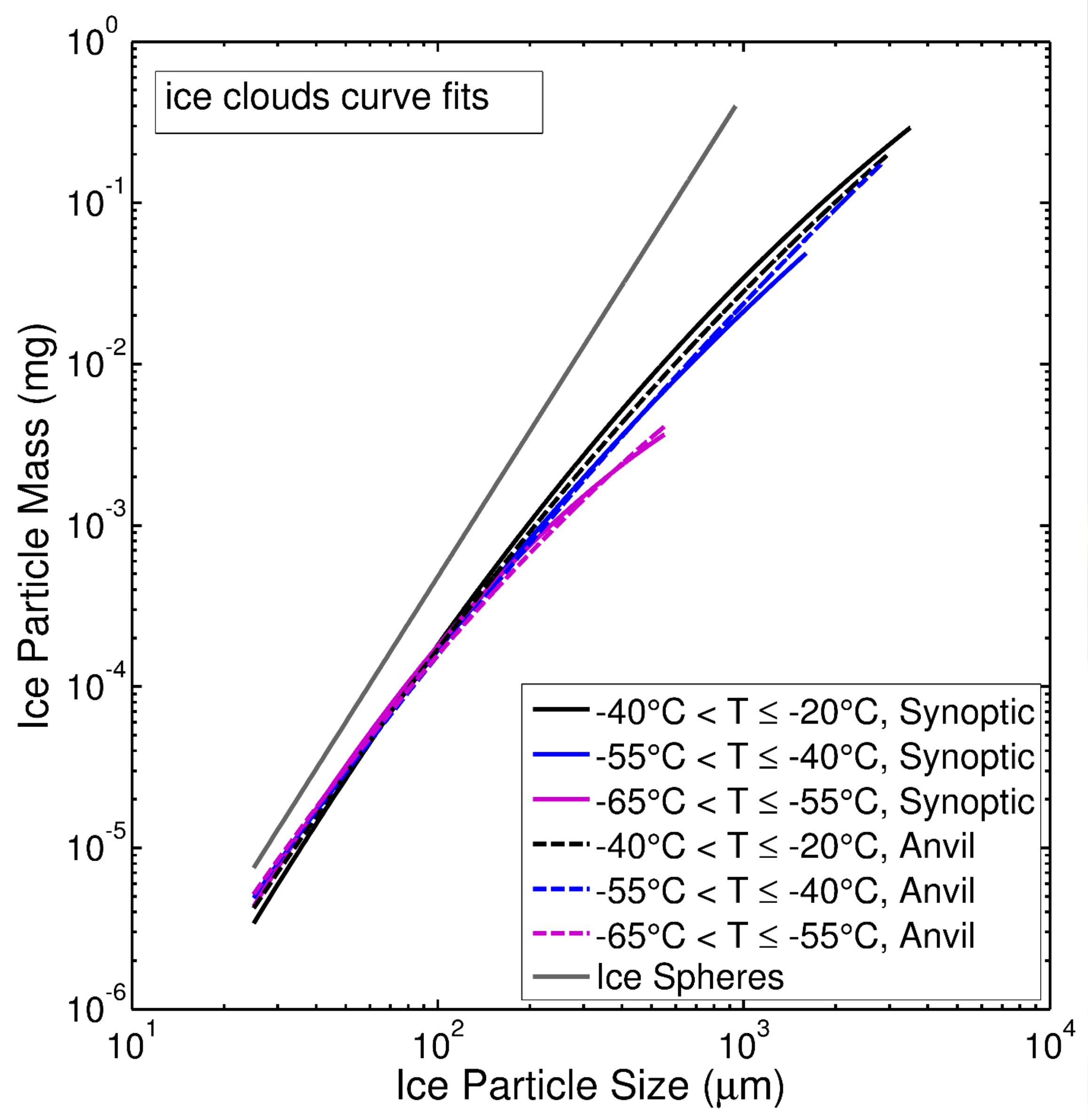
Dependence of m-D and A-D Curves on Temperature and Cloud Types

Mean dependence of mass on particle size is not extremely variable between different ice clouds (synoptic vs. anvil) and/or temperature regime.

Exception:

coldest temperature category

(-65 °C ≤ T < -55 °C)



Application to Modeling

- **How to reduce m-D & A-D polynomial fits to power laws?**

$$\ln m = a_o + a_1 \ln D + a_2 (\ln D)^2 \longrightarrow m = \alpha D^{\beta}$$

In this new approach, α, β γ, and δ are size-dependent:

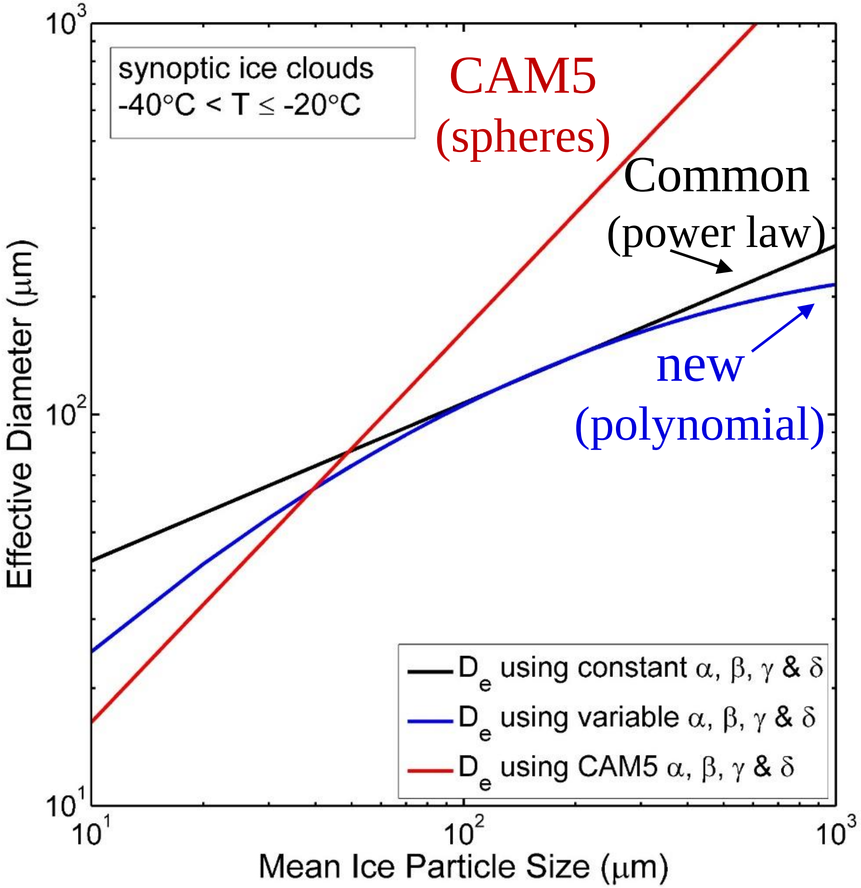
$$\beta = a_1 + 2a_2 \ln D \qquad \alpha = \frac{\exp\left[a_o + a_1 \ln D + a_2 (\ln D)^2\right]}{D^{\beta}}$$

α and β are not constants over all ice particle sizes, but they can be approximated as constants over a range of particle sizes

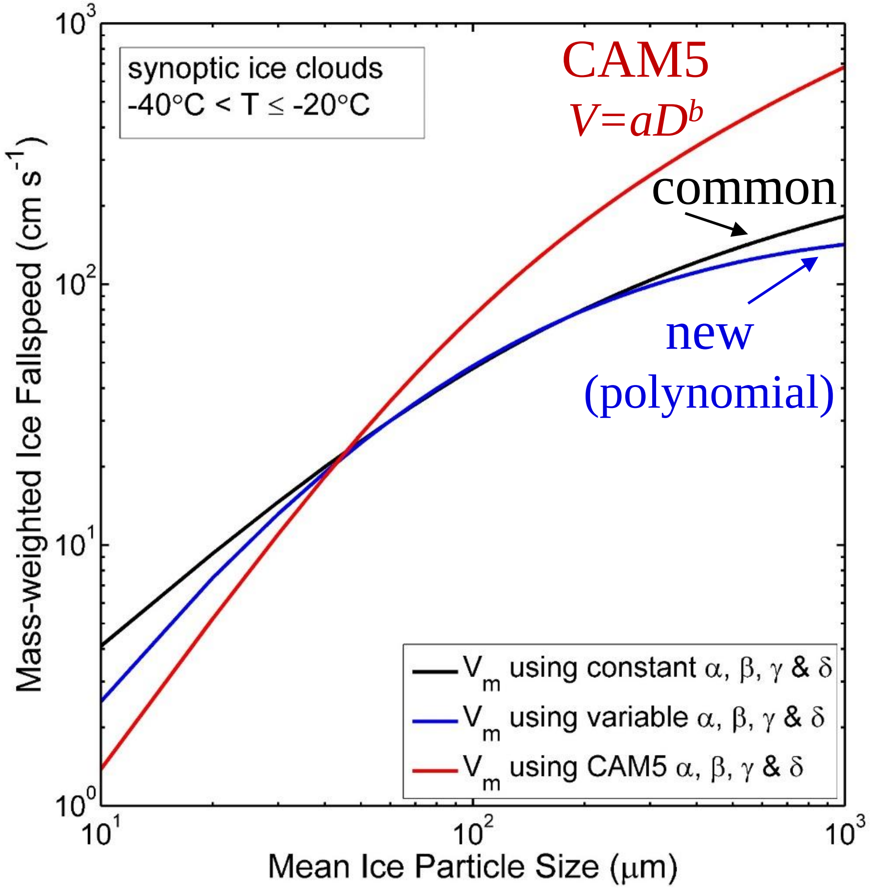
Application to Modeling

Contrasting new scheme with CAM5

cloud optical properties strongly depend on effective diameter



Cloud lifetime, coverage and IWP strongly depend on fall speed



Common and new: effective diameter and fall speed are function of mass / area ratio.

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Limitations in Microphysics Schemes

MG2: common CAM5 microphysics scheme

- two-moment bulk scheme
  - Morrison and Gettelman (2008) and Gettelman and Morrison (2015)
- Separation into two different categories: cloud ice and snow, each with different features.
- Need for autoconversion from ice to snow
  - poorly constrained and arbitrary threshold size
- All particles are spheres.

- Calculates fallspeed using a *V*-*D* power law with fixed coefficients
  - inconsistent with density change

$$V = aD^b$$

- Effective diameter calculated based on spherical particles
  - inconsistent with power law parameterization of fallspeed

How to develop a microphysics scheme addressing such limitations?

Approach for Improvement

P3: Predicted Particle Properties

- Morrison and Milbrandt (2015)
- *m-D* from Brown and Francis (1995), *A-D* from Mitchell (1996)

EM15: Erfani and Mitchell (2015)

- *m-D* and *A-D* polynomial fit.

Both **P3** and **EM15** Calculate fallspeed from Mitchell and Heymsfield (2005) by using *m-D* and *A-D* expressions: fallspeed is a function of particle mass-to-projected area ratio.

$$V \propto \frac{m}{A}$$

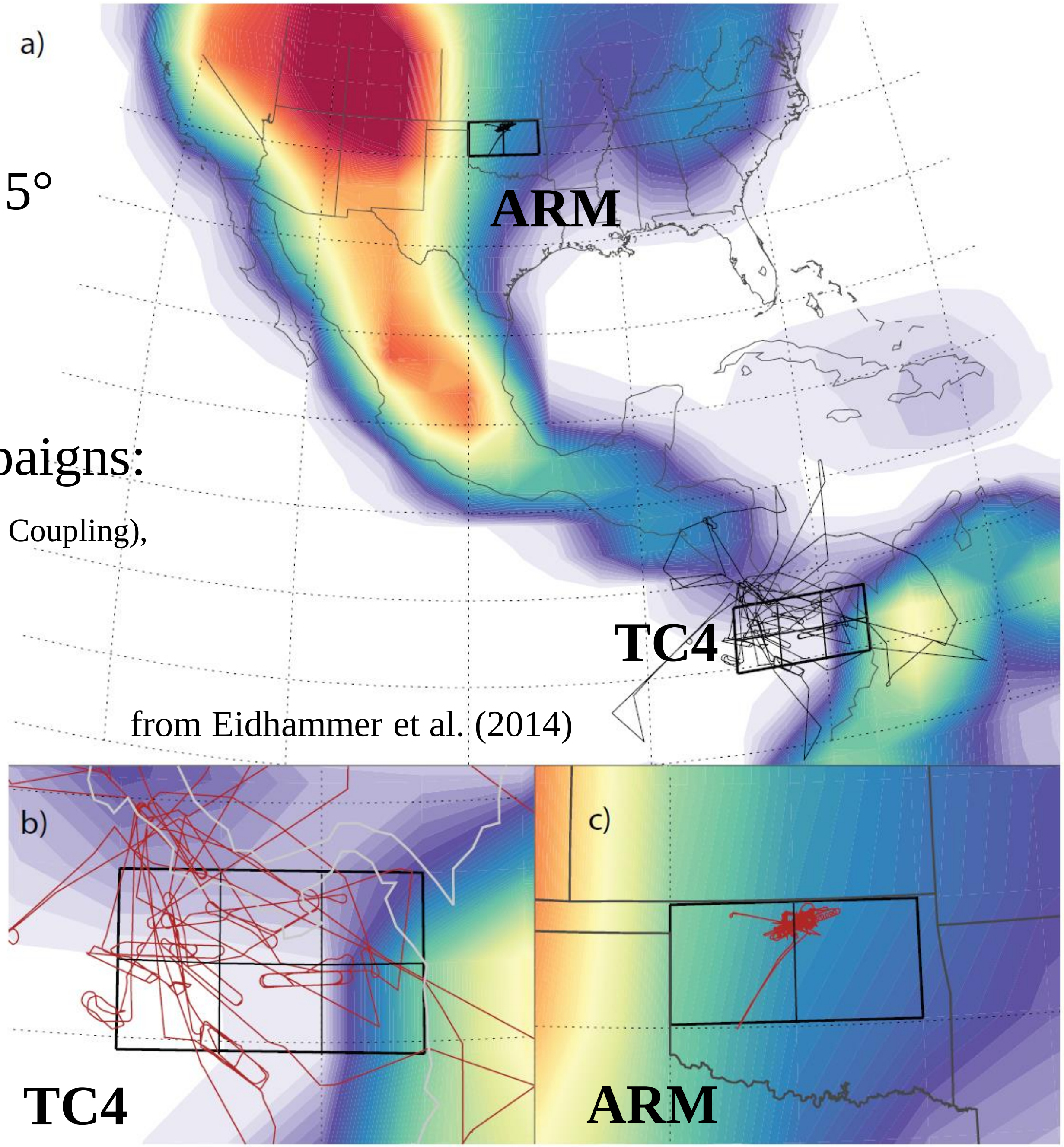
- Represent the physical coupling between particle mass, projected area, fallspeed, and effective diameter, so they remain **self-consistent.**
- Use a **single ice category**: So, autoconversion from cloud ice to snow and specification of threshold size are no longer needed.

Model Setup

- CAM5 version 5.3
- 6 years (2001-2006)
- horizontal resolution: 1.9° x 2.5°
- 30 vertical layers

Comparison with two field campaigns:

- **TC4** (Tropical Composition, Cloud and Climate Coupling),
  - July 2007
  - Anvil cirrus clouds
- **ARM** (Atmospheric Radiation Measurements),
  - March 2000
  - Synoptic cirrus clouds

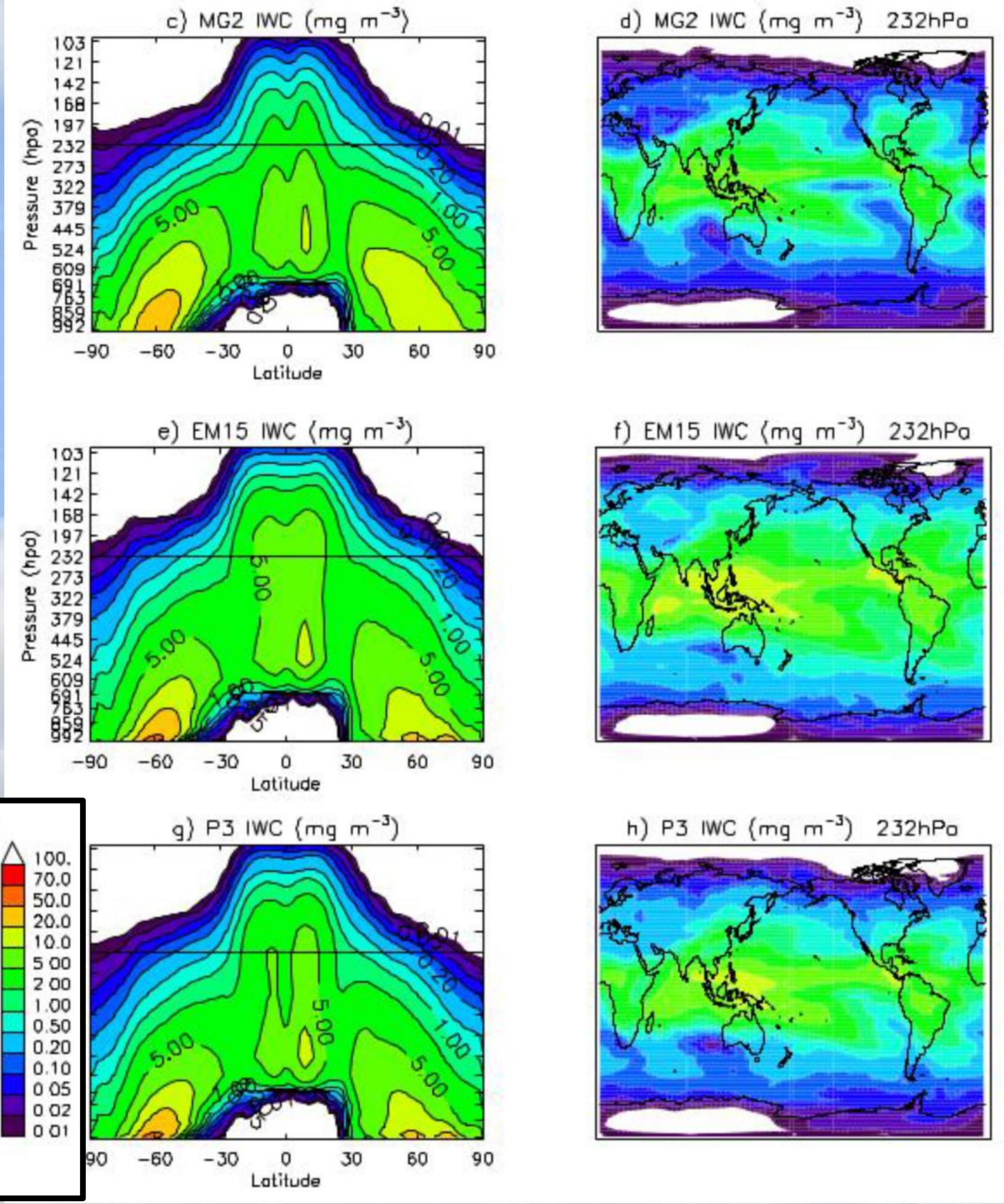


from Eidhammer et al. (2014)

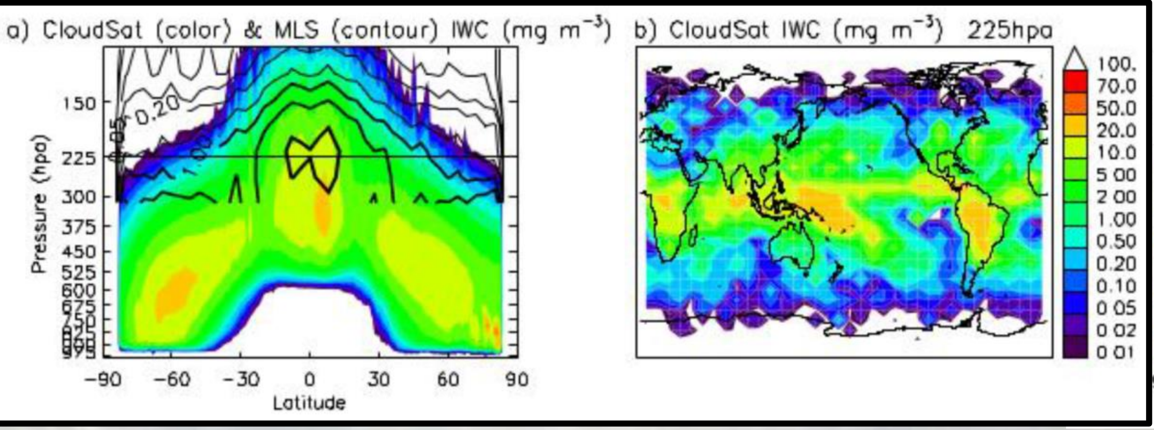
Results: Ice Water Content (IWC)

- Compared to retrievals, models produce lower magnitude in the tropics at high altitudes and a peak IWC in mid-latitudes at lower altitudes.
- P3 and especially EM15 have IWC closer to the retrievals in the tropical mid- and upper-troposphere compared to MG2.

Models

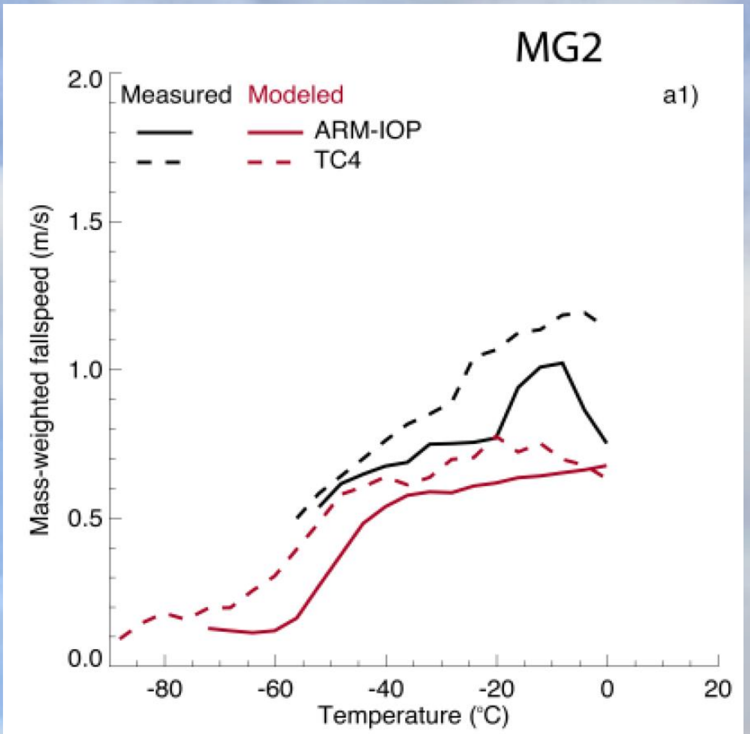


Retrievals

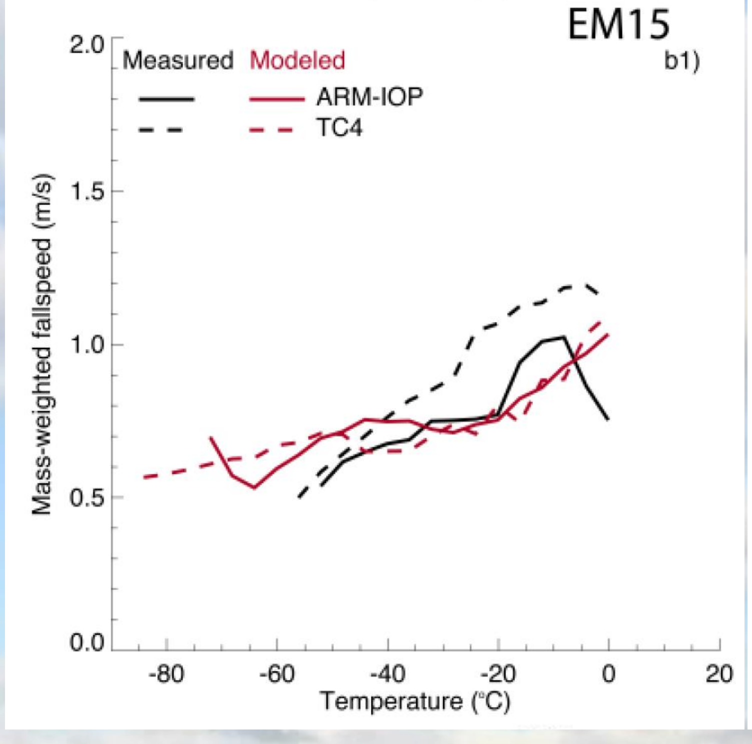


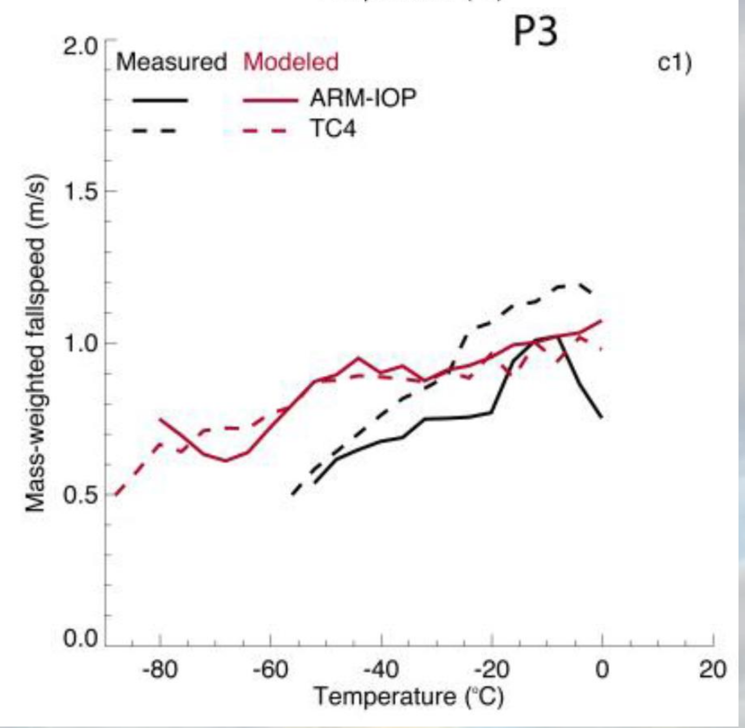
Results: Mass-weigthed Fallspeed

- V_m from MG2 are lower than observed V_m and have a sharp decrease at colder temperatures.
- V_m from EM15 and P3 have a decrease with temperature, more consistent with observations.

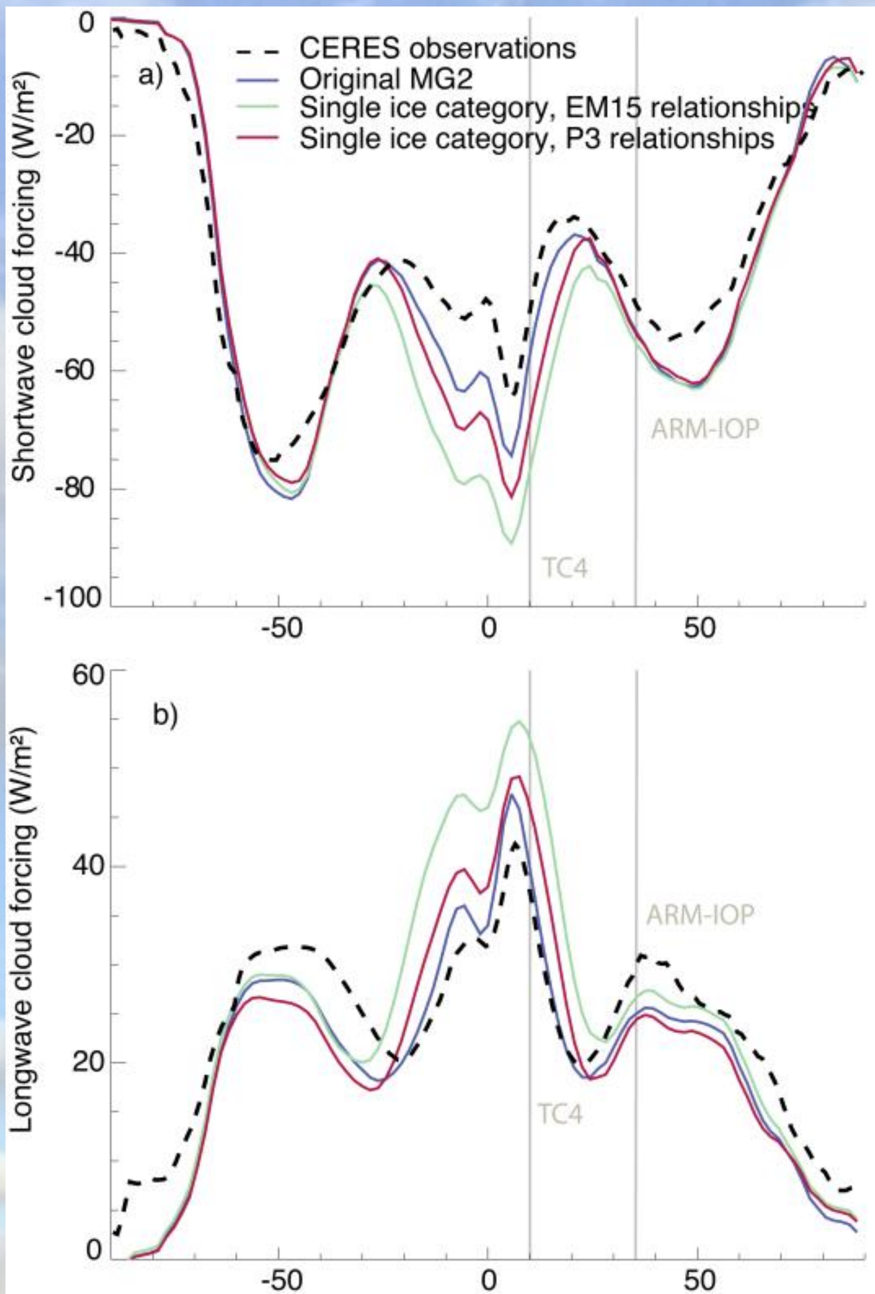


- V_m from EM15 shows low sensitivity between tropics and mid-latitude, possibly because it is originally for continental mid-latitude US.





Results: Cloud Radiative Forcing

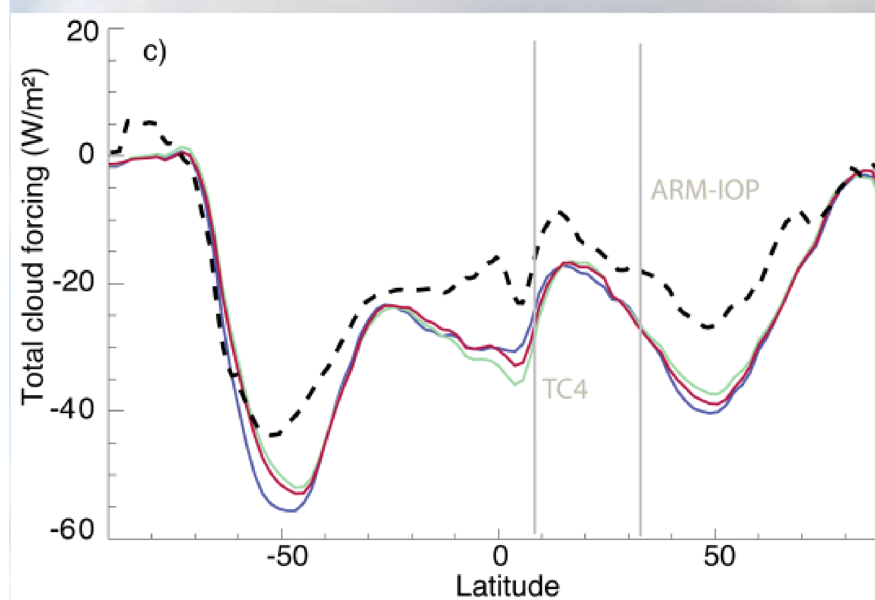


Comparing models:

- SW and LW forcing similar in mid-lat
- Largest difference in tropics
- Total forcing very similar: SW and LW differences cancel each other

Comparing models and observation:

- MG2 is closest to CERES in tropics, EM15 is closest to CERES in mid-lat



Conclusions

- Self-consistent *m*-*D* and *A*-*D* expressions are valid over the broad range of ice particles and are easily reduced to power laws (EM15).
- The new schemes (EM15 and P3) can represent the physical coupling between bulk particle density, mean fallspeed and effective diameter, which is not possible in current schemes.
- Differences in simulations using the new schemes, particularly the cloud radiative forcing, are attributable mainly to the effects on mean ice particle fallspeed, impacting sedimentation and ice water path.
- The advancement achieved is an improved physical basis for the CAM5 microphysics scheme.

Thank you!

Backup Slides

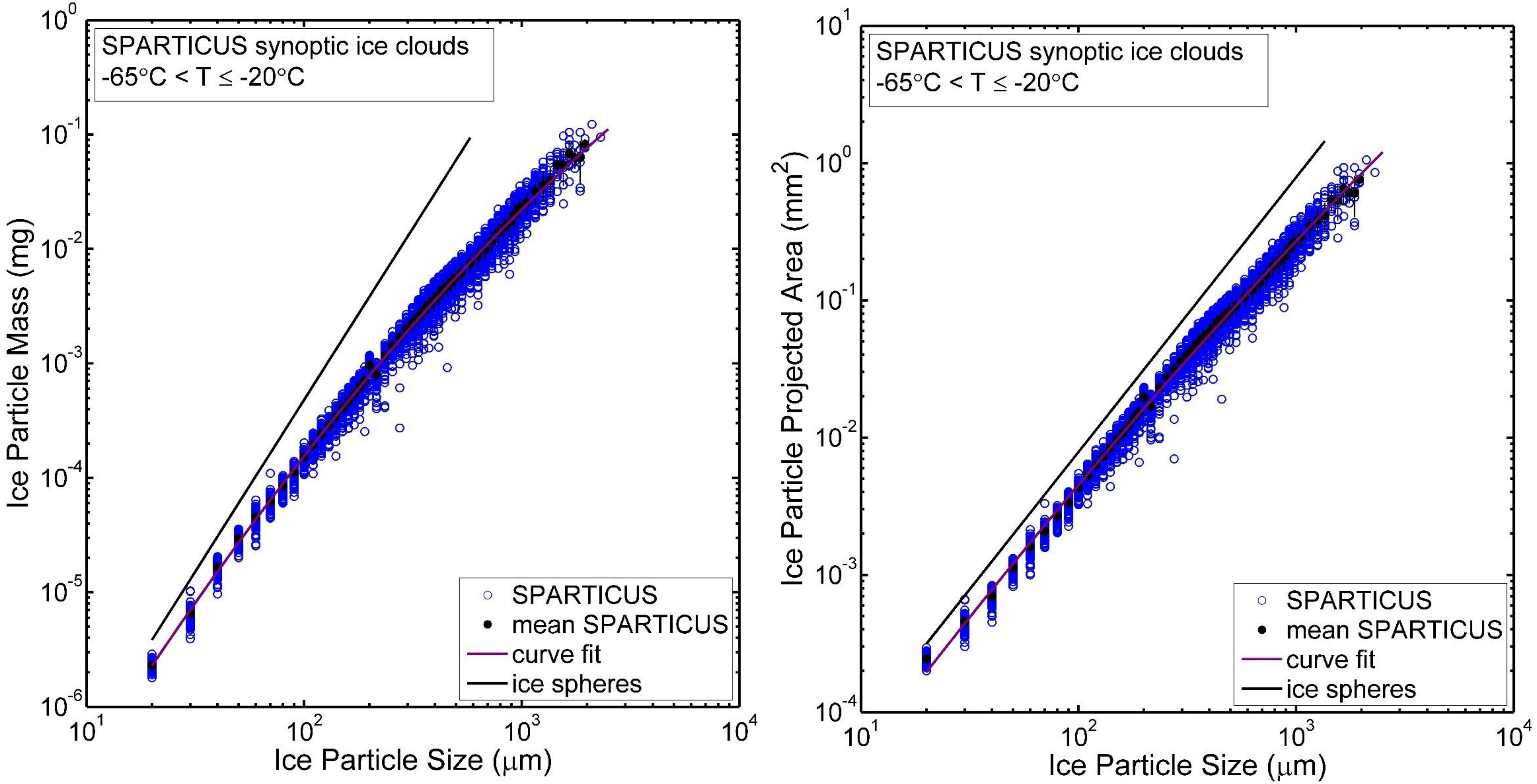
SPARTICUS Flights

January-June 2010

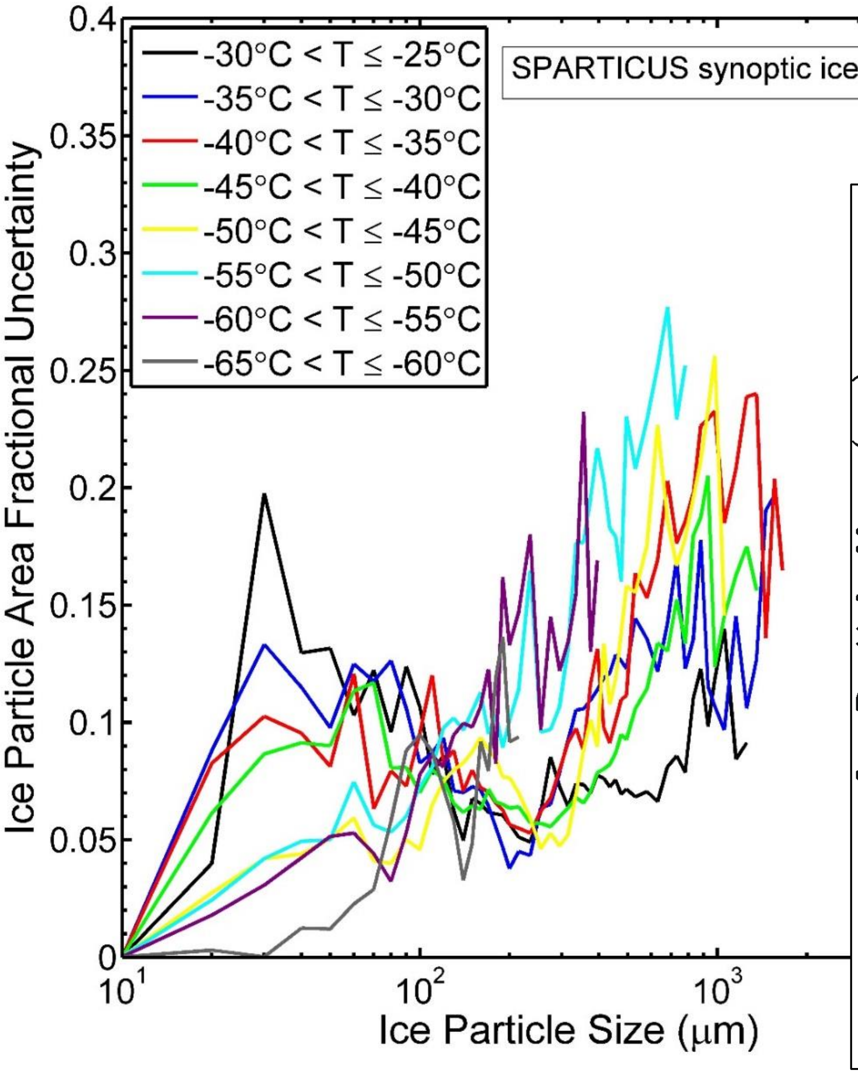
SPartICus Synoptic Cirrus Cases	SPartICus Anvil Cirrus Cases
1. Jan 19th, 2010 (Flight A)	1. April 22nd, 2010 (Flight A)
2. Jan 20th, 2010 (Flight A & B)	2. April 28th, 2010 (Flight A & B)
3. Jan 26th, 2010 (Flight A)	3. June 12th, 2010 (Flight A & B)
4. Jan 27th, 2010 (Flight A)	4. June 14th, 2010 (Flight A)
5. Feb 11th, 2010 (Flight A & B)	5. June 15th, 2010 (Flight A)
6. March 23rd, 2010 (Flight A, B & C)	6. June 24th, 2010 (Flight A & B)
7. March 26th, 2010 (Flight A)	
8. April 1st, 2010 (Flight A & B)	

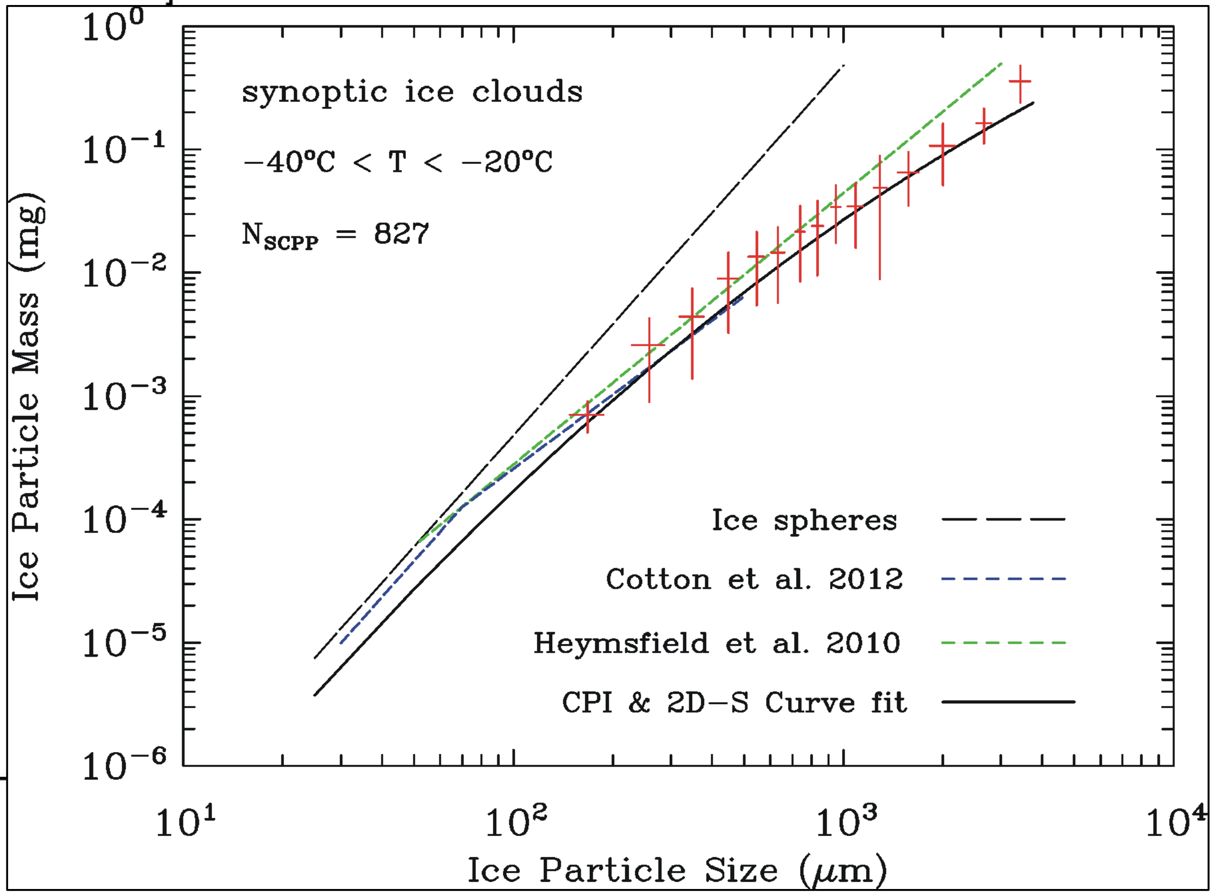
Mishra et al. 2014

Temperature-independent m-D and A-D



Uncertainty in m-D and A-D expressions

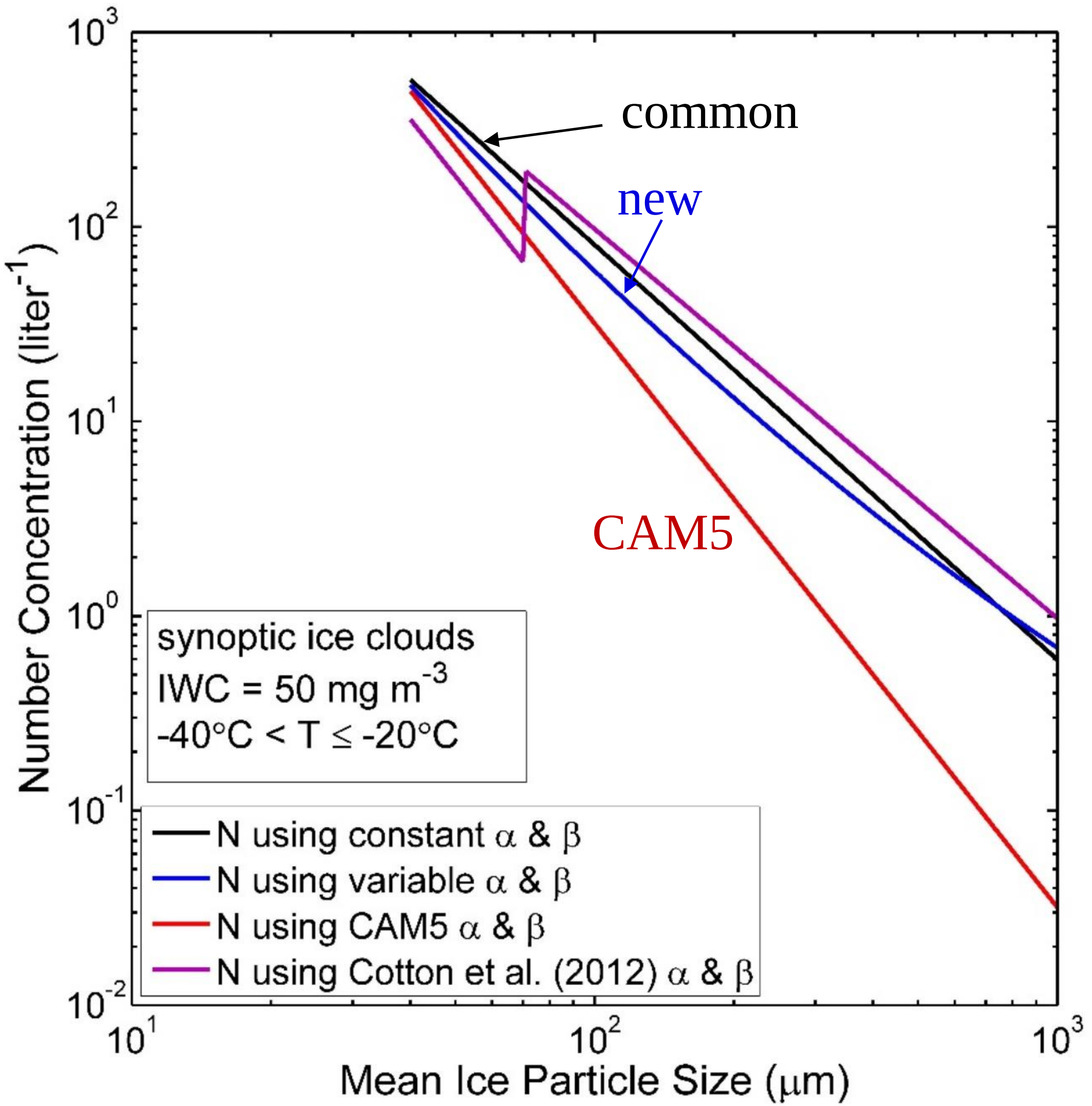




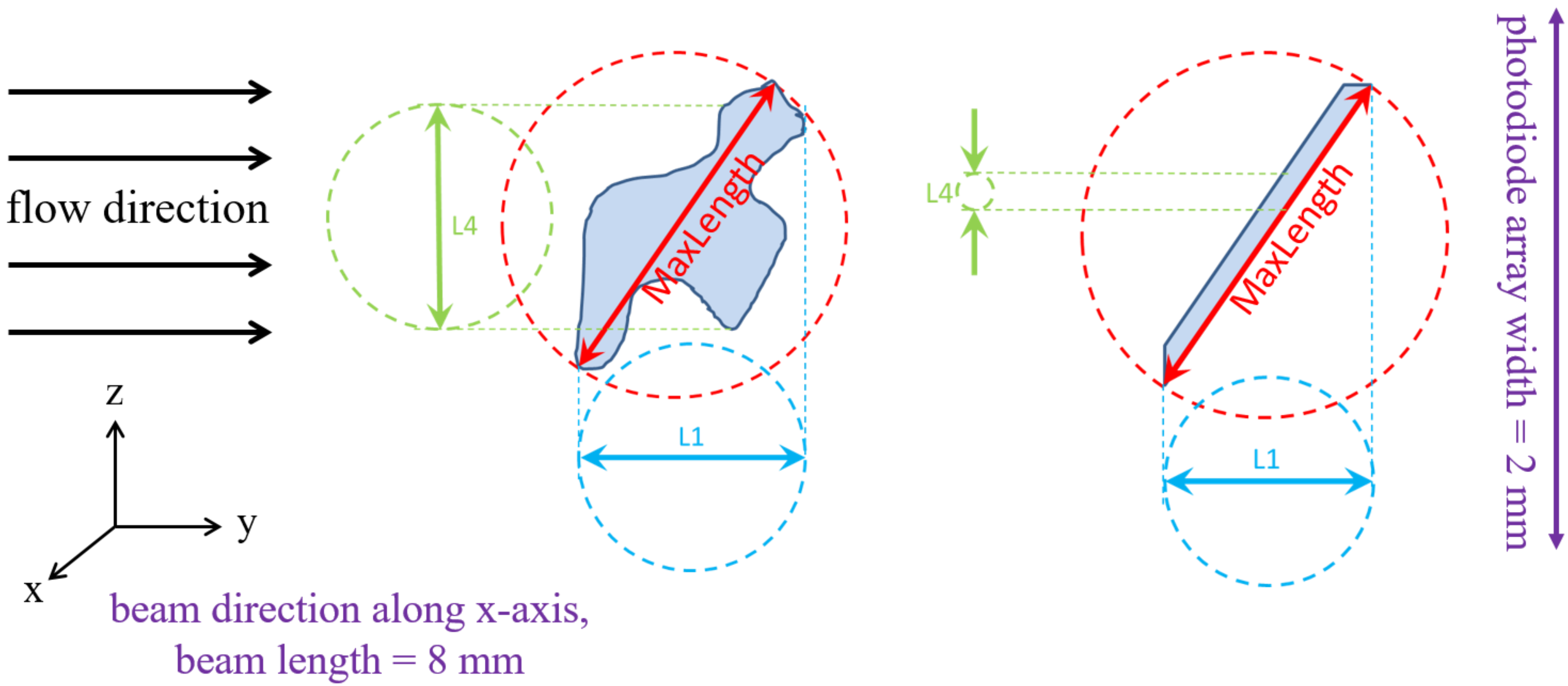
Application to Modeling

Contrasting new scheme with CAM5

- Spherical particles have higher density.
- Conservation of ice water content (IWC) leads to less number concentration of spherical particles.

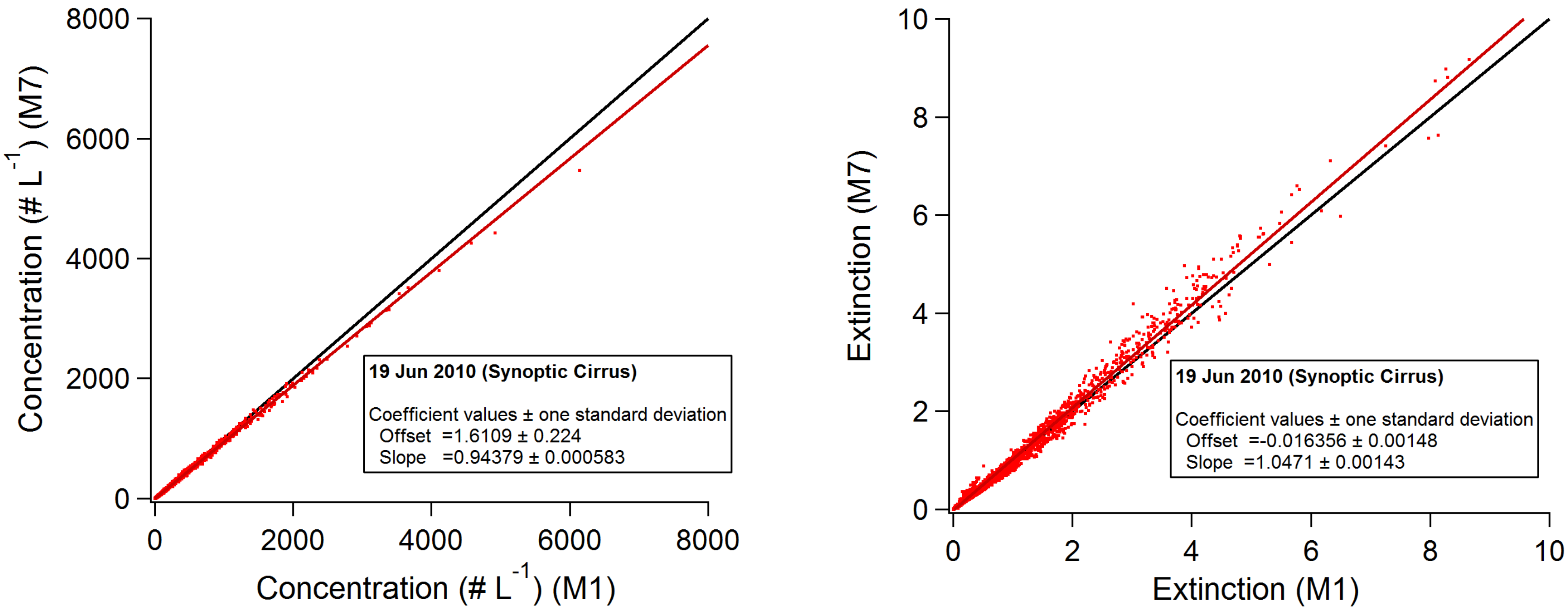


M1 and M7 Comparison



Geometry of dimension measurements showing length scales for the M1 method (*L1*) and the M7 method (MaxLength) for two ice particles with different shapes. Adapted from Paul Lawson and Sara Lance.

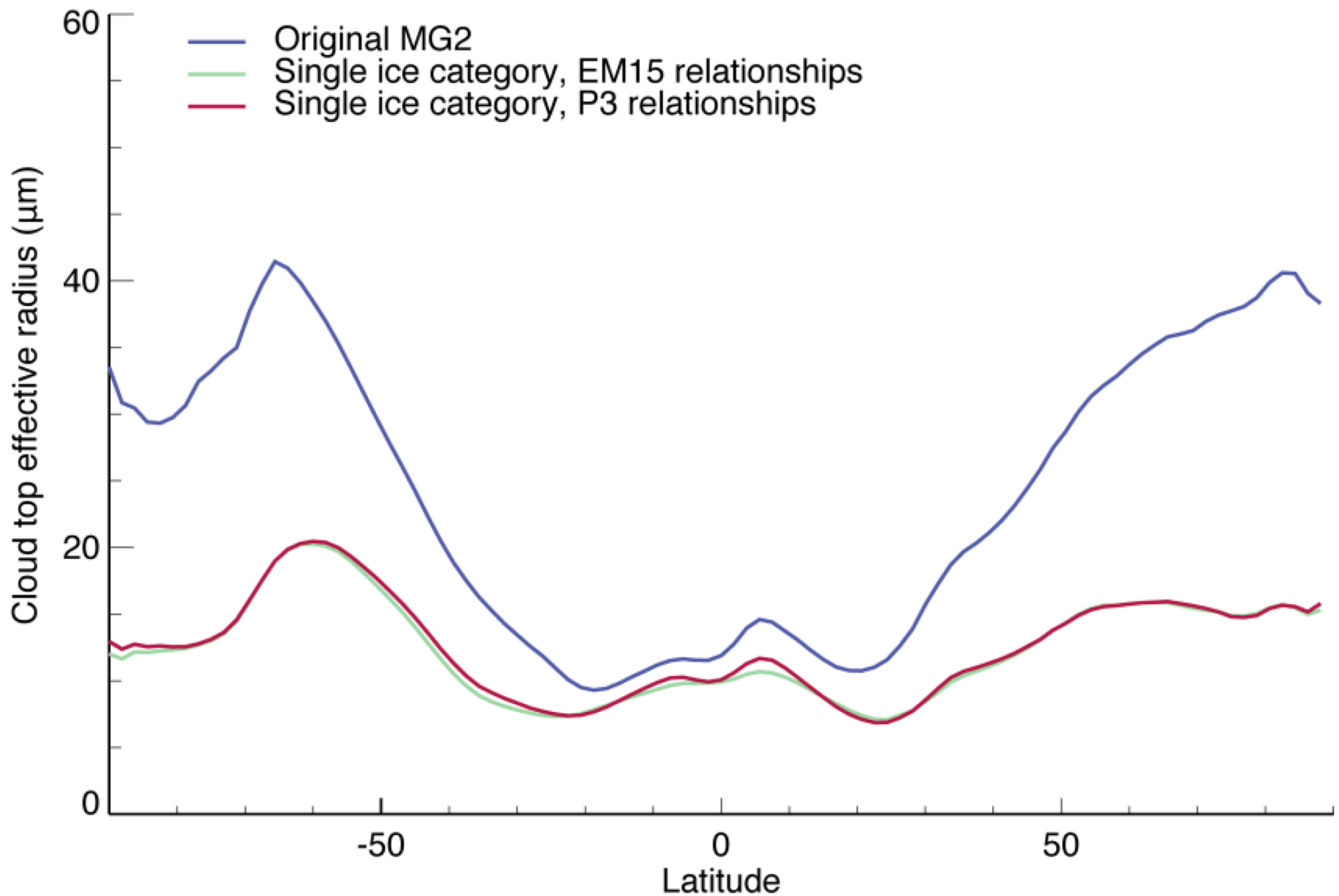
M1 and M7 Comparison



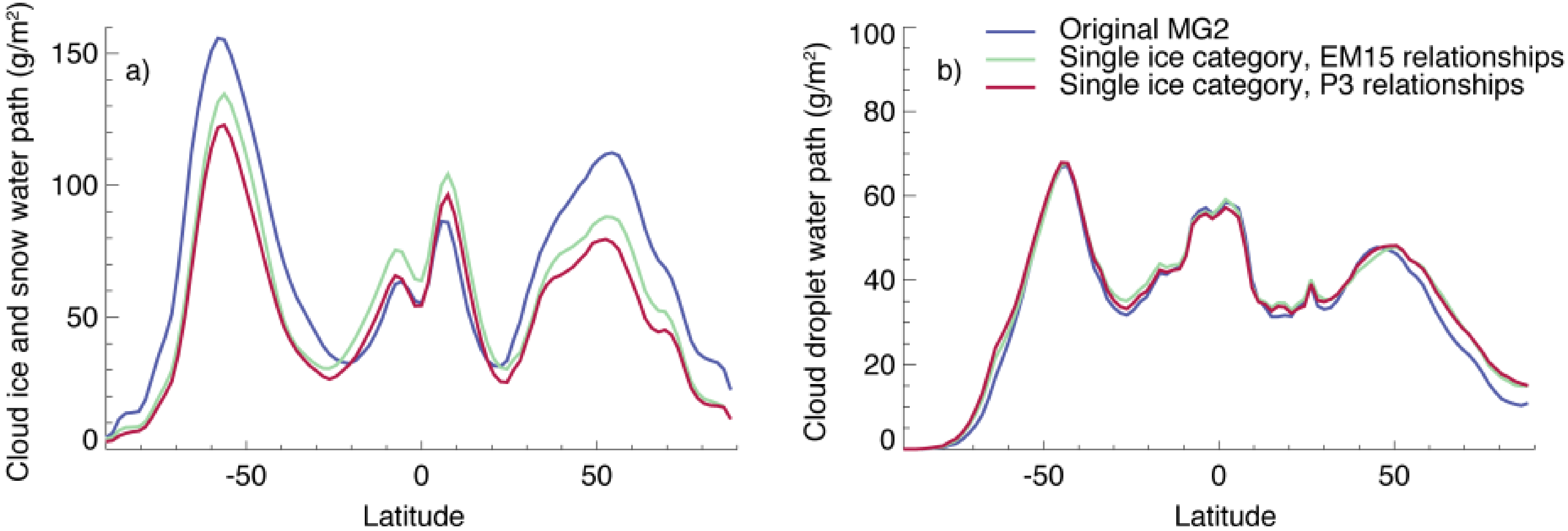
PSD number concentration from 2D-S M7 versus PSD number concentration from 2D-S M1 (left panel), and extinction from 2D-S M7 versus extinction from 2D-S M1 (right panel), during flight A on 19 Jan. 2010 (as example of synoptic cirrus clouds). Courtesy of Paul Lawson and Sara Lance.

Results: Effective Radius

- The ice effective radius in EM15 and P3 is about one-half the cloud ice effective radius from MG2 in the midlatitudes.



Results: IWP and LWP



Zonal mean a) ice water path (cloud ice + snow for the MG2 simulation), b) cloud droplet water path.

Results: Microphysical Processes

- There are large differences between EM15 and MG2 and between P3 and MG2 (deposition and sublimation of ice and snow)
- Differences between EM15 and MG2 are much smaller.
- Particles of all sizes can undergo vapor deposition and sublimation in EM15 and P3, improving physical realism and consistency.