EFFECTS OF NON-SPHERICAL ICE CRYSTAL SHAPE ON MODELED PROPERTIES OF THIN TROPICAL TROPOPAUSE LAYER CIRRUS

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INTRODUCTION

- Cirrus in TTL important for:
  - Radiative absorption
  - Water vapor transport into stratosphere
- Why use a cloud-resolving model?
  - Understand effects of mesoscale, radiatively induced circulations
- Previous work (Dinh *et al.*, 2010, 2012, 2014) assumed all spheres
  - Observations (Lawson *et al.*, 2008) suggest at least some plates and columns
  - Existing code could not maintain largest crystals

INTRODUCTION

- New simulations incorporate more realistic ice crystal shapes
  - Fall speed
  - Growth rate
  - Radiative absorption

- How does this affect time evolution of clouds?

MODEL OVERVIEW

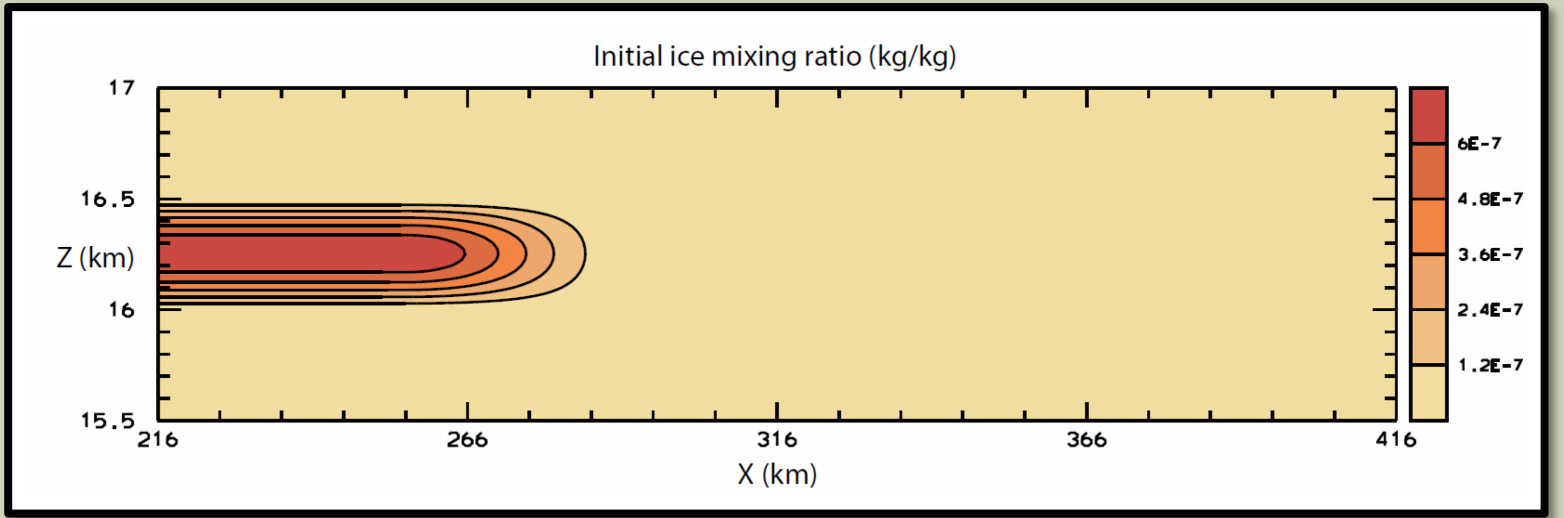
COMPONENTS OF MODEL

- Dynamics:
  - System for Atmospheric Modeling (SAM) (Khairoutdinov and Randall, 2003)
- Microphysics:
  - Bin microphysics scheme (Dinh and Durran, 2012)
- Radiation:
  - Lookup table of broadband ice crystal absorption cross sections

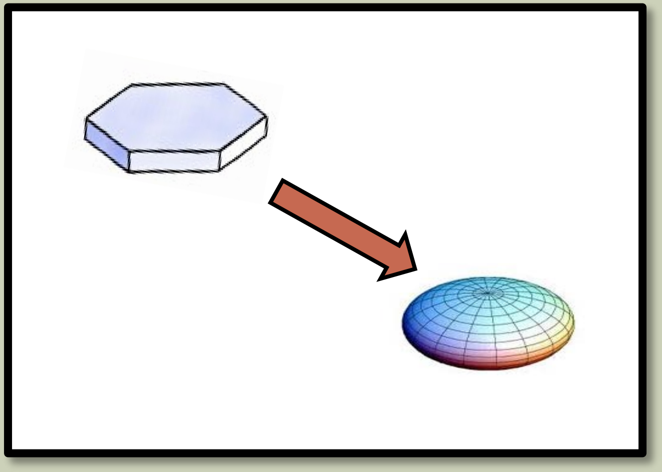
SIMULATION SETUP

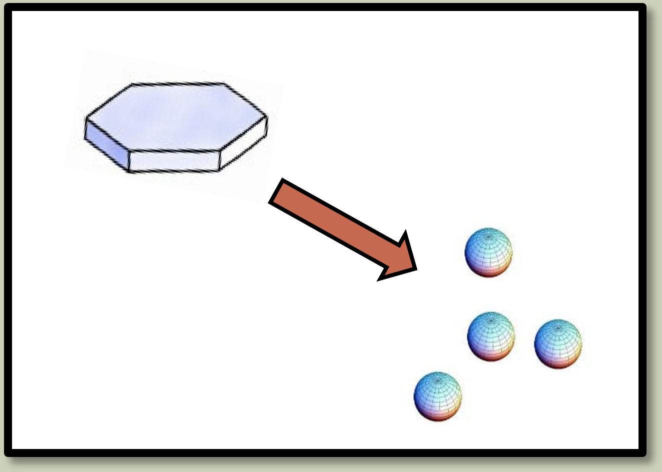
- Domain:
  - 2D (*x* and *z*)
  - 432 km (*x*) by 3.25 km (*z*)
  - Δx = 100 m
  - Δz = 25 m
  - Δt = 6 s

- Initialization:
  - No large-scale flow
  - Pre-existing cloud
  - Ice crystals: 3 μm radius
  - Sounding: Nauru, January average



REPRESENTING PLATES AND COLUMNS





- For microphysics: oblate and prolate spheroids
- For radiation:
  - Collection of spheres
  - Conserve SA/Volume ratio (Neshyba et al., 2003)
- Aspect ratio of 6 for now

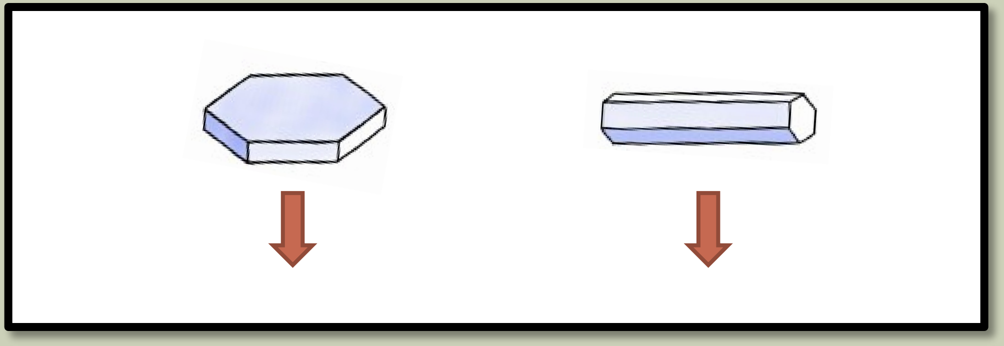
FALL SPEED

FALL SPEED: CALCULATION

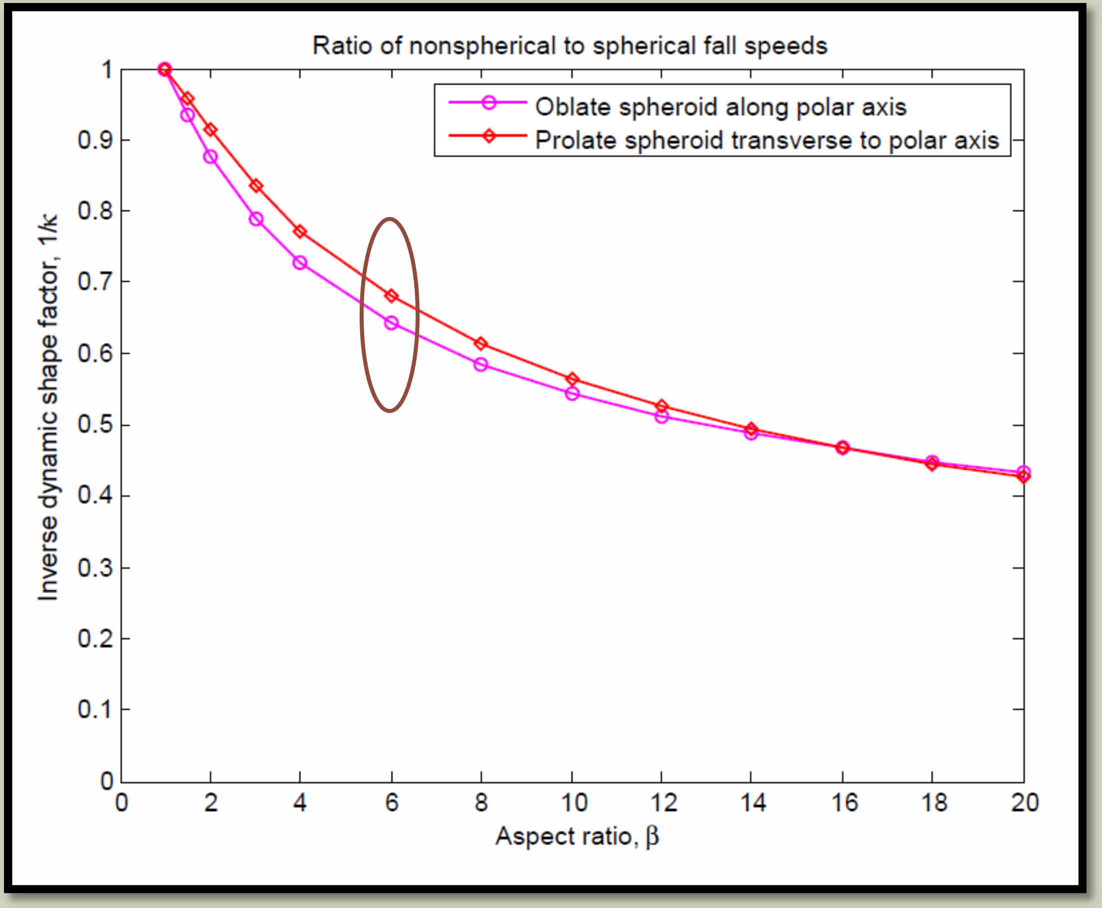
- Stokes regime:
  - Large enough that fluid is continuum
  - Small enough that fluid's inertia is negligible
  - Analytical expression for terminal velocity

- Corrections for spheroids: functions only of aspect ratio (Fuchs, *Mechanics of Aerosols*, 1964)

- Orientation: maximize horizontal cross section



FALL SPEED: EFFECT OF SHAPE



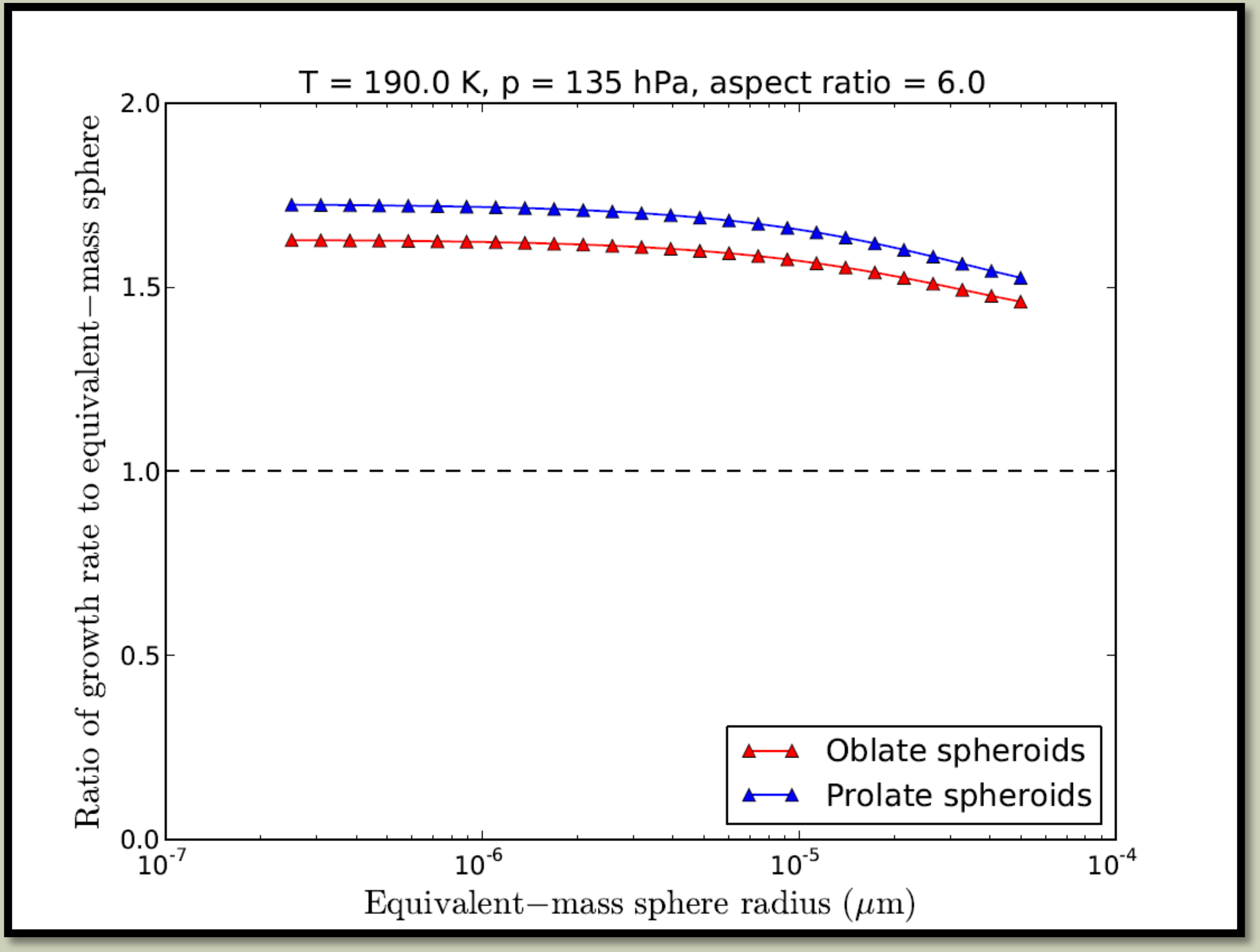
GROWTH RATES

GROWTH RATE: CALCULATION

- How to account for both size and shape?

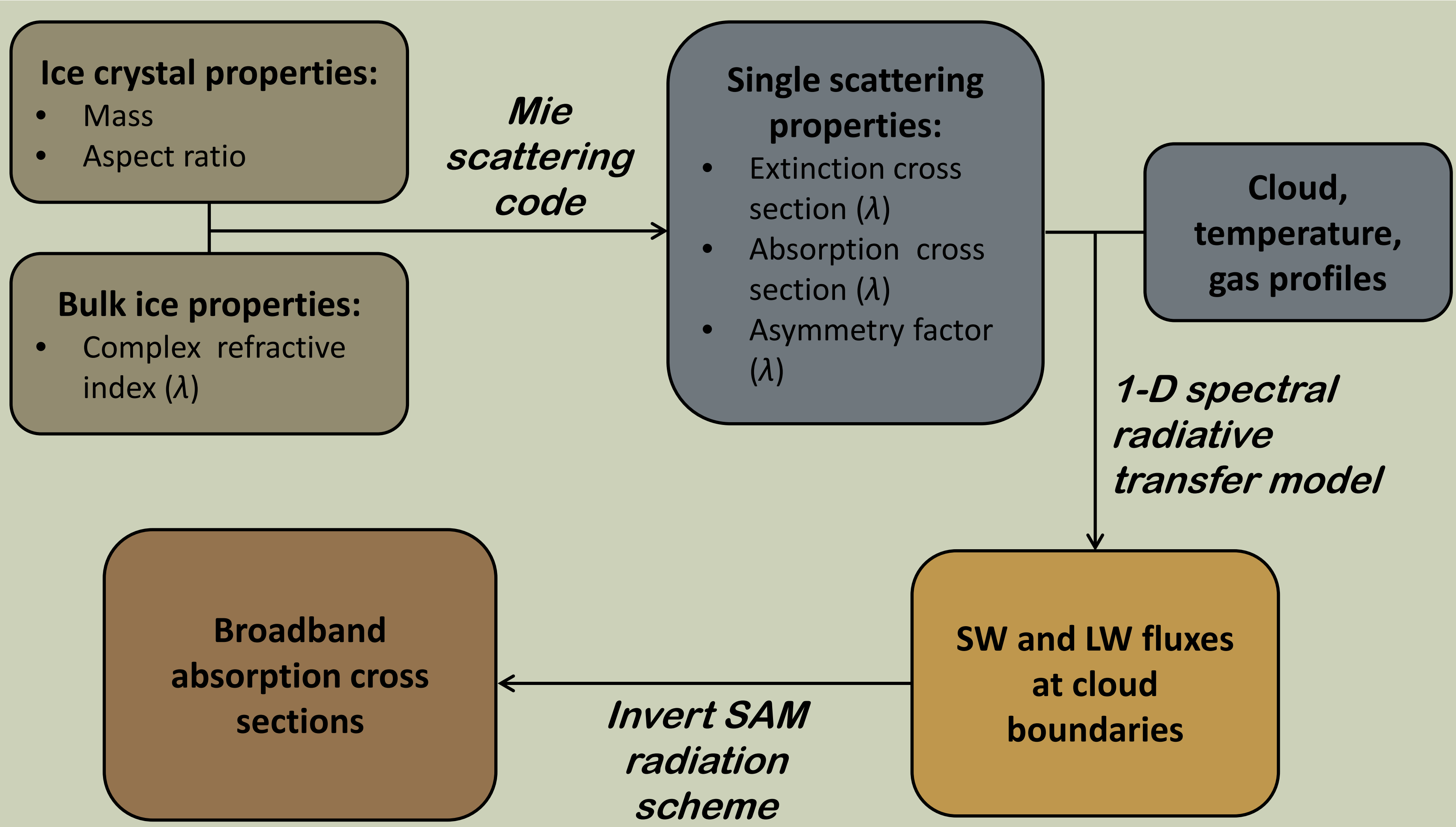
- Electrostatic analogy: growth rate $\propto$ **capacitance**
  - Equal to radius for spheres
  - Spheroids: function of major and minor axes

GROWTH RATE: EFFECT OF SHAPE

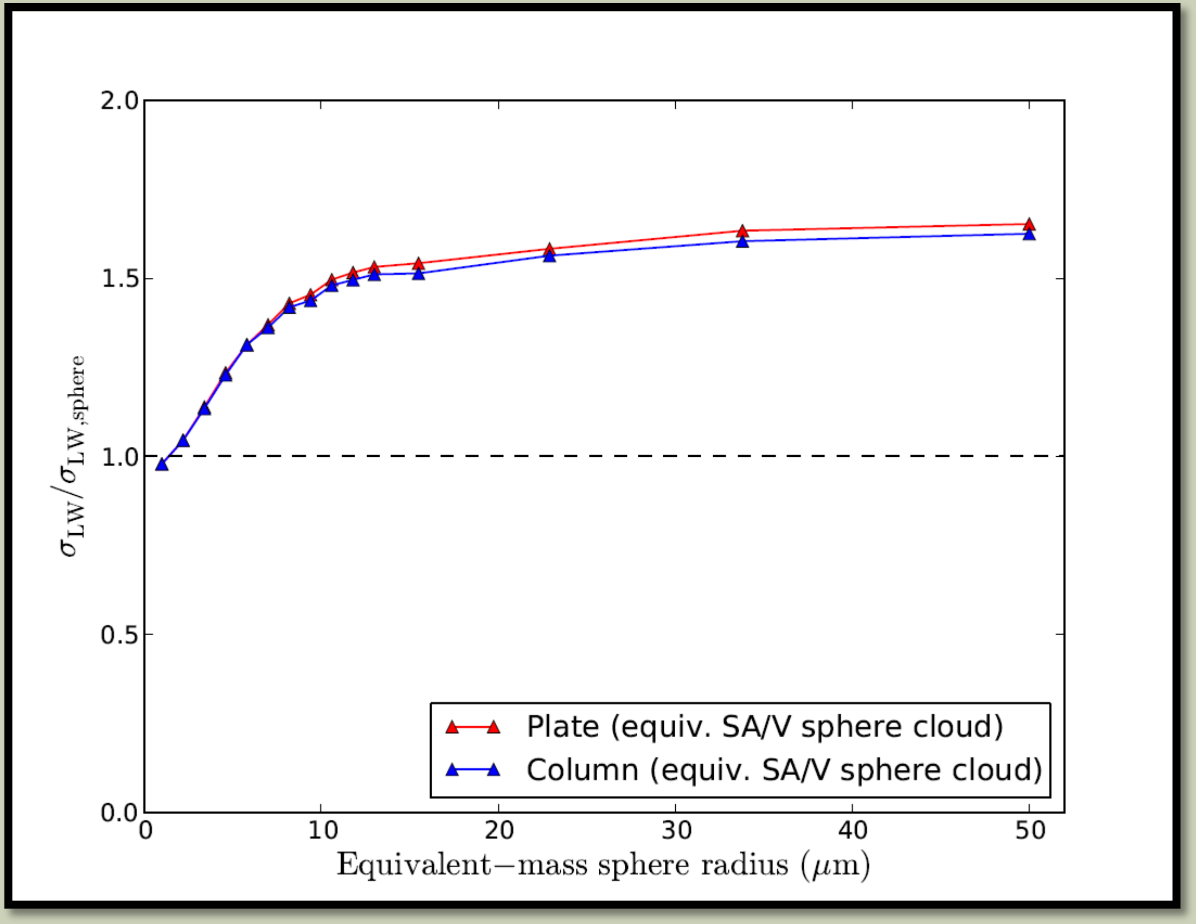


RADIATIVE ABSORPTION

RADIATION: PARAMETERIZATION PROCESS

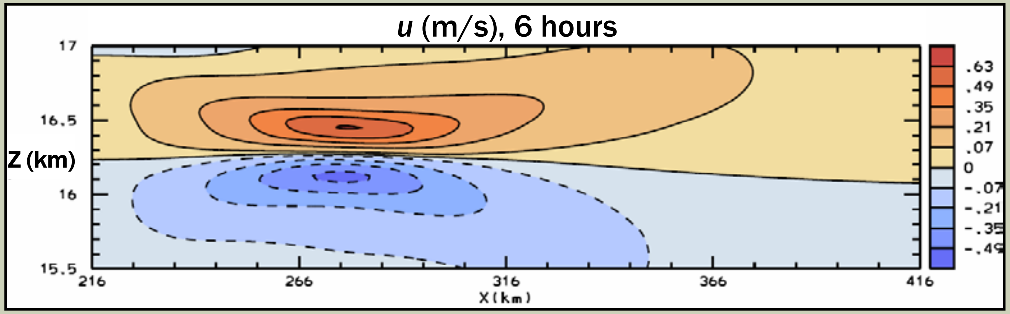


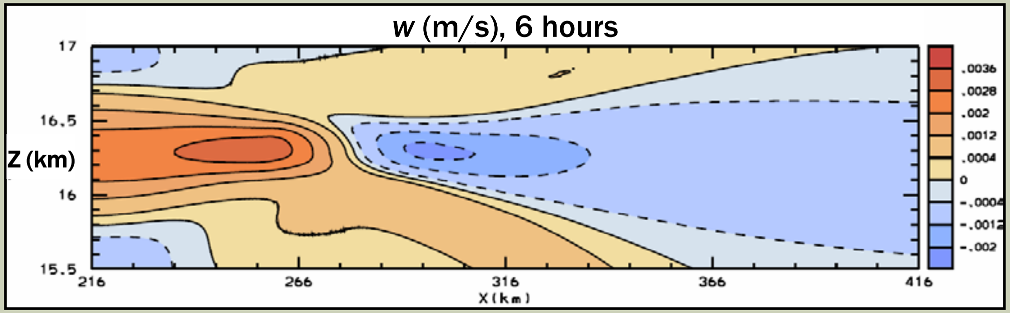
RADIATION: EFFECT OF SHAPE



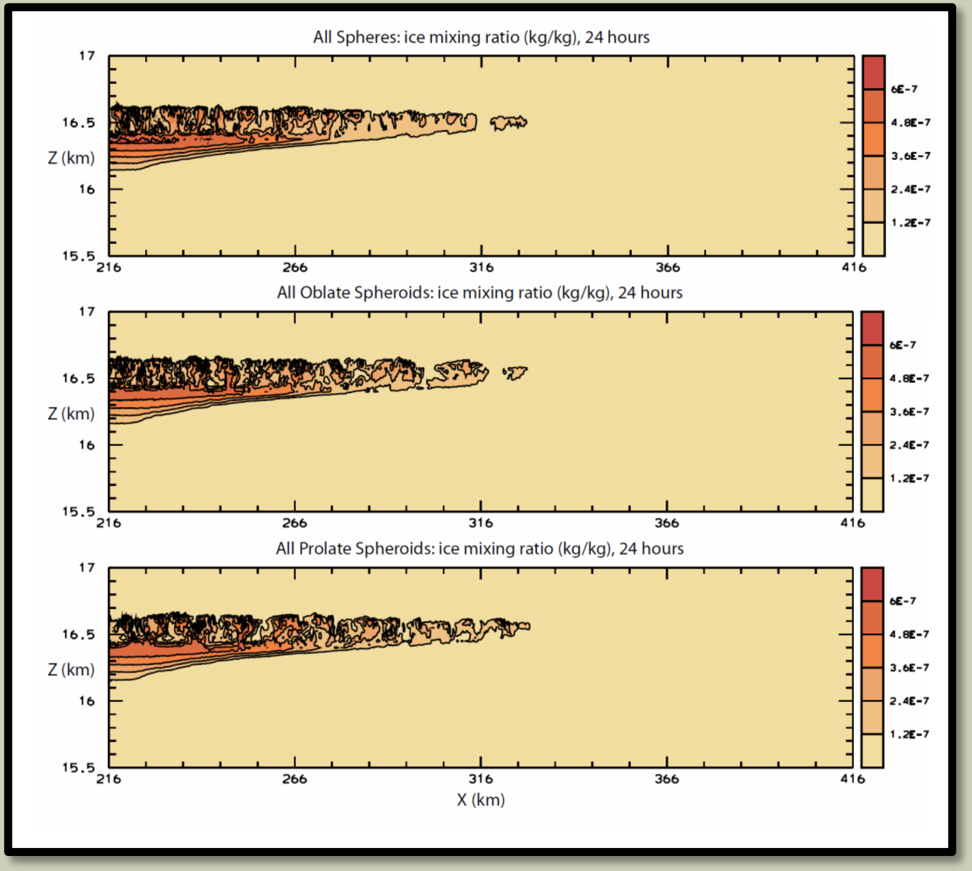
RESULTS AND FUTURE WORK

CIRCULATION AT 6 HOURS

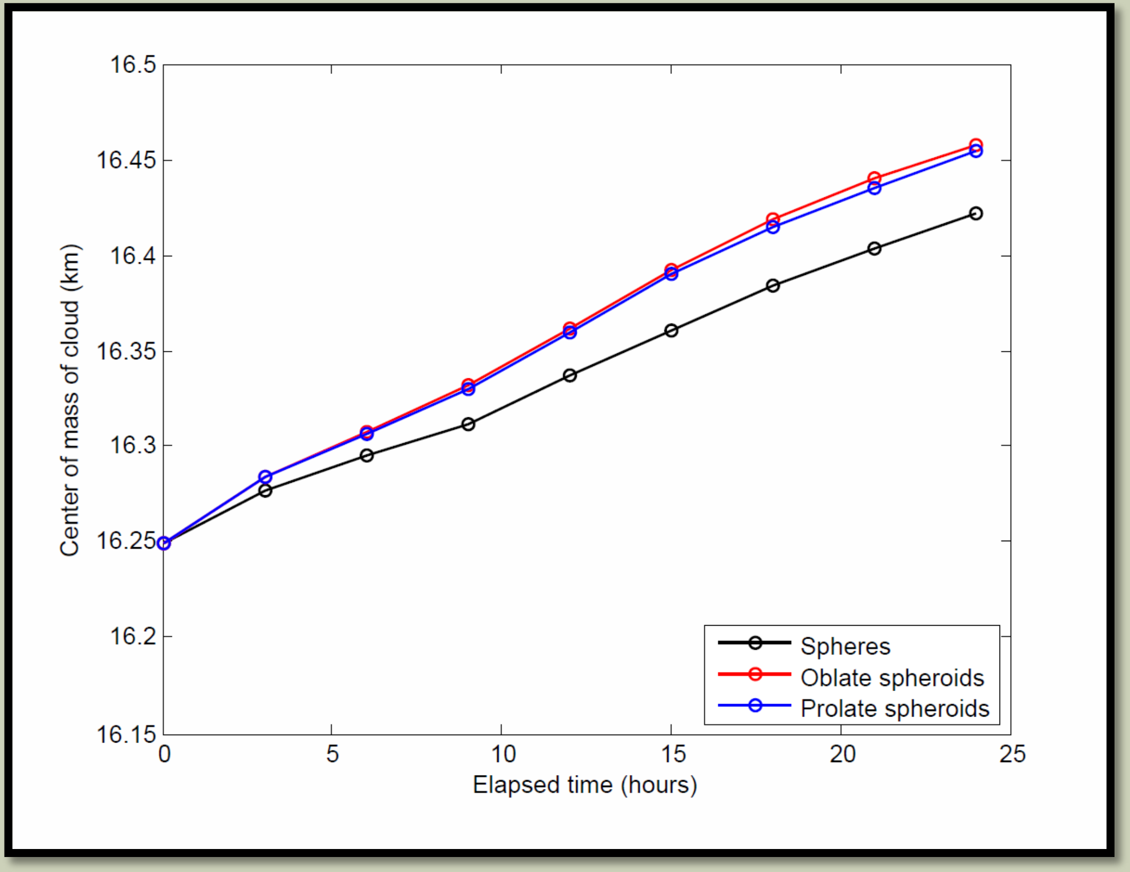




CLOUD AT 24 HOURS

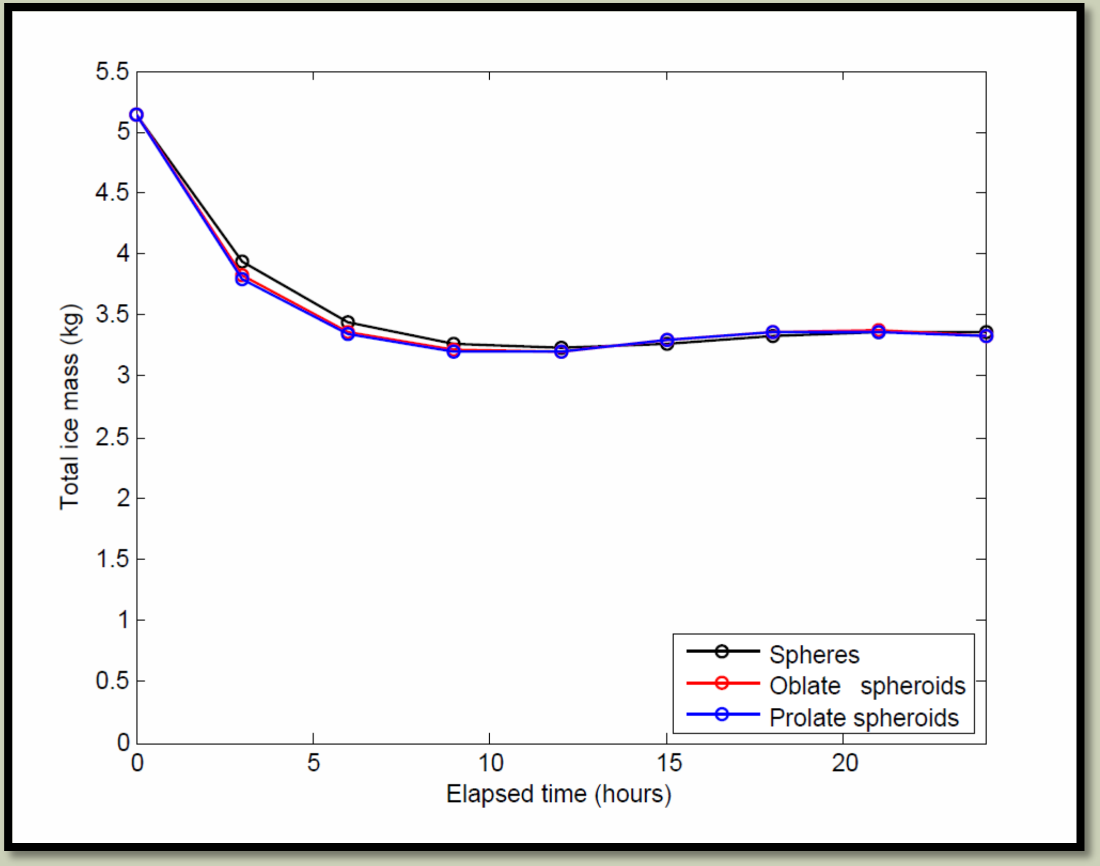


LIFTING OF CLOUD



- Preliminary: additional lifting due to
  - Fall speeds (2/3)
  - Radiation (1/3)

TOTAL CLOUD MASS



FUTURE WORK

- Distinguish effects of fall speed, growth rate, and radiation

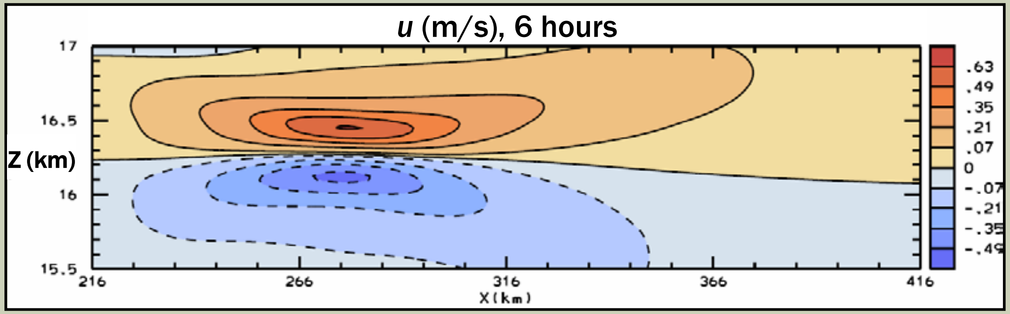
- Other ways to get single-scattering properties
  - T-Matrix method (Mishchenko & Travis, 1998)
  - Improved geometric optics method (Yang & Liou, 1996)

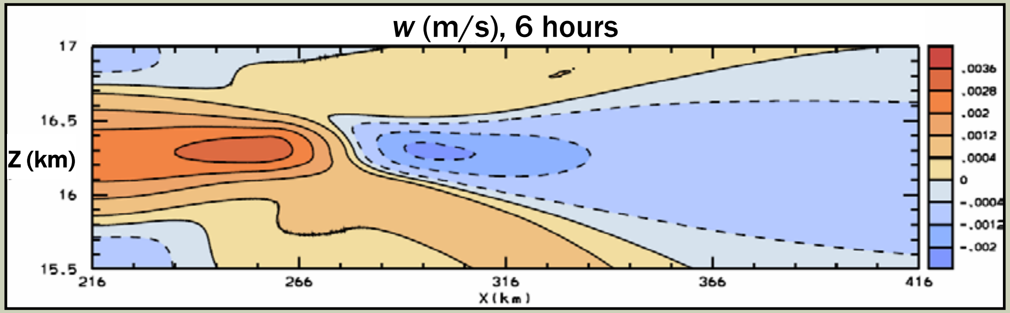
- Use of ATTREX data:
  - Ice crystal size distributions (also habits)
  - Environmental water vapor distributions
  - Inertial-gravity waves?

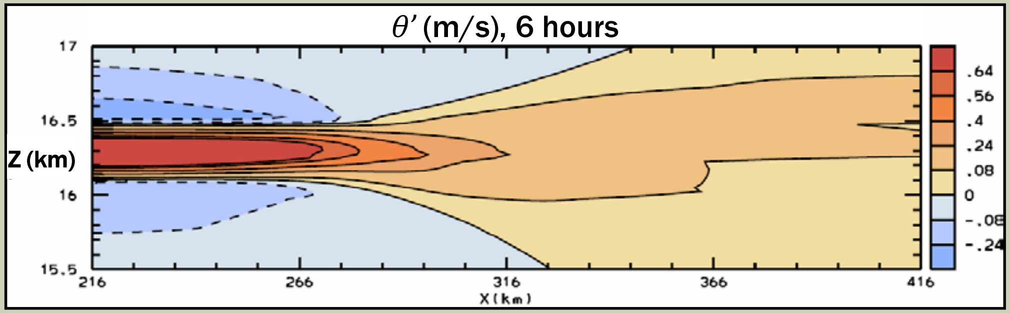
QUESTIONS?

ADDITIONAL SLIDES

CIRCULATION AT 6 HOURS







- Other ways to get single-scattering properties
  - T-Matrix method (Mishchenko & Travis, 1998)
  - Improved geometric optics method (Yang & Liou, 1996)
  - Existing databases (Fu et al., 1999; Yang et al., 2013)
  - Exact scattering solution for spheroids (Asano & Sato, 1980)

GROWTH RATE: CALCULATION

- General growth rate equation: (Pruppacher and Klett, 1978)

$$\frac{dm}{dt} = \frac{4\pi C(S_{\text{ice}} - 1)}{\frac{R_{\text{v}}T}{e_{\text{sat,ice}}D'_{\text{v}}} + \frac{L_s}{k'_{\text{a}}T}\left(\frac{L_s}{R_{\text{v}}T} - 1\right)}$$

- Shape dependence for:
  - C
  - D'_v
  - k'_a

m = ice crystal mass
C = capacitance
S_{ice} = saturation ratio w.r.t. ice
R_v = gas constant for water vapor
T = temperature
$e_{sat,ice}$ = sat. vapor pressure over plane surface
L_s = latent heat of sublimation
k'_a = modified thermal conductivity of air
D'_v = modified diffusivity of water vapor in air

GROWTH RATE: CAPACITANCE METHOD

- General growth rate equation (Pruppacher and Klett, 1978):

$$\frac{dm}{dt} = \frac{4\pi C(S_{\mathrm{ice}} - 1)}{\frac{R_{\mathrm{v}}T}{e_{\mathrm{sat,ice}}D'_{\mathrm{v}}} + \frac{L_S}{k'_{\mathrm{a}}T}\left(\frac{L_S}{R_{\mathrm{v}}T} - 1\right)}$$

- Expressions for capacitance, C:
  - Spheres: $C = r$
  - Oblate spheroids:

$$C = \frac{ae}{\sin^{-1} e} \quad \text{where} \quad e = \sqrt{1 - \frac{b^2}{a^2}}$$

  - Prolate spheroids:

$$C = \frac{A}{\ln\left(\frac{a+A}{b}\right)} \quad \text{where} \quad A = \sqrt{a^2 - b^2}$$

r = radius of sphere

a = semi-major axis of ellipse of revolution
b = semi-minor axis “ “ “ “
e = eccentricity “ “ “ “
A = linear eccentricity “ “ “ “

m = ice crystal mass
C = capacitance
S_{ice} = saturation ratio w.r.t. ice
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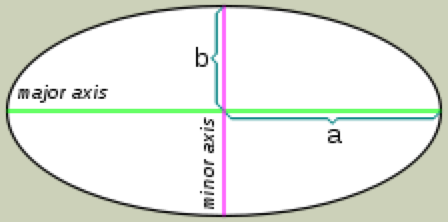
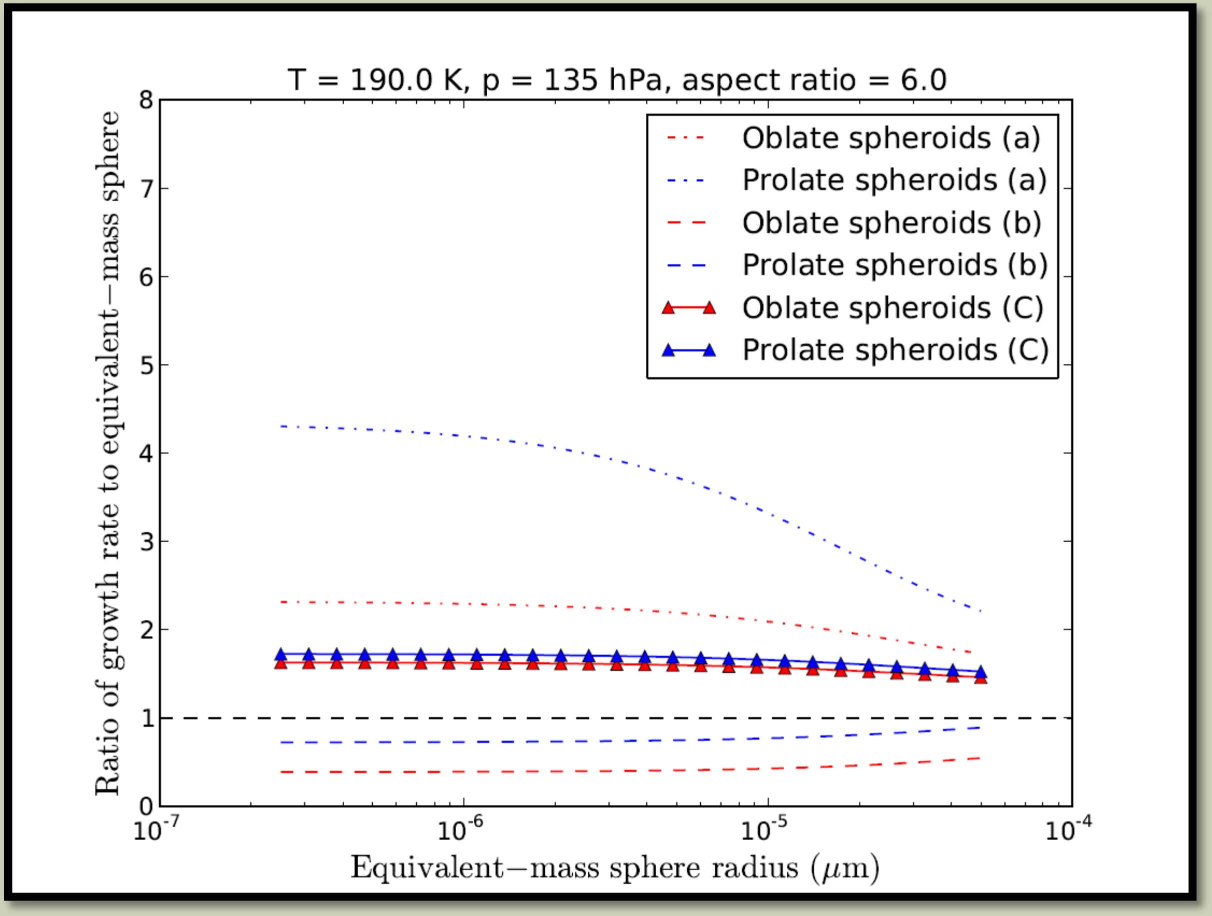


MORE ON GROWTH RATE

Field discontinuity corrections for thermal conductivity and water vapor diffusivity (D_v', k_a') depend on particle size. What measure of size to use for spheroids? Makes a big difference.



FALL SPEEDS

- Stokes regime:
  - Large enough that fluid is a continuum
  - Small enough that fluid's inertia is negligible
- Analytical expression for drag coefficient
  - And therefore terminal velocity
- For spheres:

$$v_T = \frac{2}{9}\frac{\rho_{ice}g}{\mu_{air}}r^2$$

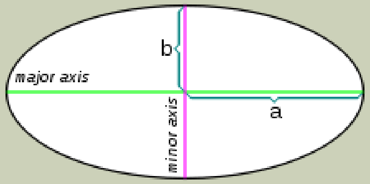
FALL SPEEDS

- Corrections for spheroids from Fuchs, *Mechanics of Aerosols* (1964)
- Dynamic shape factor $\varkappa$:

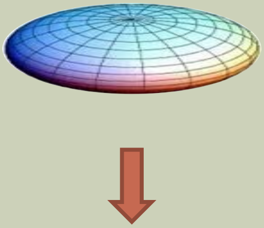
$$\varkappa \equiv \frac{\text{rate of settling of equivalent mass sphere}}{\text{rate of settling of spheroid particle}}$$

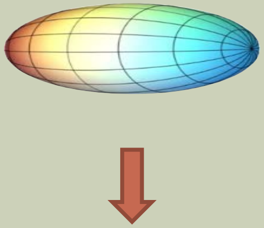
- $\varkappa$ function only of aspect ratio β

$$\beta = \frac{a}{b}$$



- Fall directions: maximize horizontal cross section



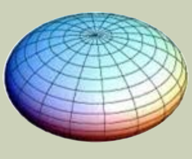


FALL SPEED: STOKES' LAW METHOD

- Corrections for spheroids from Fuchs, *Mechanics of Aerosols* (1964)
- Dynamic shape factor $\varkappa$:

$$\varkappa \equiv \frac{\text{rate of settling of equivalent mass sphere}}{\text{rate of settling of spheroid particle}}$$

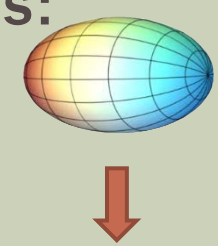
- For oblate spheroids, falling along the polar axis:



$$\varkappa = \frac{\frac{4}{3}(\beta^{1/3})(\beta^2 - 1)}{\frac{\beta(\beta^2 - 2)}{\sqrt{\beta^2 - 1}}\tan^{-1}\left(\sqrt{\beta^2 - 1}\right) + \beta}$$

β = aspect ratio = (major axis)/ (minor axis)

- For prolate spheroids, falling transverse to the polar axis:



$$\varkappa = \frac{\frac{8}{3}(\beta^{-1/3})(\beta^2 - 1)}{\frac{(2\beta^2 - 3)}{\sqrt{\beta^2 - 1}}\ln\left(\beta + \sqrt{\beta^2 - 1}\right) + \beta}$$

FALL SPEED: STOKES' LAW METHOD

- Has been used before (Jensen *et al.*, 2008)
- Only works for low Reynolds' numbers, but that should be the case here:

$$\mathrm{Re} = \frac{\rho v L}{\mu}$$

Estimates:

$\rho \approx 1.2e^{-2} = 0.162\ \frac{\mathrm{kg}}{\mathrm{m}^3}$ (2 scale heights up)

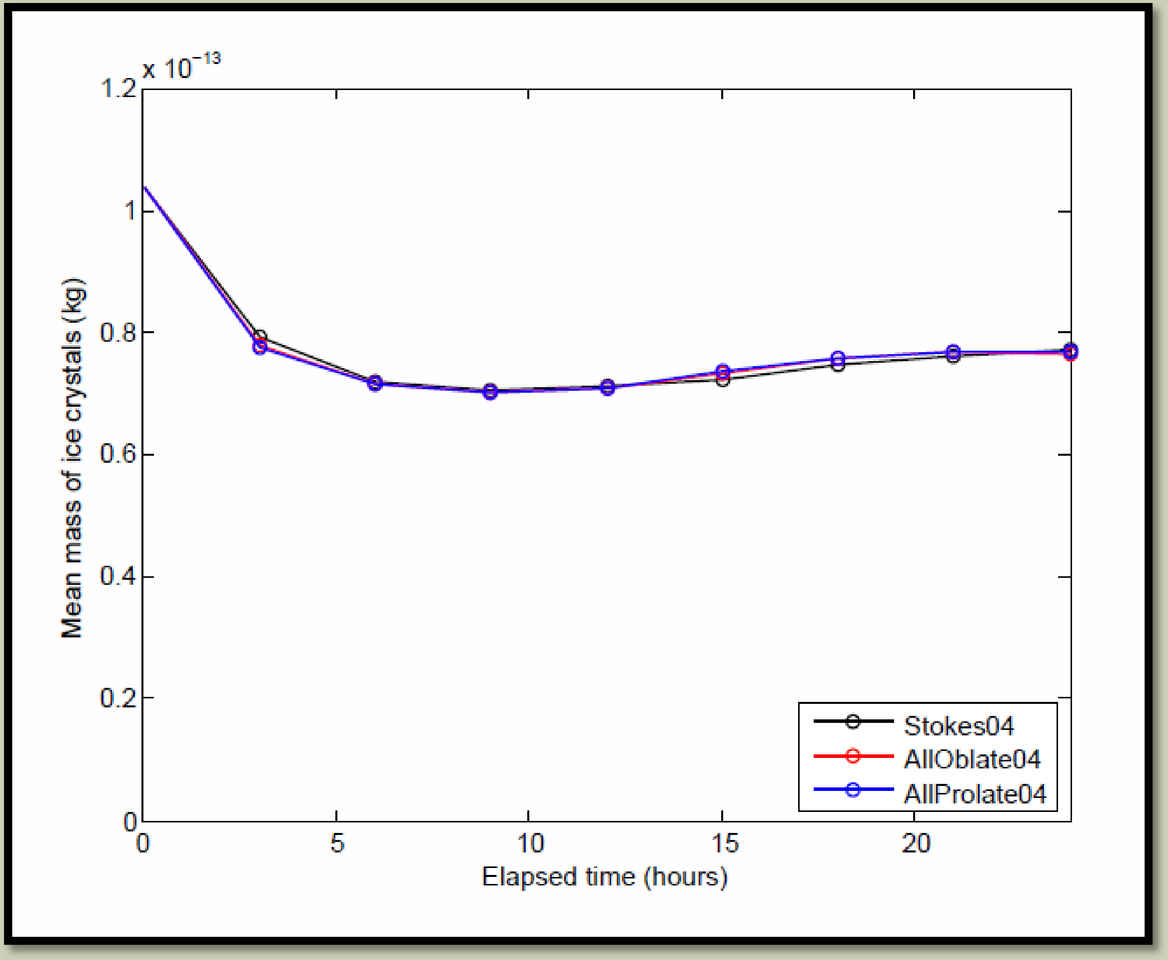
$v \approx 10\,\frac{\mathrm{mm}}{\mathrm{s}} = 0.01\,\frac{\mathrm{m}}{\mathrm{s}}$ (based on updrafts in Dinh *et al.*, 2010)

$L \approx 100\ \mu\mathrm{m} = 0.0001\ \mathrm{m}$ (conservative estimate for particle size)

$\mu \approx 1.2 \times 10^{-5}\,\frac{\mathrm{kg}}{\mathrm{m}*\mathrm{s}}$ (viscosity of air at about 180 K)

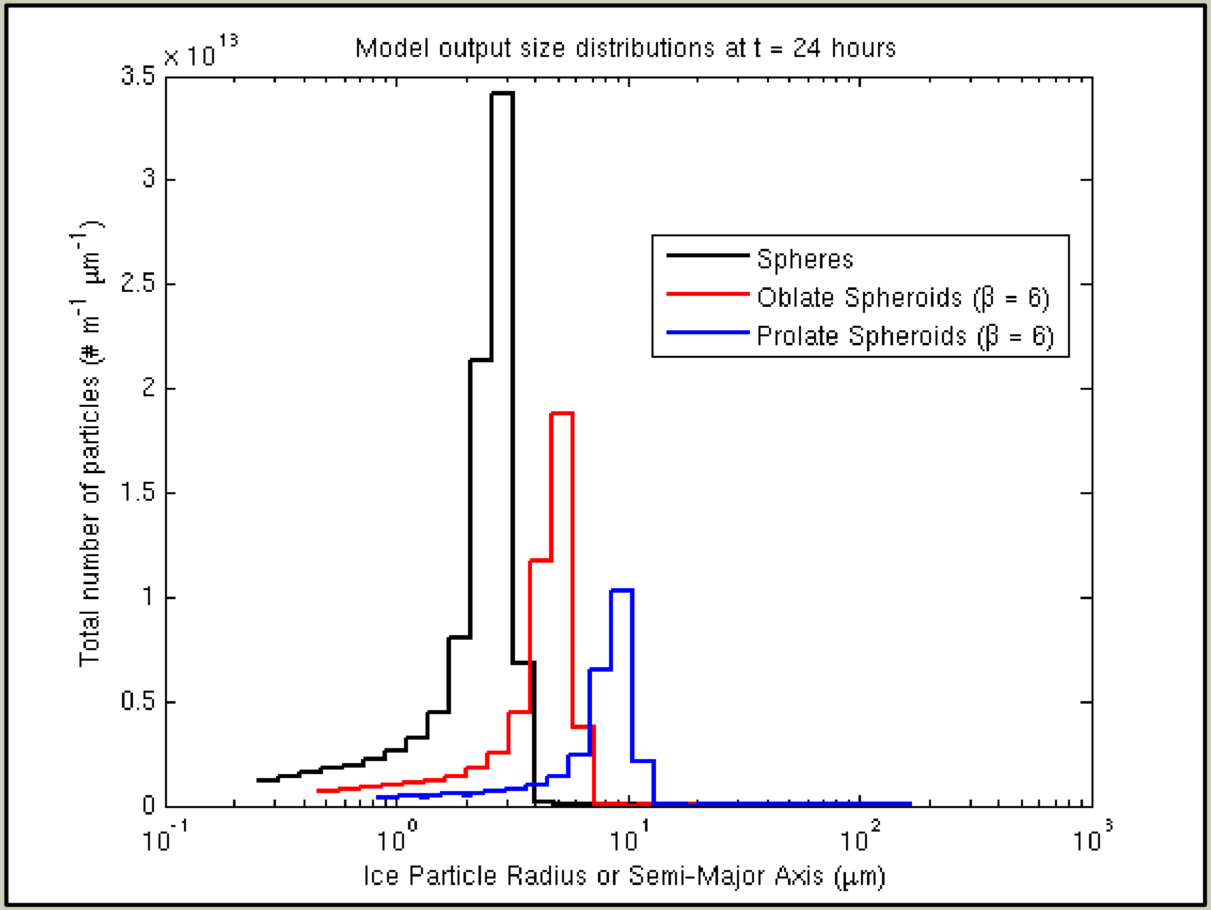
$\mathrm{Re} \approx 0.0135 \ll 1$

MEAN ICE CRYSTAL MASS

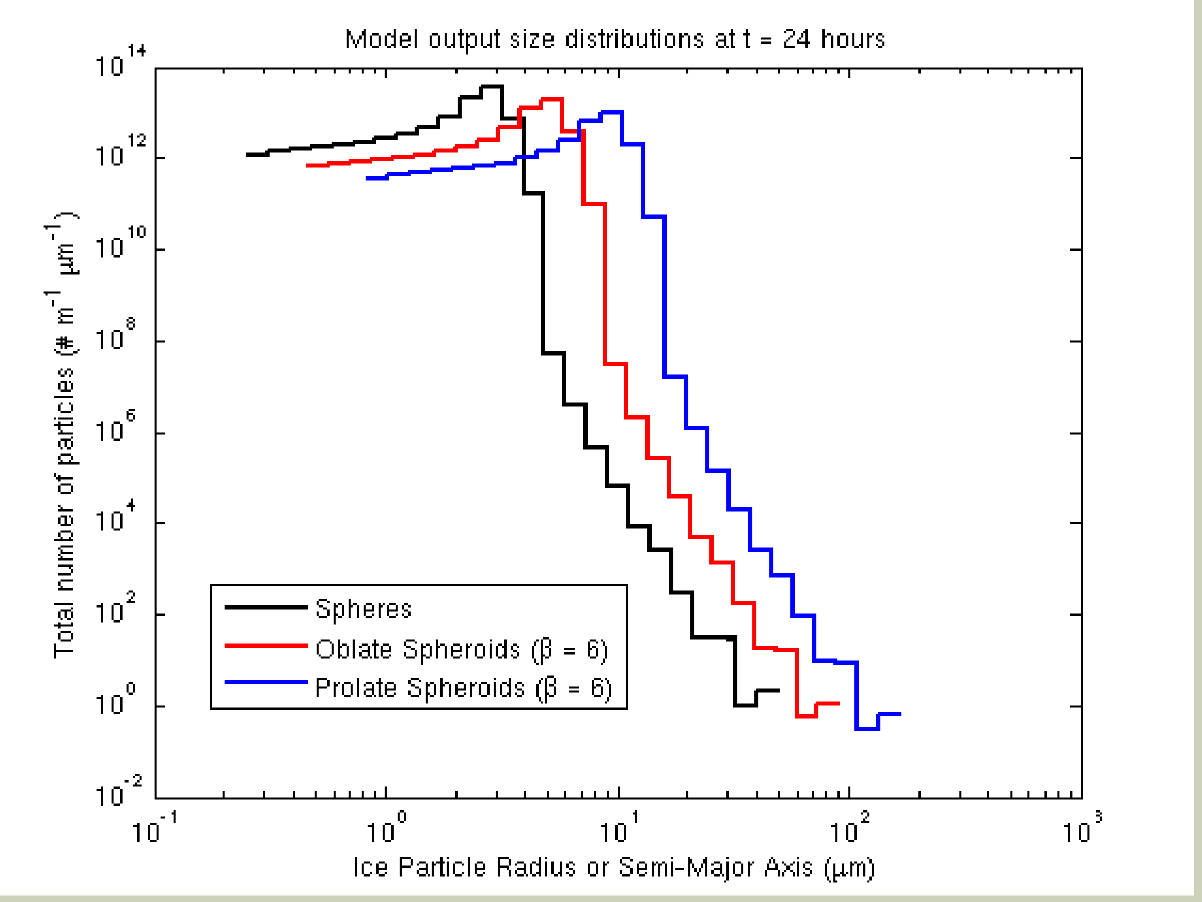


PARTICLE SIZE DISTRIBUTIONS

- Note: these are earlier simulations that did not consider effects of shape on radiation, and also had a different growth rate calculation.

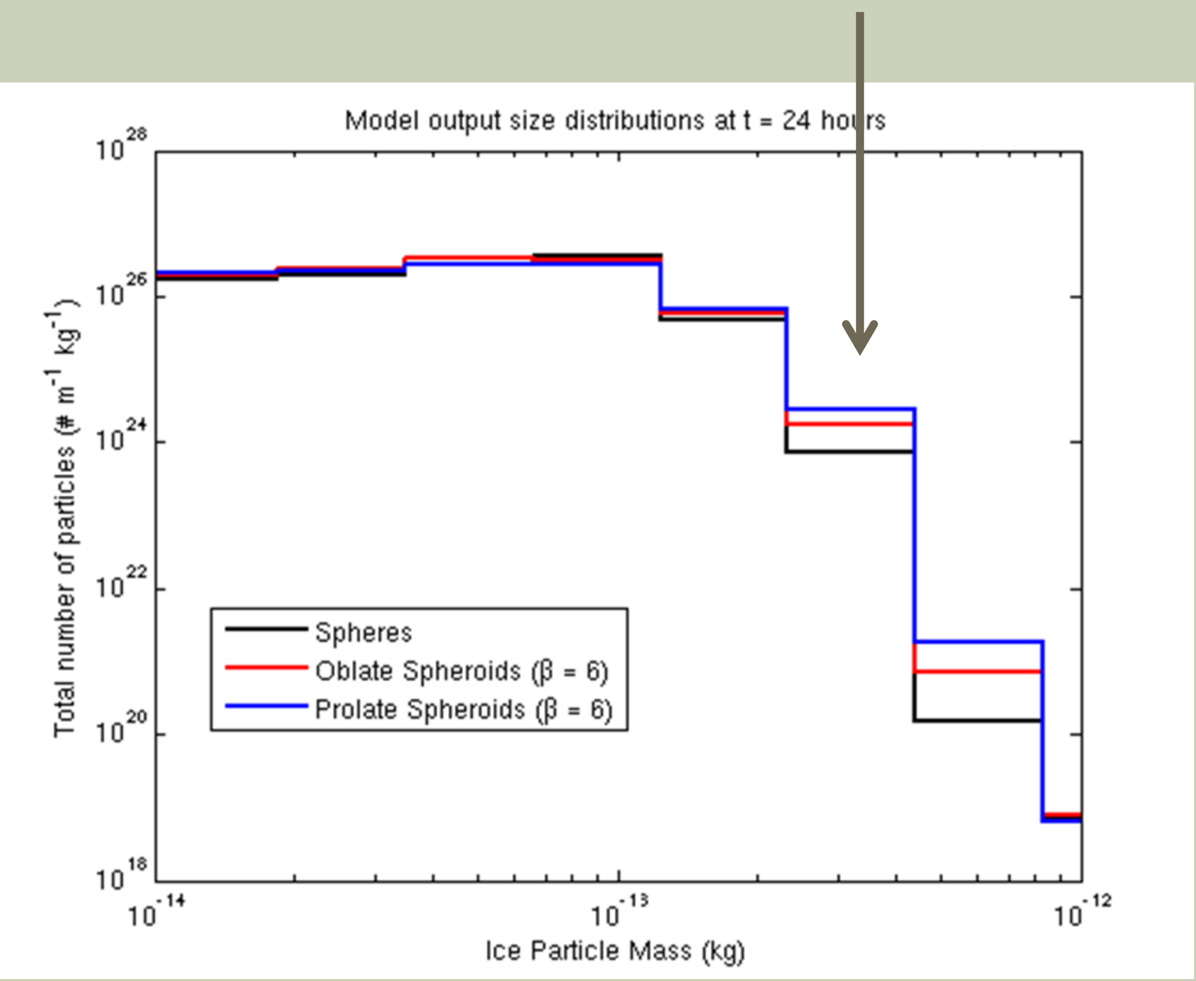


PARTICLE SIZE DISTRIBUTIONS



PARTICLE SIZE DISTRIBUTIONS

Starting Bin



PARTICLE SIZE DISTRIBUTIONS