A 3D Code: MCARaTS

- Variance Reduction Techniques for Monte Carlo Radiation Model

Hironobu Iwabuchi
Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan

Third I3RC Workshop
11-14 Oct 2005, Kiel

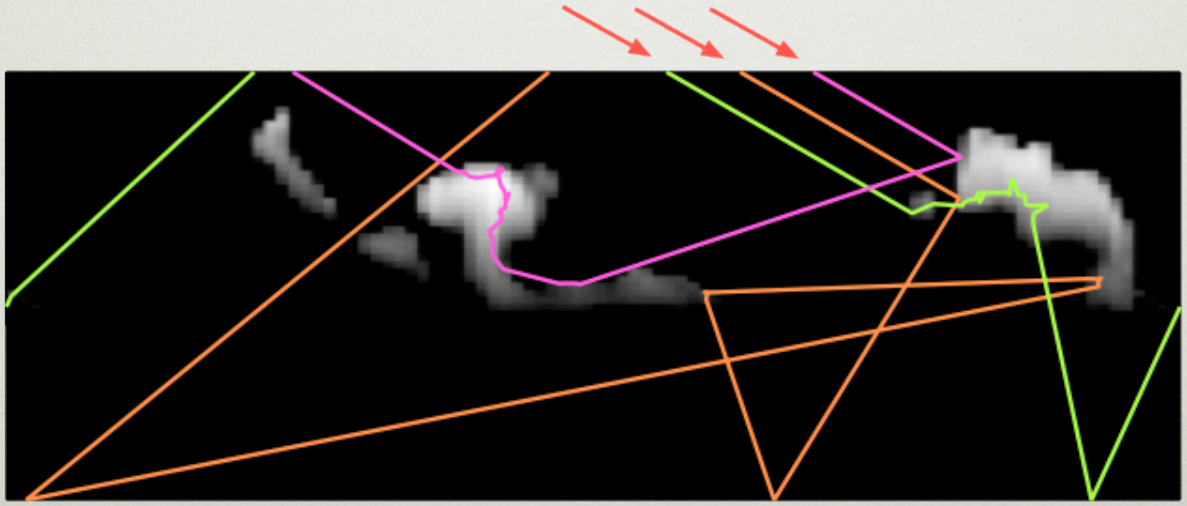
MCARaTS

Monte **C**arlo **A**tmospheric **Ra**diative **T**ransfer **S**imulator

- http://www.geocities.jp/null2unity/mcarats/
- Can be found at Google!
- Source codes, examples, and documentation are available

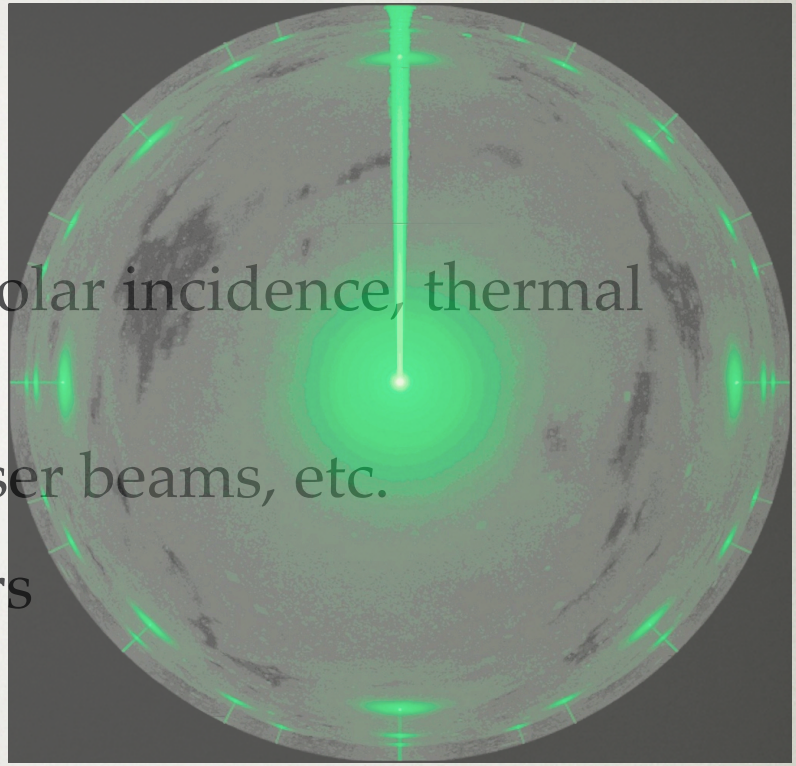
Algorithm

- Forward-propagating photon-transport algorithm
- Very small bias + random noise (depending on computer power)



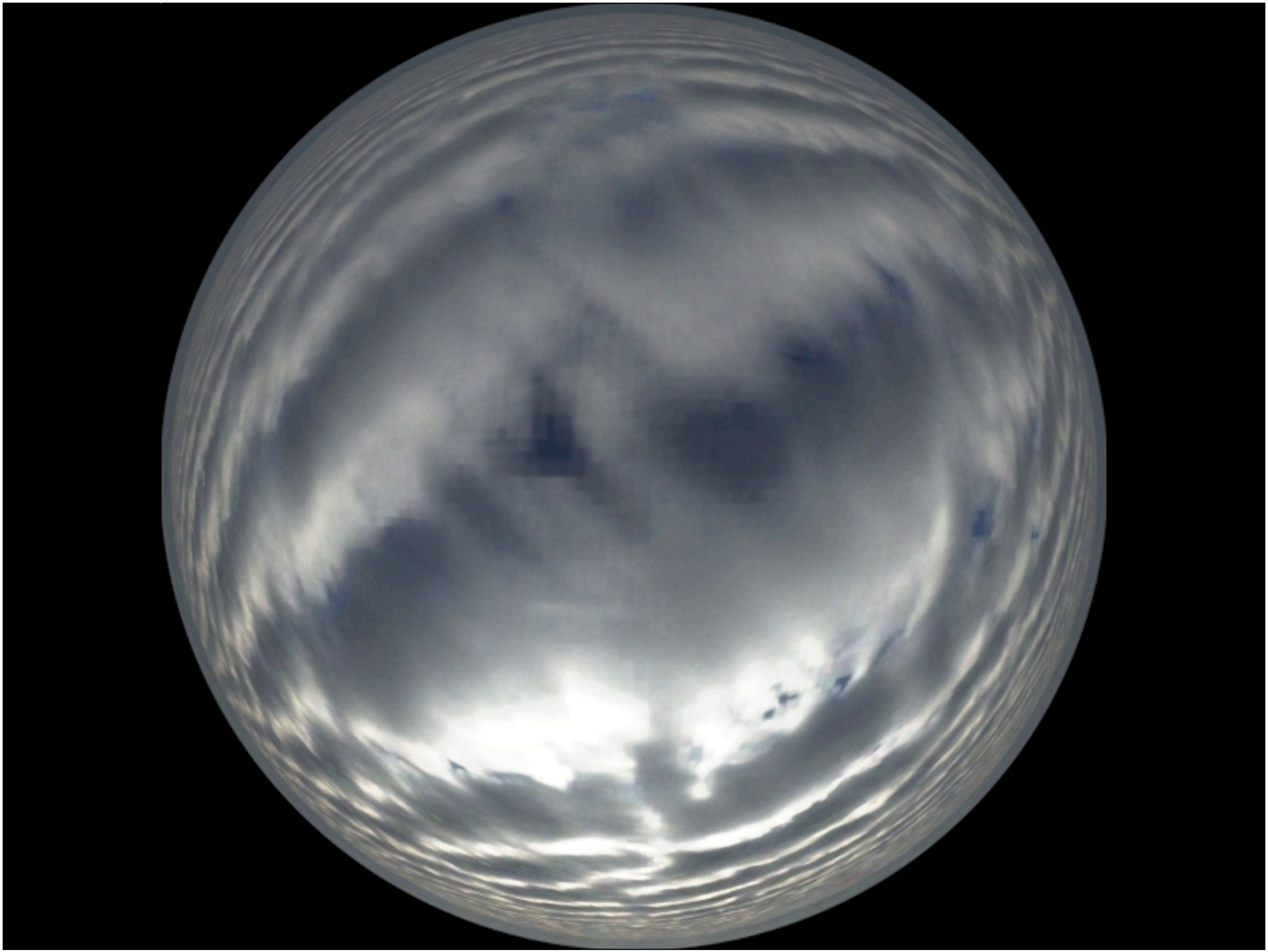
Modeled Processes

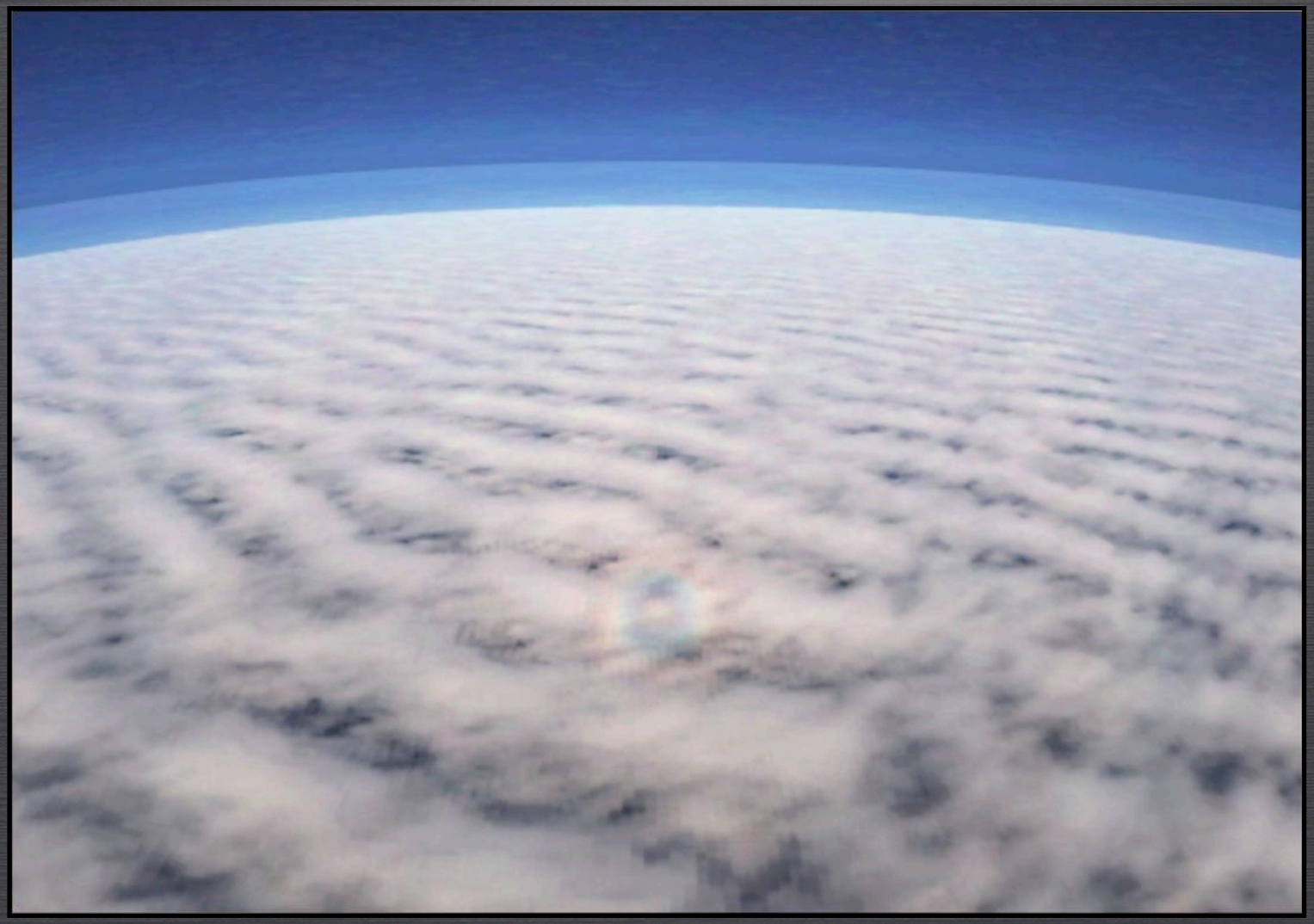
- Atmosphere (3-D)
  - Scattering/absorption by molecules, aerosols, & hydrometeors (cloud water, cloud ice, etc.)
  - Refraction/reflection due to air density changes
- Surface (2-D, macroscopically flat)
  - Mixed model of diffuse reflection and specular reflection: Roughness of surface facets can be variable (e.g., ocean waves are properly treated depending on wind velocity).



- Radiation sources
  - Distributed sources: Solar incidence, thermal emission
  - Localized sources: Laser beams, etc.
- Radiative transfer solvers
  - Fully 3-D
  - Partially 3-D (3-D for low-order scattering, while 1-D for high-order)
  - ICA (1-D for independent columns)
  - PPA (1-D for large-scale single column)

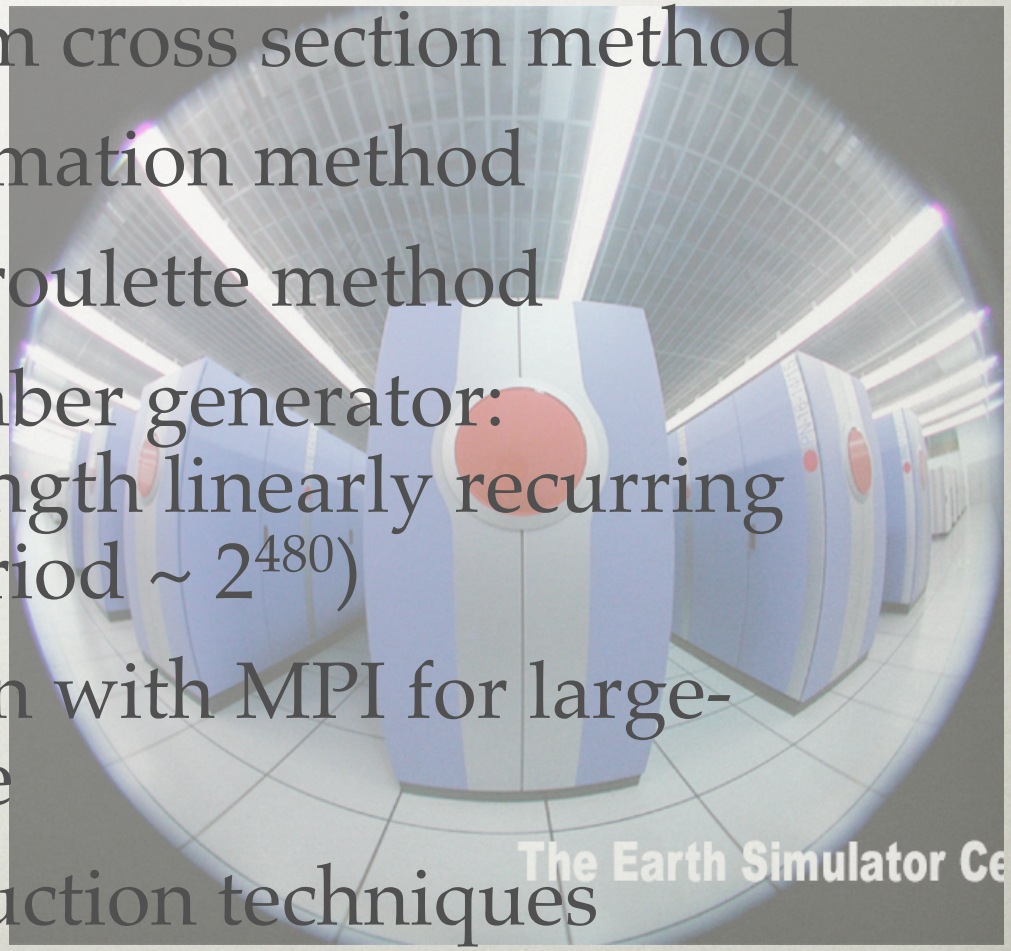
- Output
  - Radiative flux & heating rate
  - Area-averaged radiances at specific altitude
  - Angle-averaged radiances at specific location
  - Pathlength statistics (for DOAS modeling)
  - Lidar signal
- Applications
  - Radiation budget at cloud-resolving scale
  - Signal simulation for optical sensors
  - Validation of approximate radiation models





Used Methods & Techniques

- The maximum cross section method
- The local estimation method
- The Russian roulette method
- Random number generator: Maximum-length linearly recurring sequence (period ~ 2^{480})
- Parallelization with MPI for large-scale machine
- Variance reduction techniques

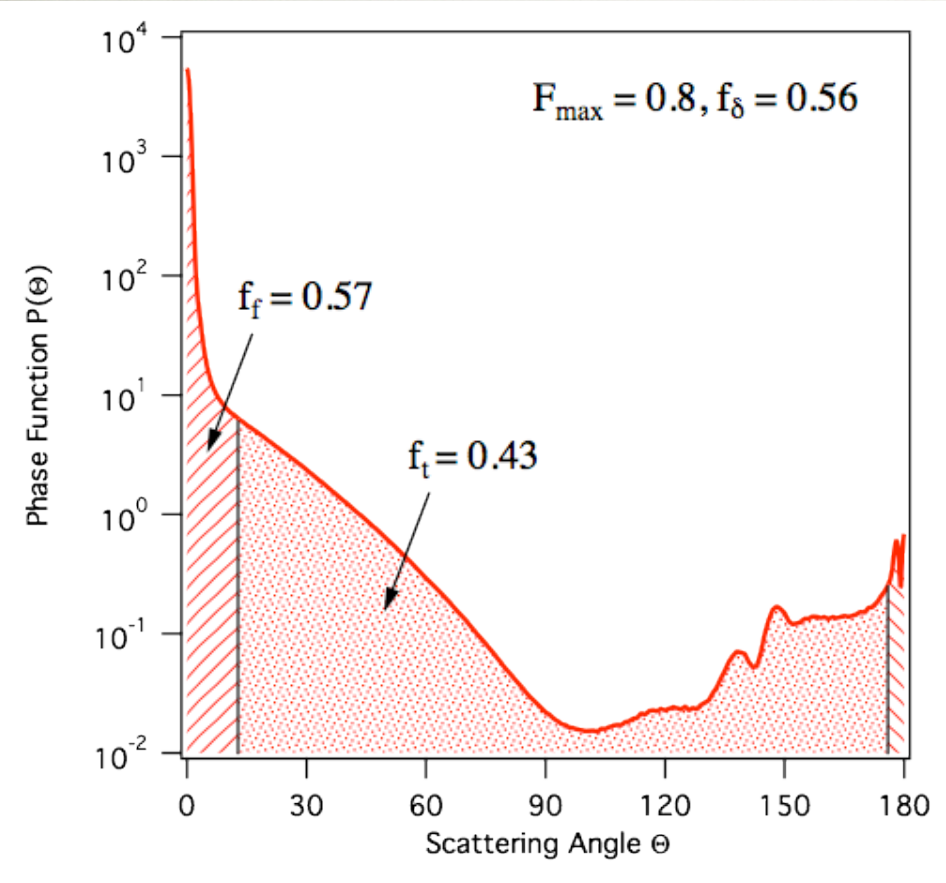


Variance Reduction Techniques

Problem 1: Phase Function Spikes

- Radiance computation is usually difficult for realistic Mie phase functions
- Significant noises due to rare sampling of diffraction peaks in the forward scattering direction (Barker et al., 2003)
- ---> The peak can be approximated by Dirac's delta function (truncation approximation)

Dual-end Truncation Approximation



$$Q(\Theta) = \rho_\Theta$$

$$\Rightarrow \quad Q(\Theta) = f_f + f_t \rho_\Theta$$

- Does not require additional computer memory for the truncated phase functions
- 1st and 2nd moments of modified phase function are equated as the originals

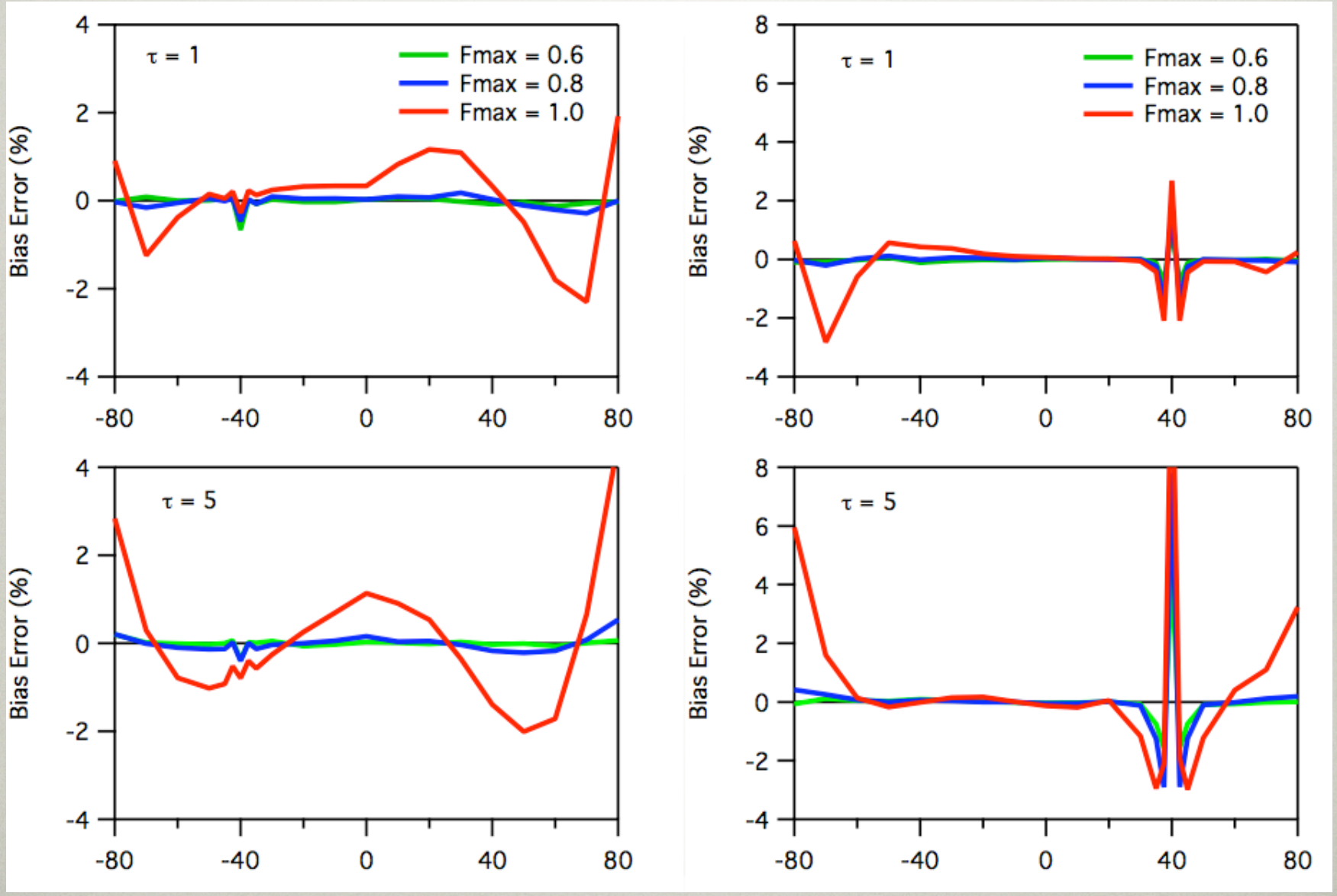
Delta Fraction

$$f_\delta(n+1) = F_{\max} G(P) H(\chi_n)$$

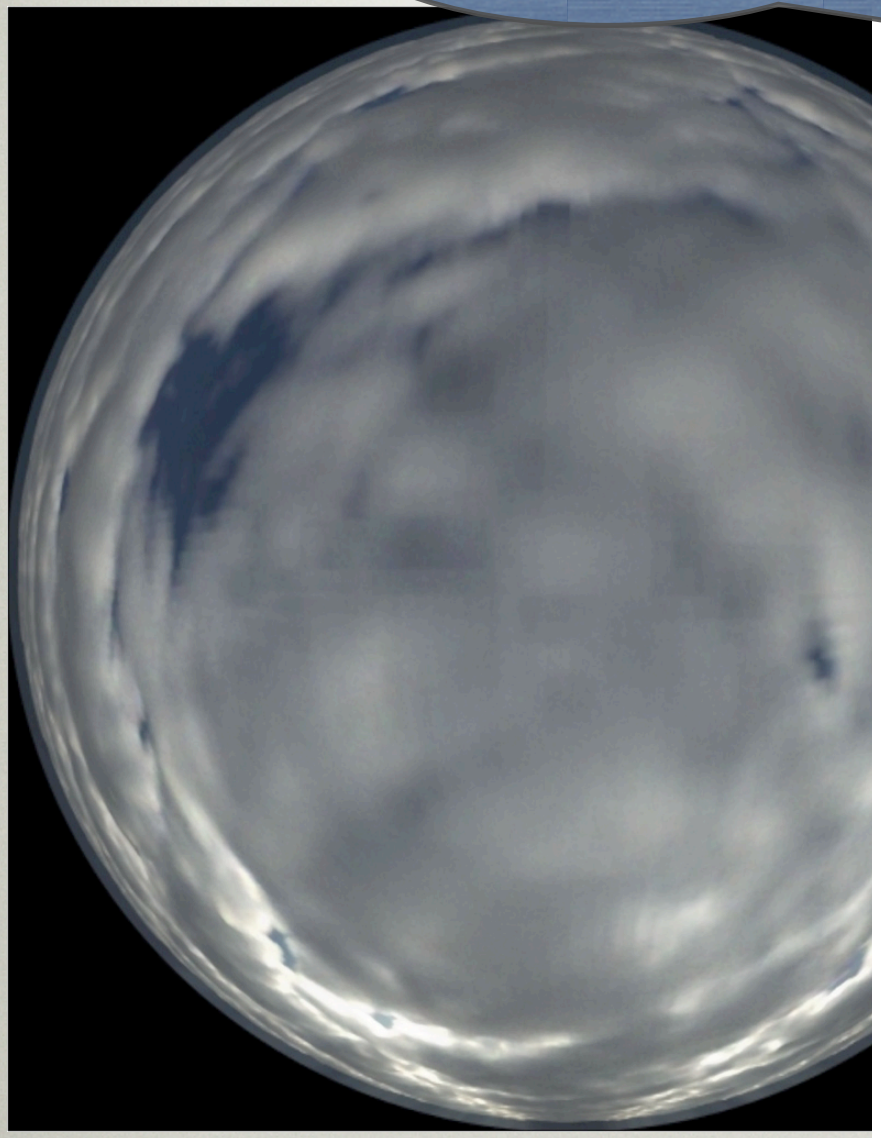
- $F_{\max}$ is a tuning parameter
- Large for sharply peaked $P(\Theta)$
- Set as null for solar direct beam
- Increases with decreasing directionality of light (high-order scattering)
- ---> High accuracy (very small bias)

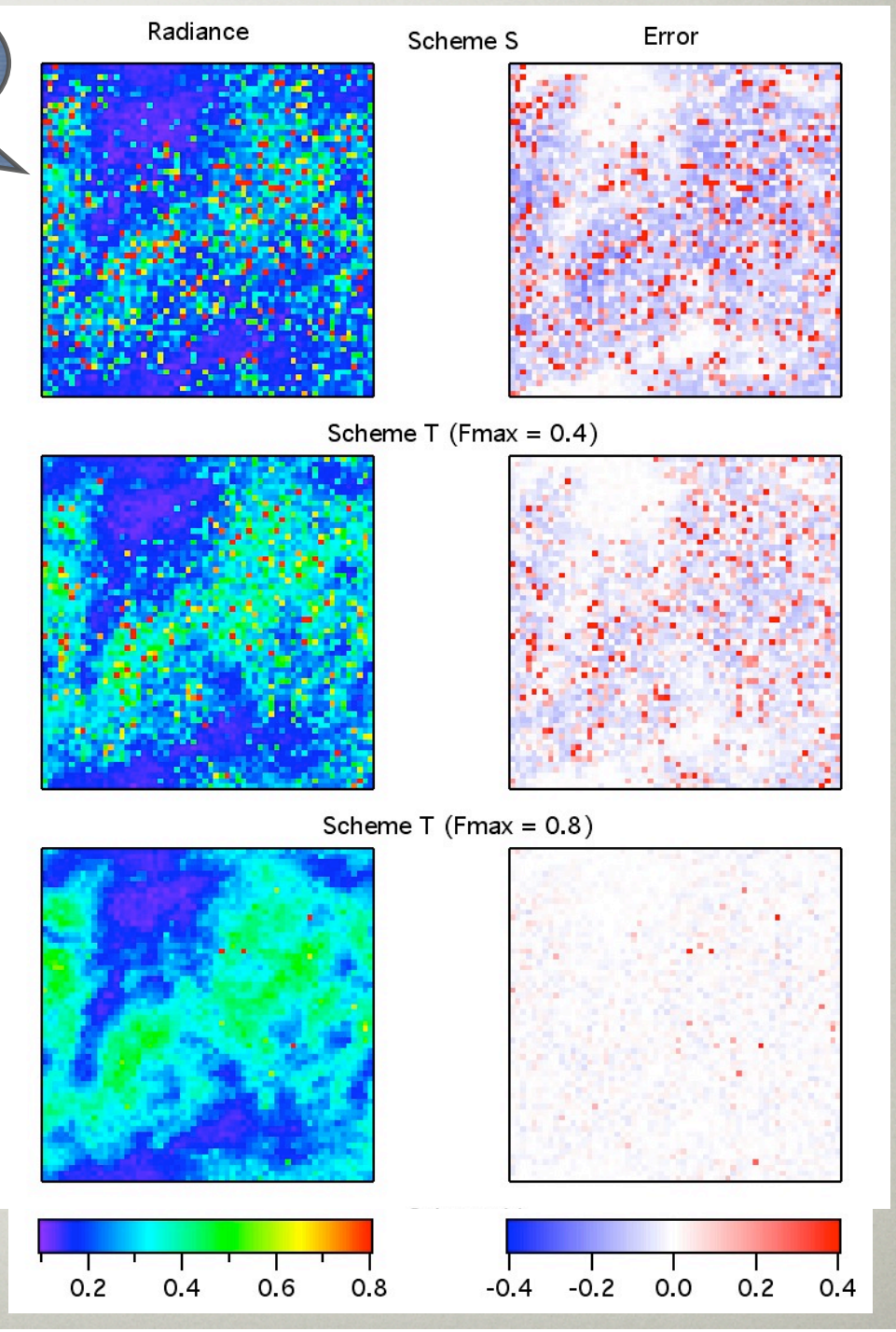
Upward Radiance

Downward Radiance



Ncol = 1000




Radiance
Scheme S
Error
Scheme T (Fmax = 0.4)
Scheme T (Fmax = 0.8)
0.2
0.4
0.6
0.8
-0.4
-0.2
0.0
0.2
0.4

Problem 2: Small ζ

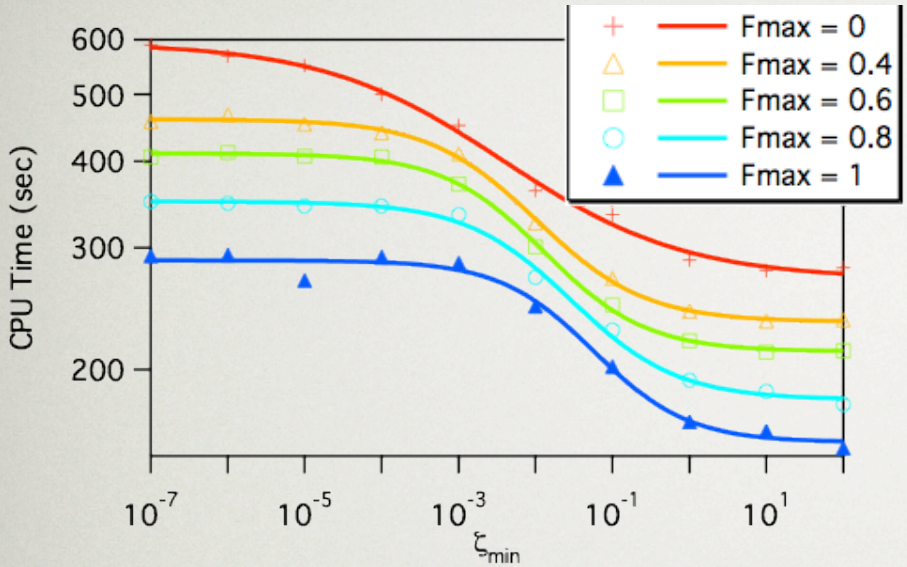
$$\zeta = \pi\Psi(\theta,\phi,\theta',\phi')T(\tau)$$

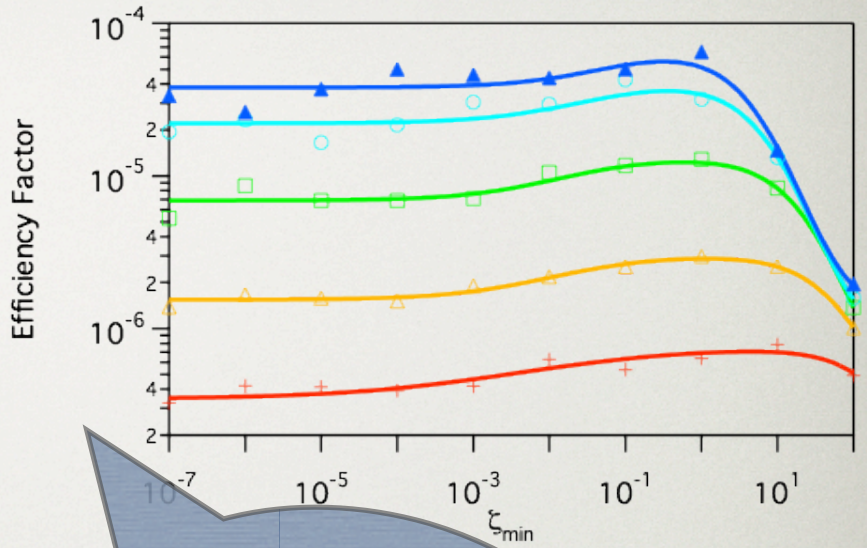
- Sampled energy ζ is often very small, despite that their contribution to total radiance is small (Barker et al., 2003)
- Ray tracing for small ζ is inefficient use of CPU time

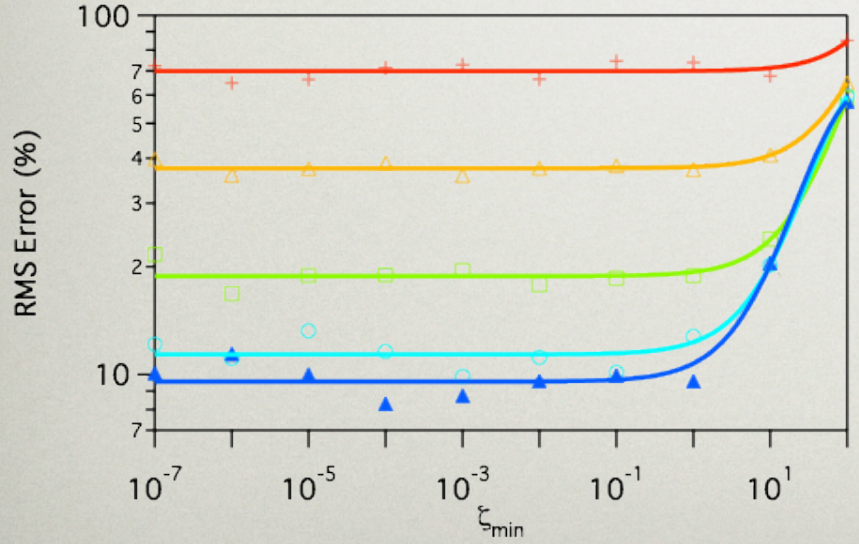
Unbiased Modification of the Local Estimate

- Sampled ζ is modified to $\zeta' = 0$ or a value > threshold (ζ_{min}) according to Monte Carlo manner (using random numbers)
- Ray tracing can be immediately terminated when $\zeta' = 0$; This case is frequently seen when Ψ is small or partially-integrated τ exceeds a limit.
- This method
  the threshold
  reduction

$$\zeta = \pi\Psi(\theta,\phi,\theta',\phi')T(\tau)$$







$$\text{Efficiency} = 1/\left(\varepsilon^2 T\right)$$

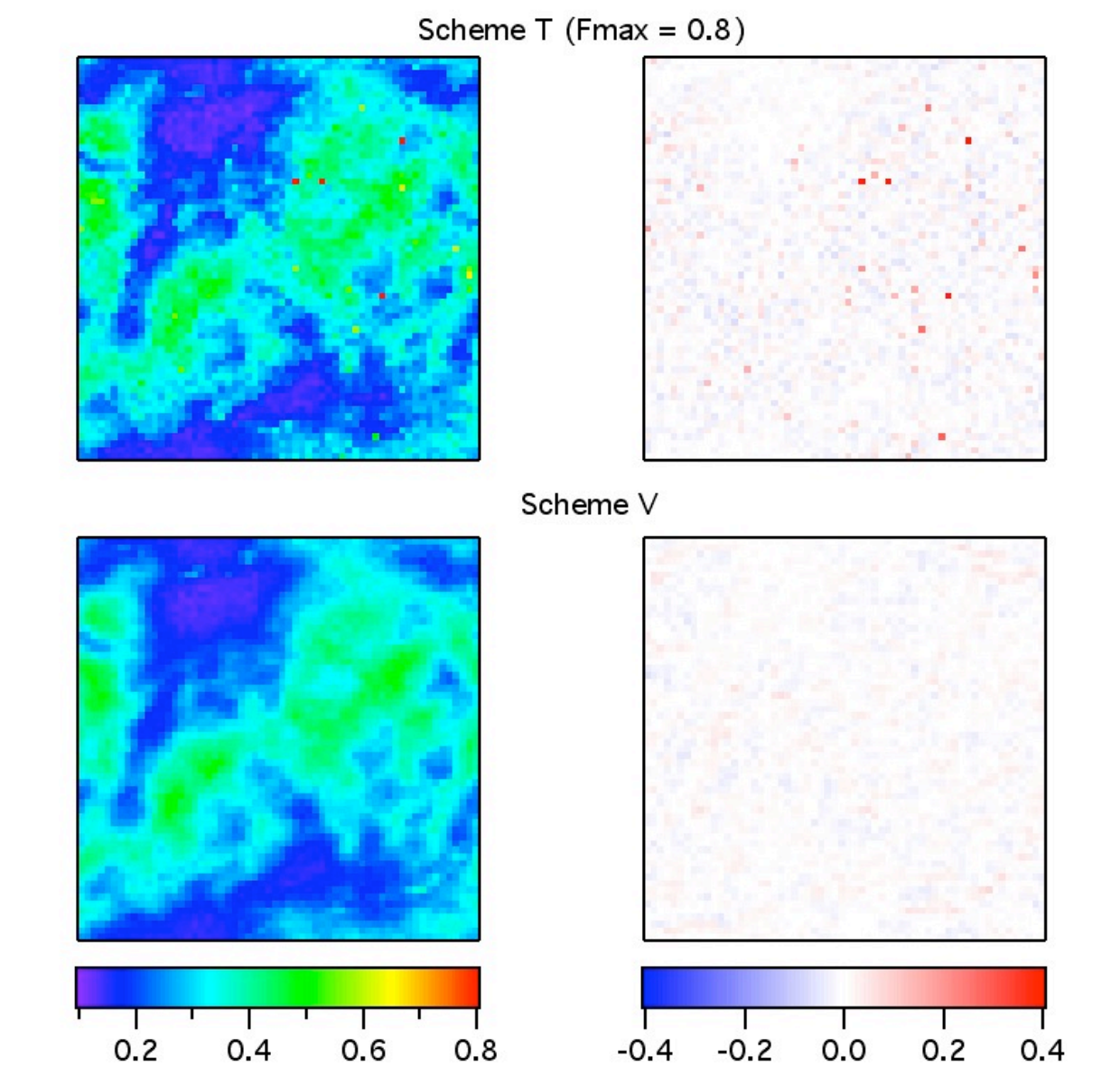
Problem 3: Optically-Thin Media

- Collisions are rare in optically-thin media
- ---> Collision-forcing method; We can force virtual collisions by increasing extinction coefficients (scaling transformation according to the similarity relations)
- Can be used where it is needed (cloud-free regions, cloud edges, or only for first-order collision)

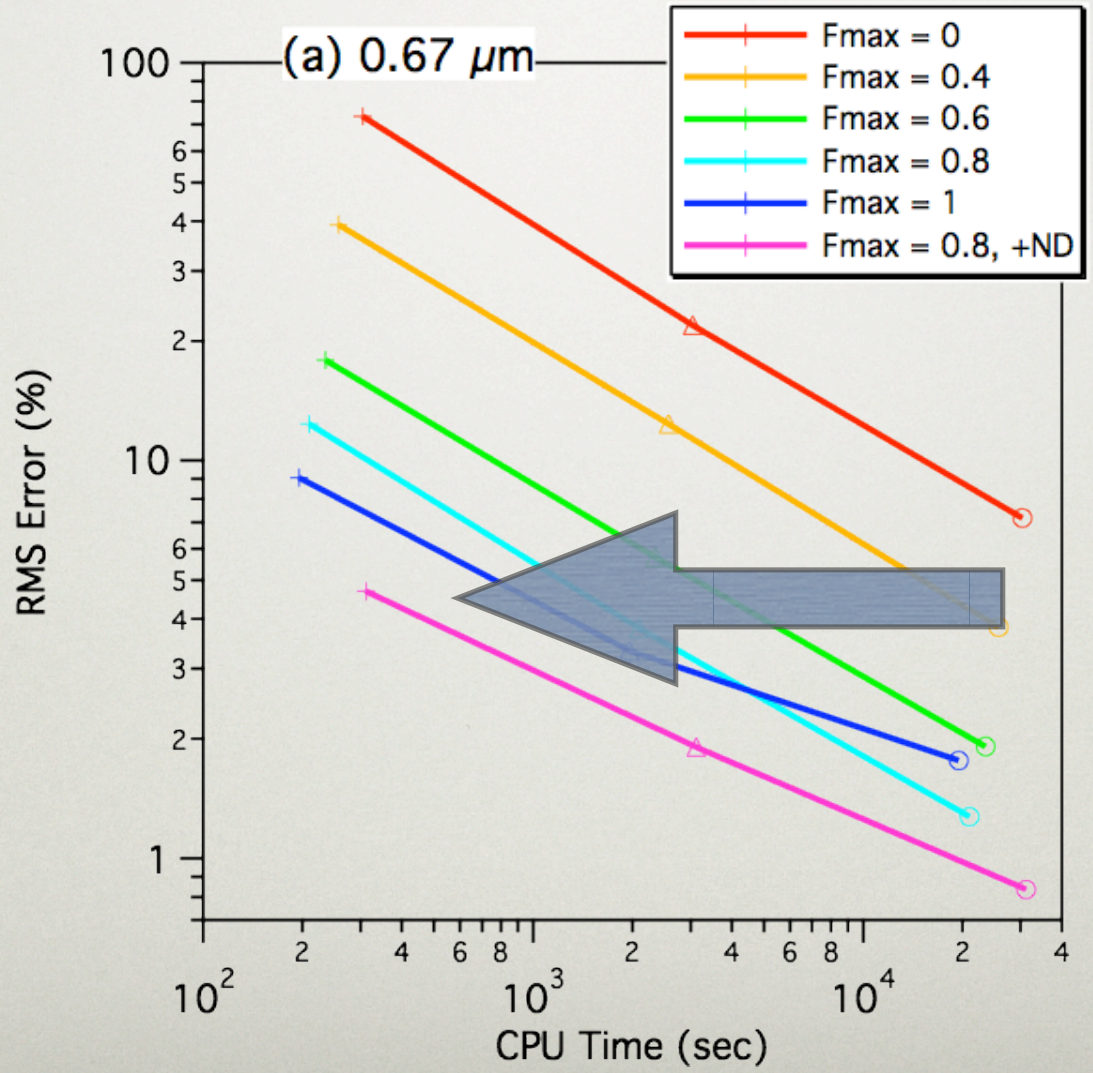
Numerical Diffusion

- Each sampled energy is simply distributed in horizontal area around the photon location (Note: Actual trajectory is not altered)
- The diffusion area is determined by number of incident photon packets, sampled weight, directionality of photon packet, etc.
- (Physically) diffusive light ---> more artificial smoothing

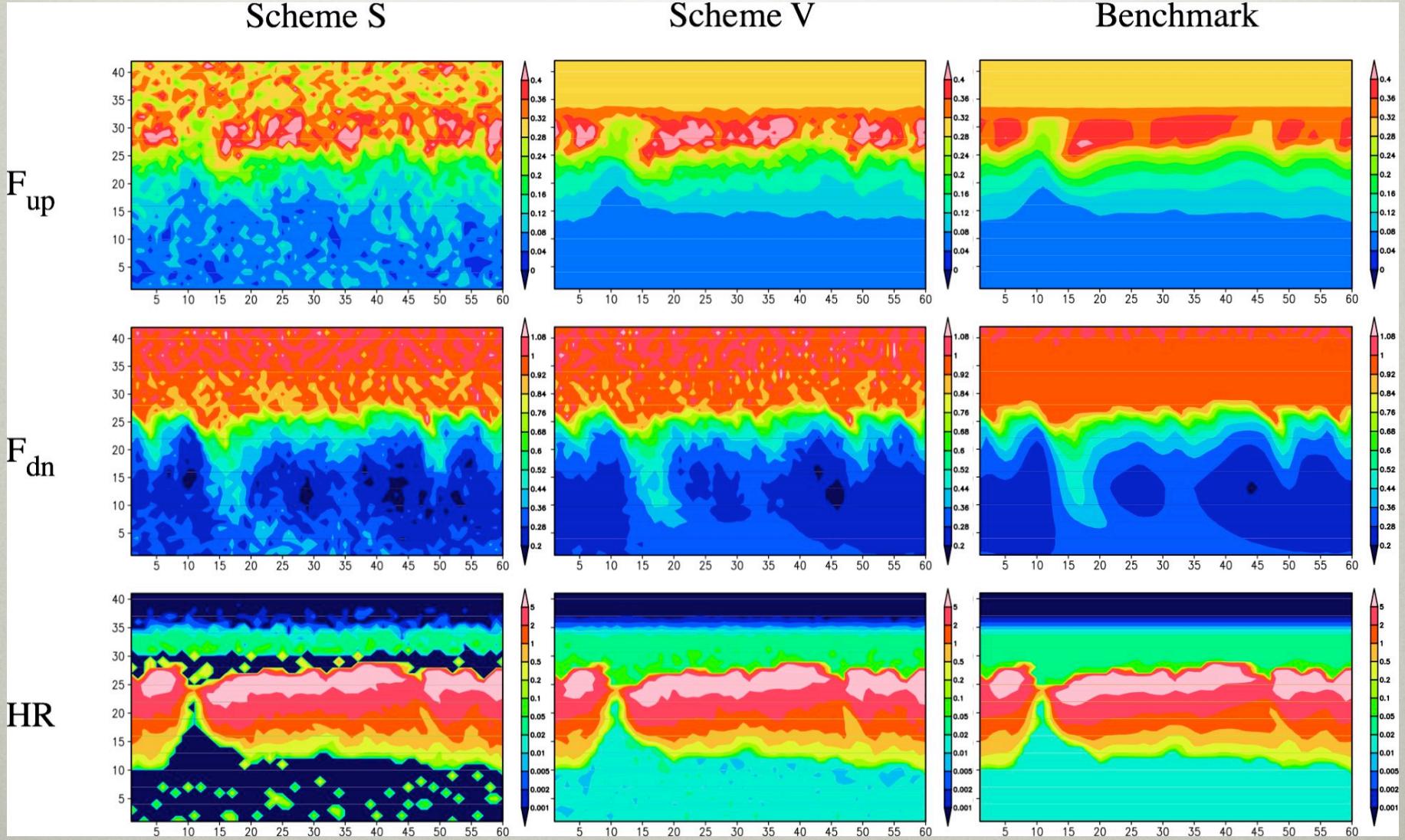
Radiance Error

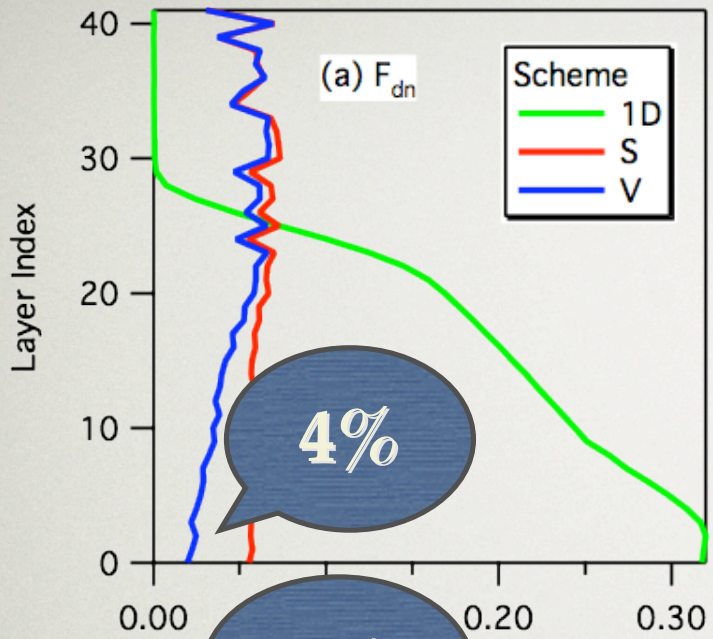


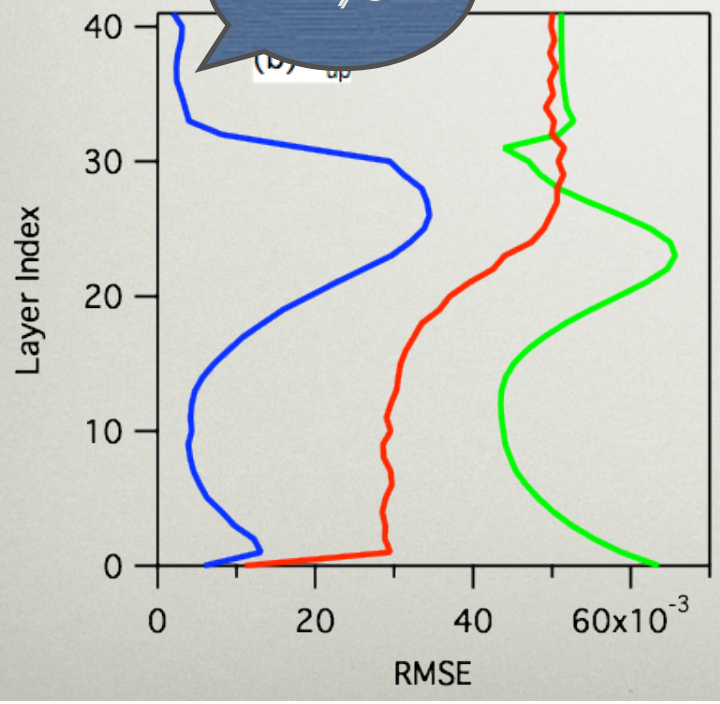
Performance improvements: Radiance

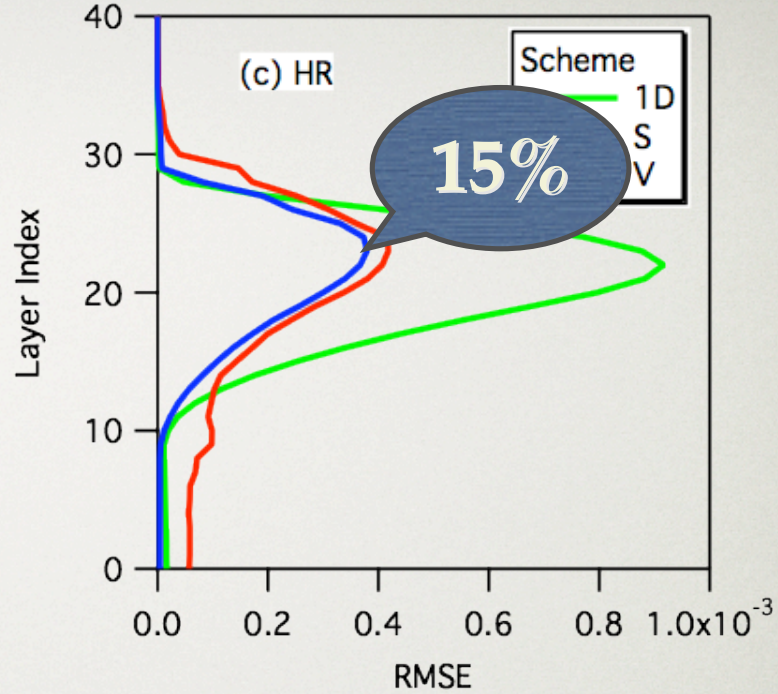


Flux & Heating Rate (N_{COL}=100)









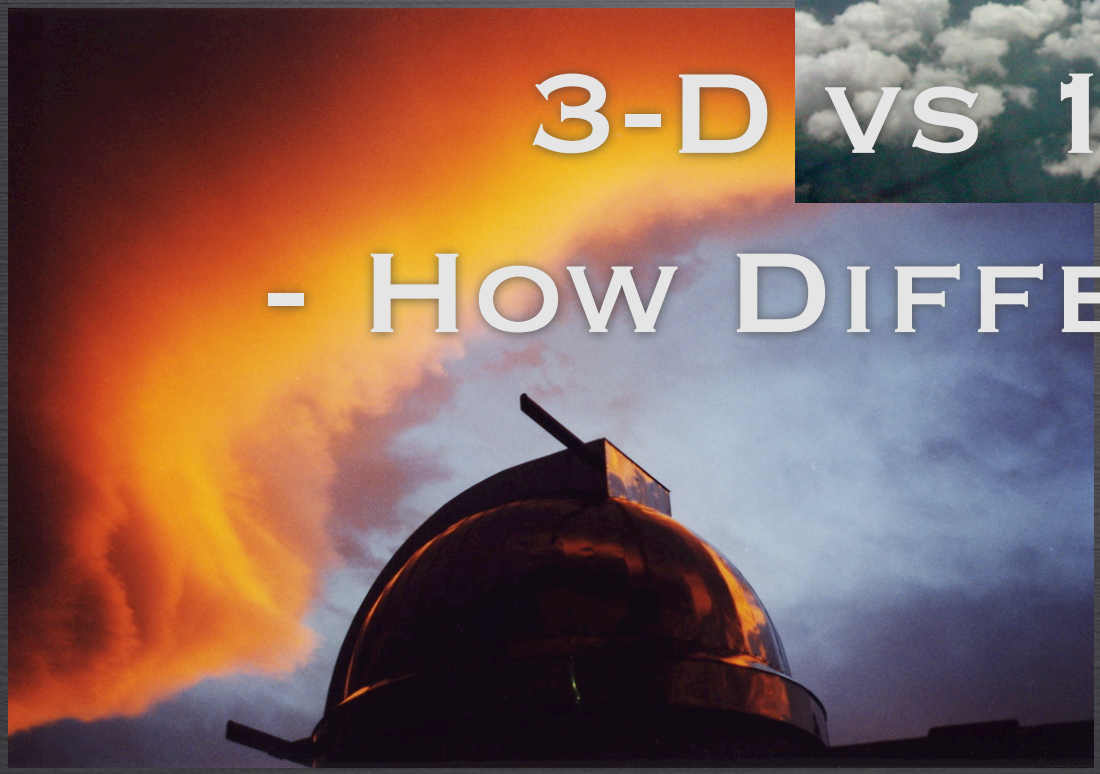
* Ncol = 100 is enough to obtain higher accuracy than 1D scheme!

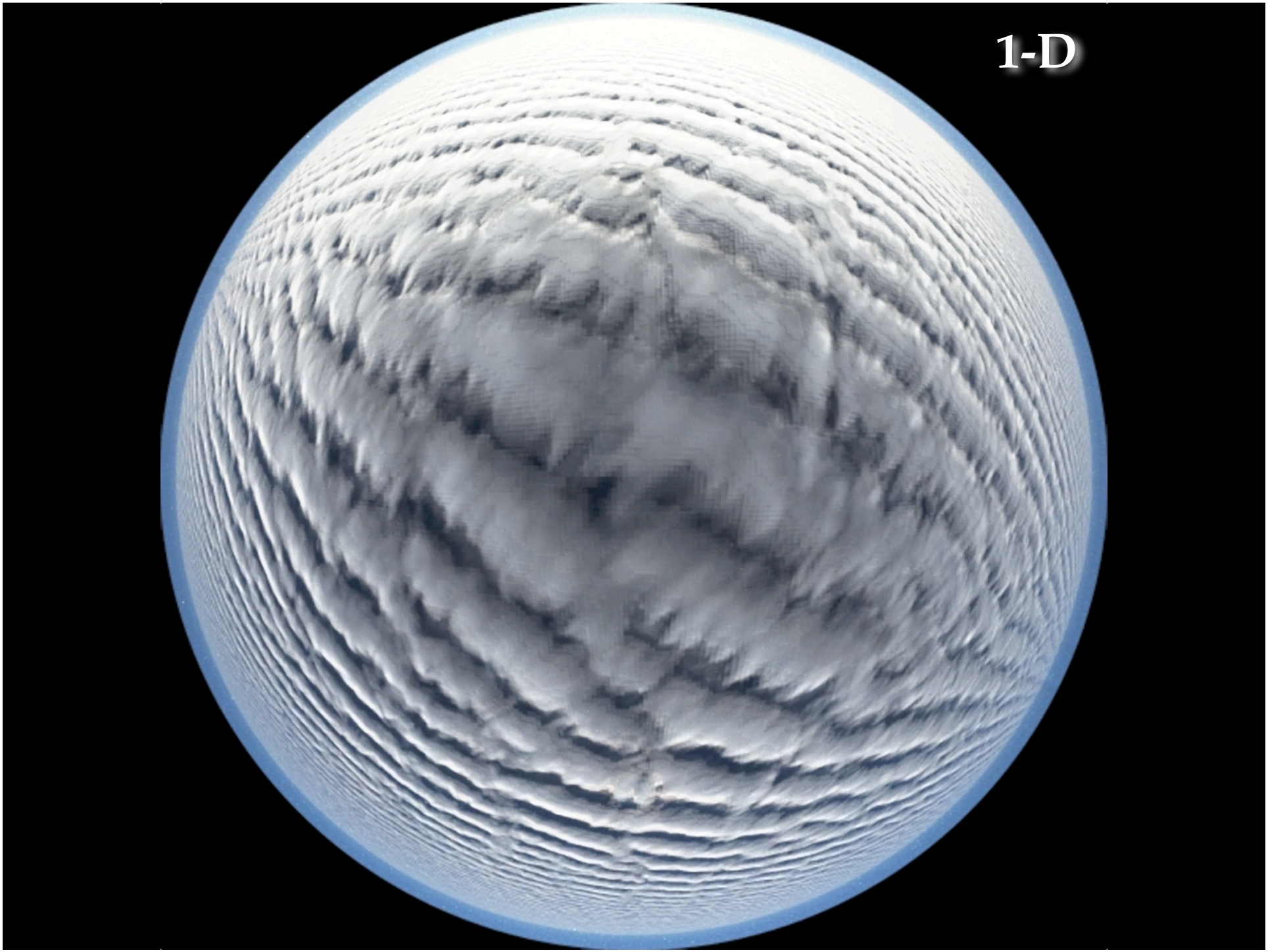
* Note that two-term 1D approximation can have bias of about 10% even for plane-parallel cloud!

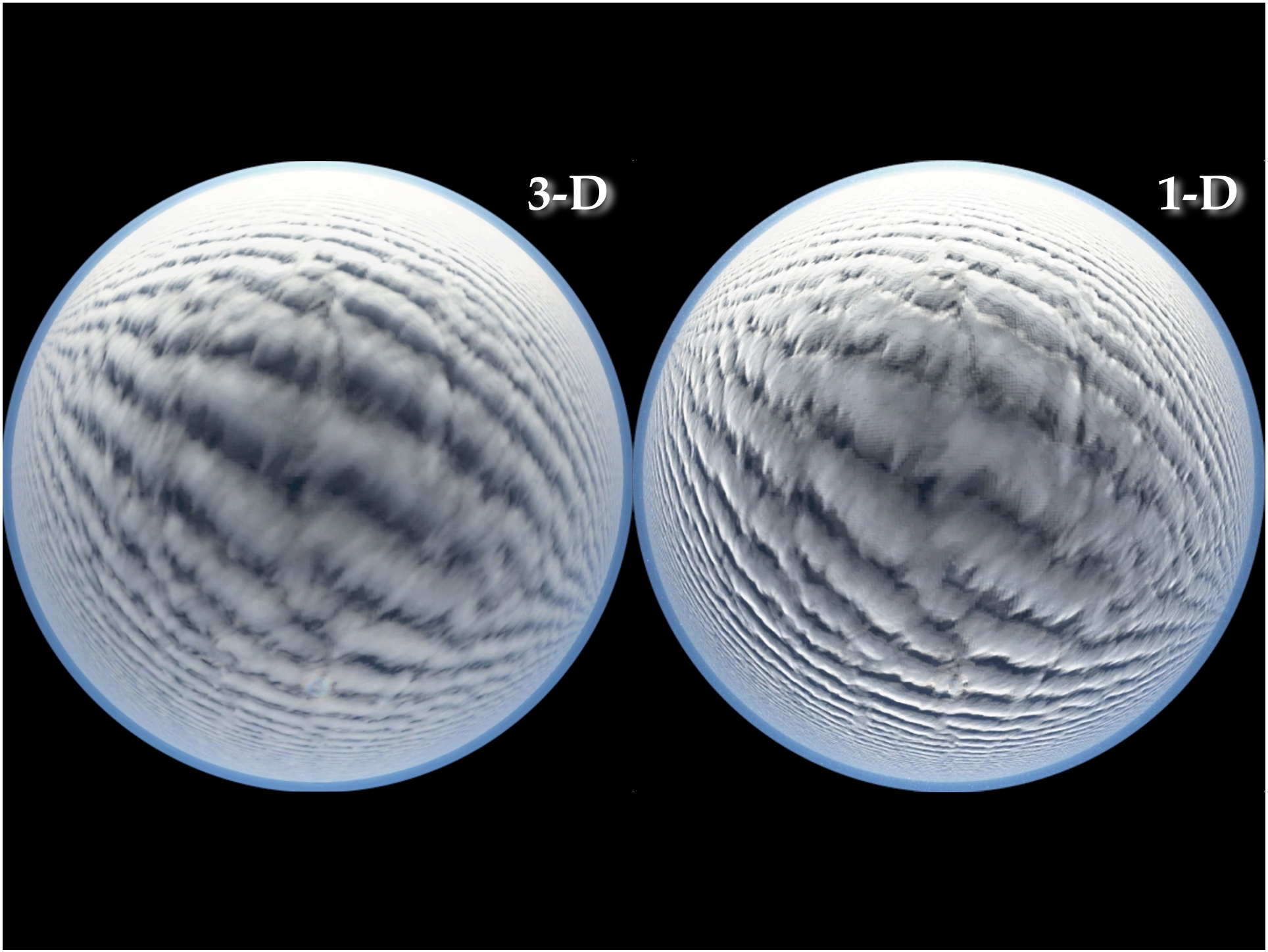
Variance Reduction Techniques

1. Truncation approximations for sharply-peaked phase function
2. Modification of local estimate
3. Collision-forcing method for optically-thin media
4. Numerical diffusion

A Small Topic:
3-D vs 1-D
- How Different?

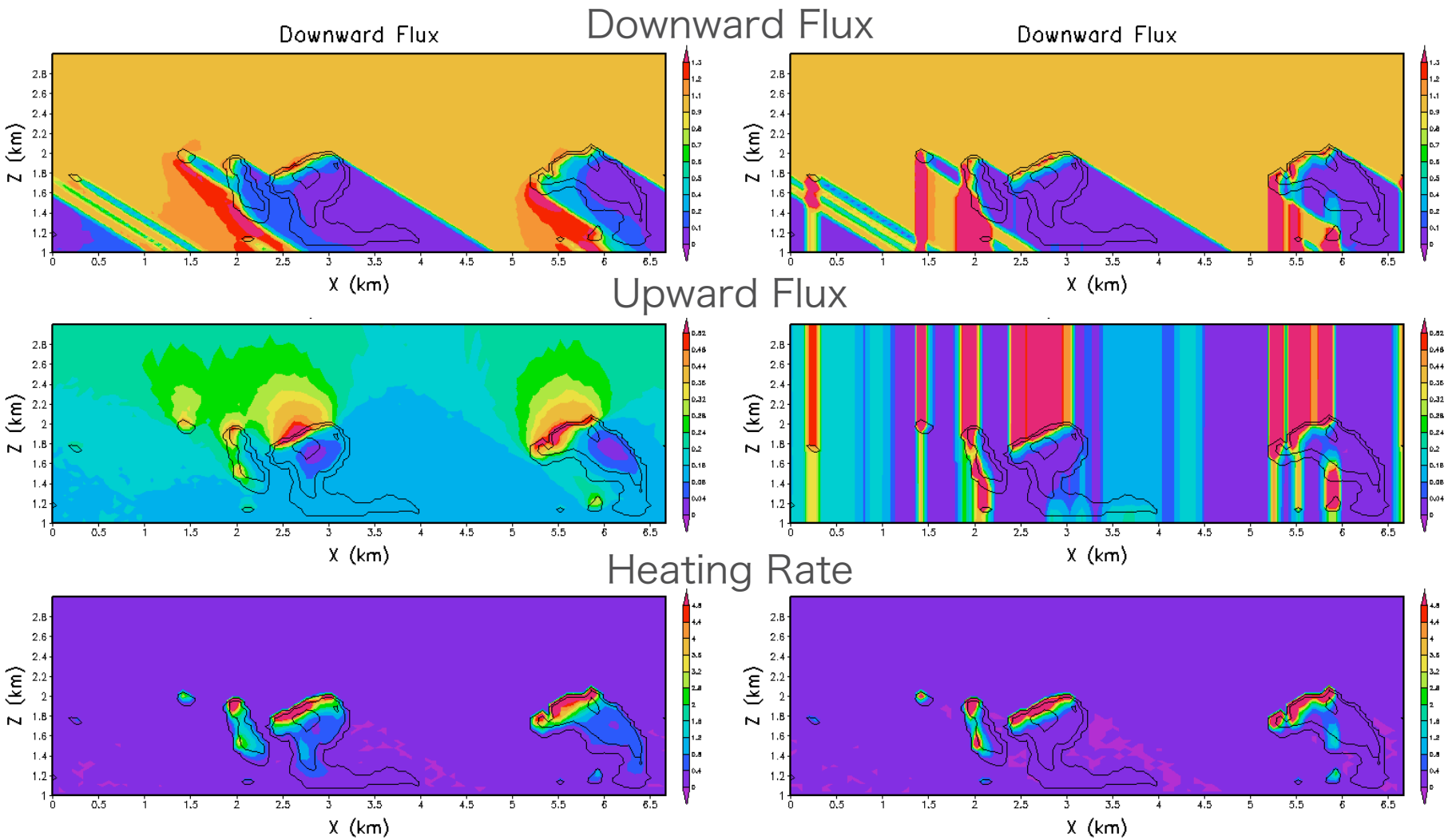



1-D


3-D
1-D

Fully 3-D

Partially 3-D



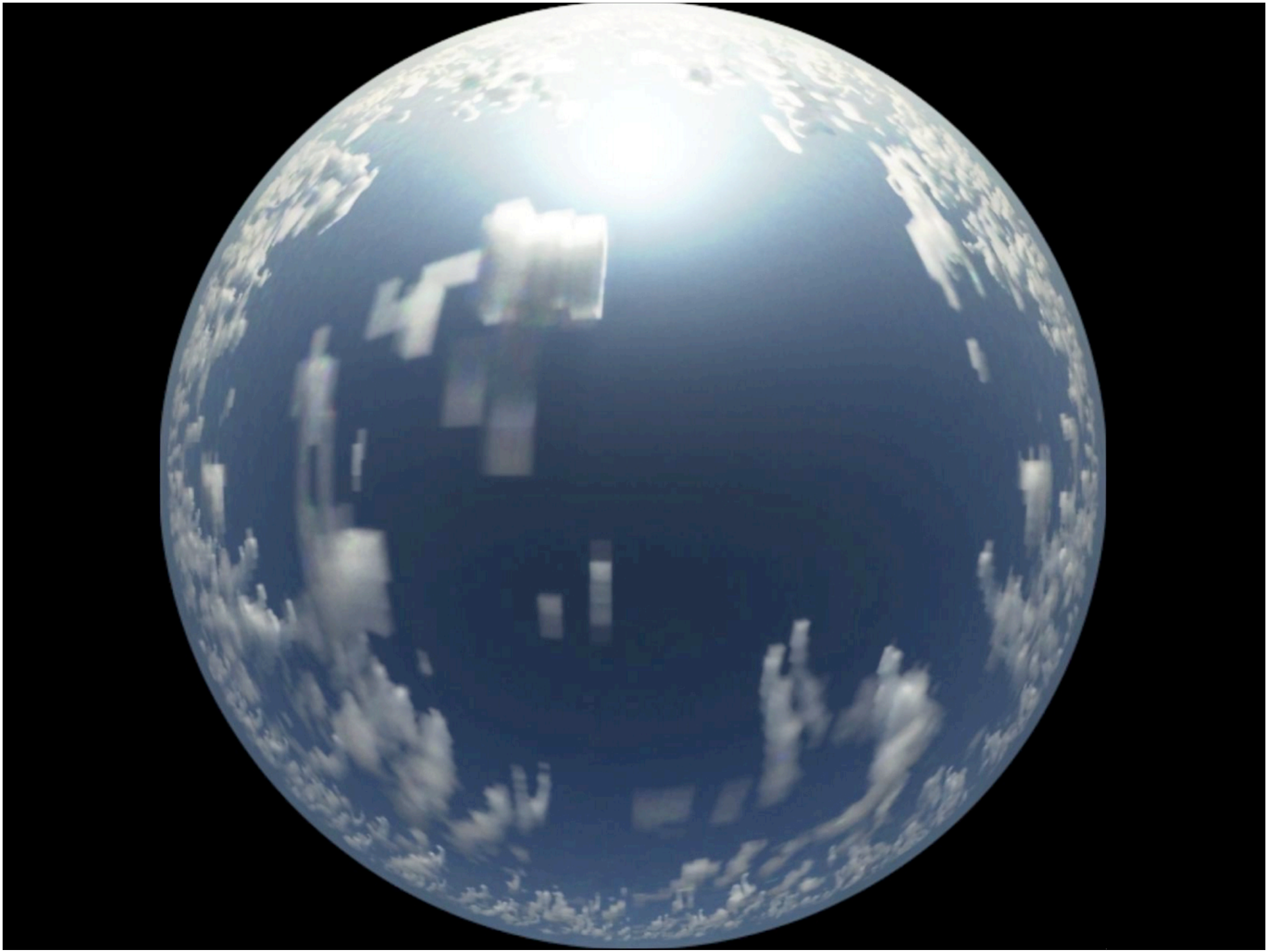
Conclusions

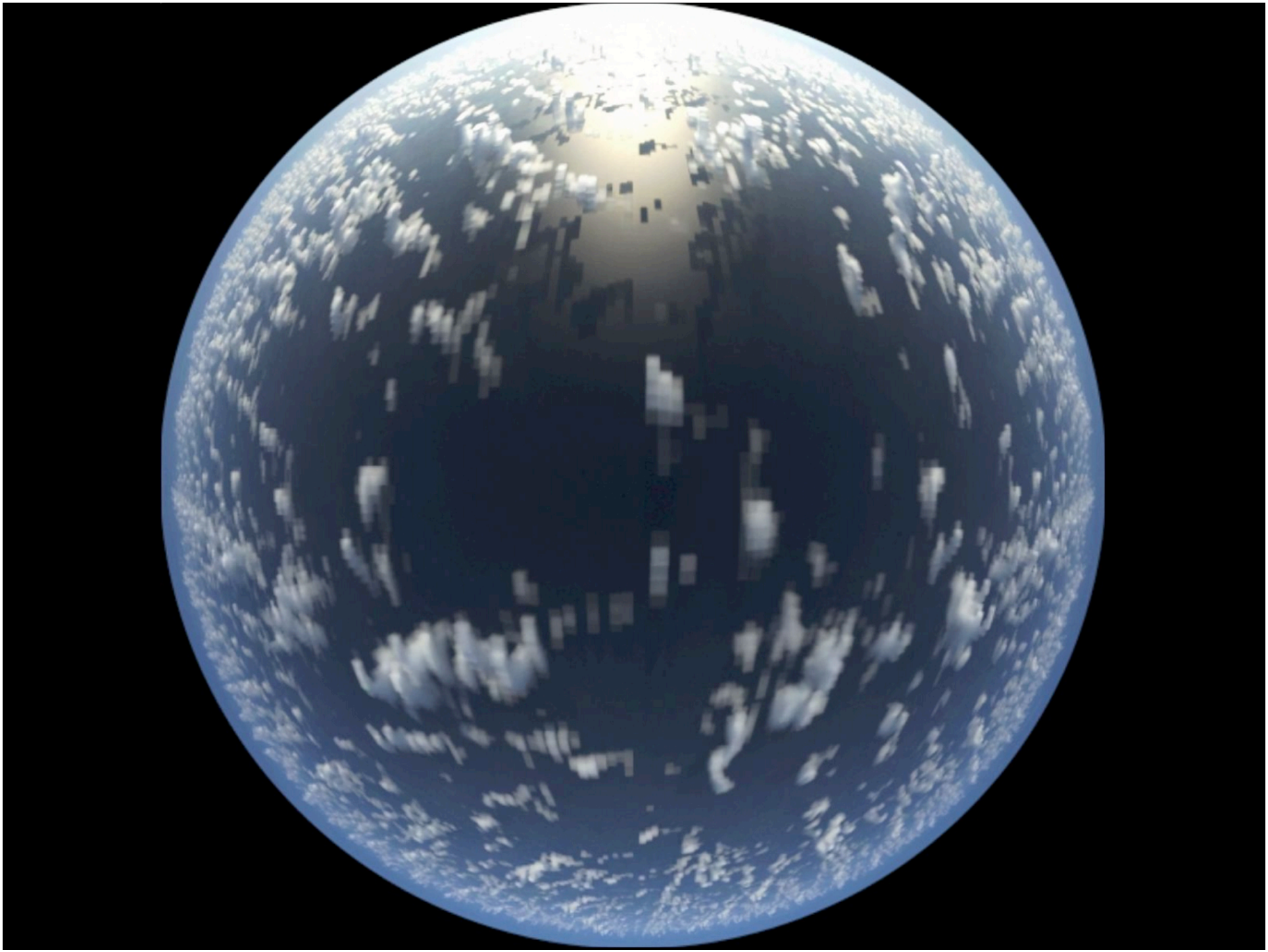
- Development of an advanced 3-D radiation model is in progress. Coupling with cloud-resolving models will be feasible in the near future, so that realistic radiation processes can be simulated.
- The 3-D radiative transfer is quite different from 1-D transfer.

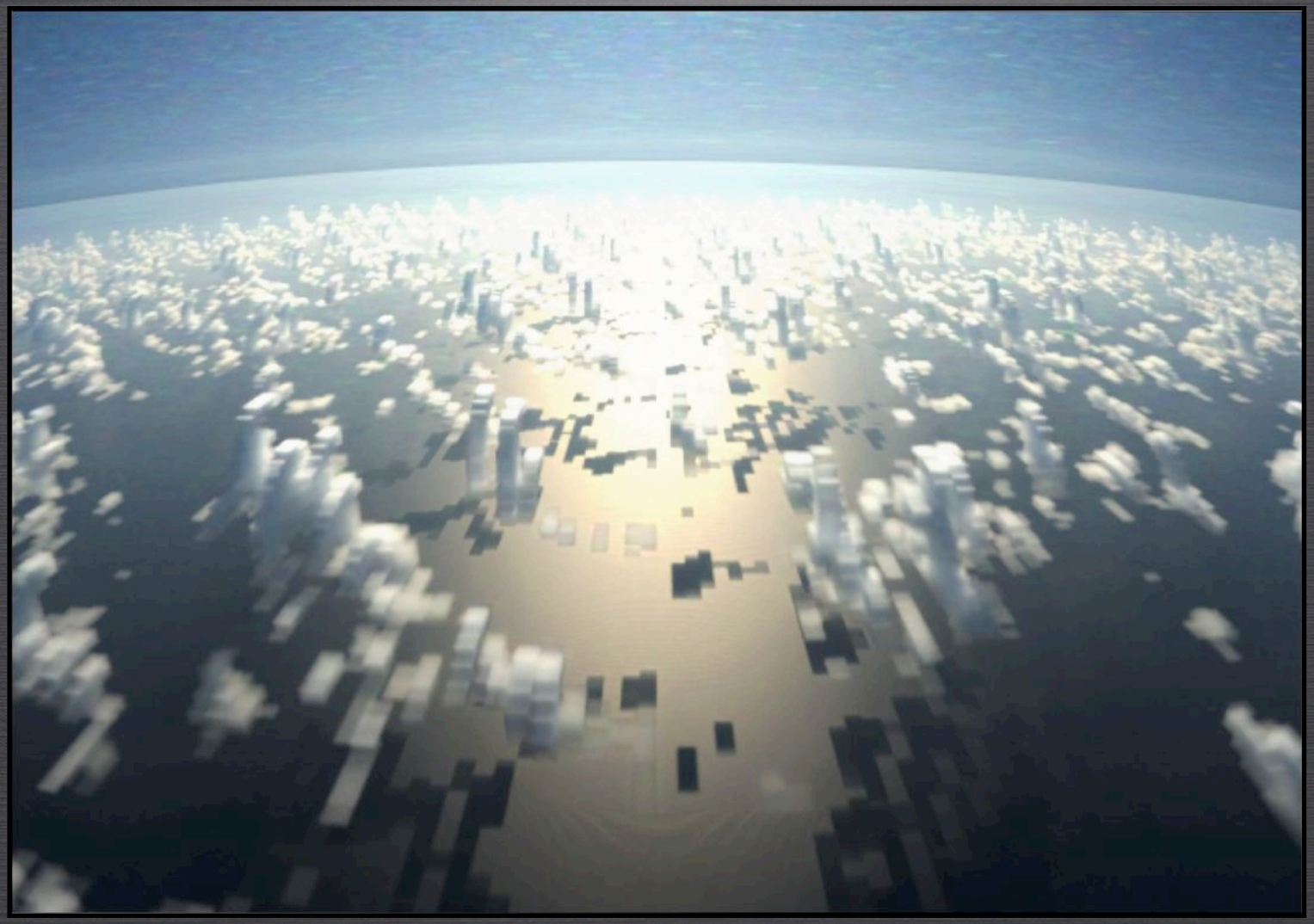
Future Works

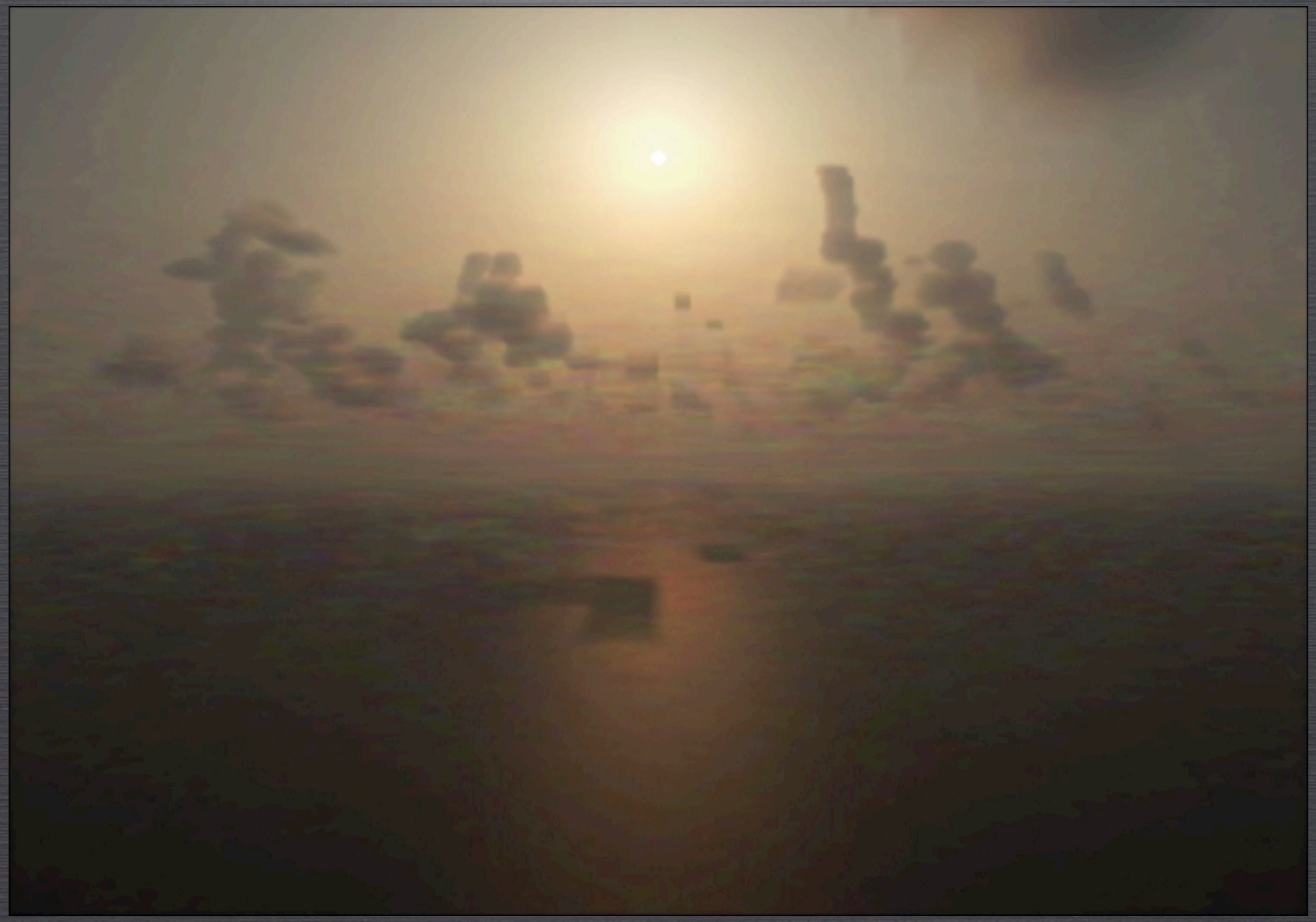
- Coupling 3DRT code with cloud-resolving model
- More realistic land and ocean processes
  - BRDFs of vegetation/city canopy, ice sheet
  - RT in water & ice
  - Terrain; rough surface

Appendix 1:
Virtual Skies
-Slideshow-



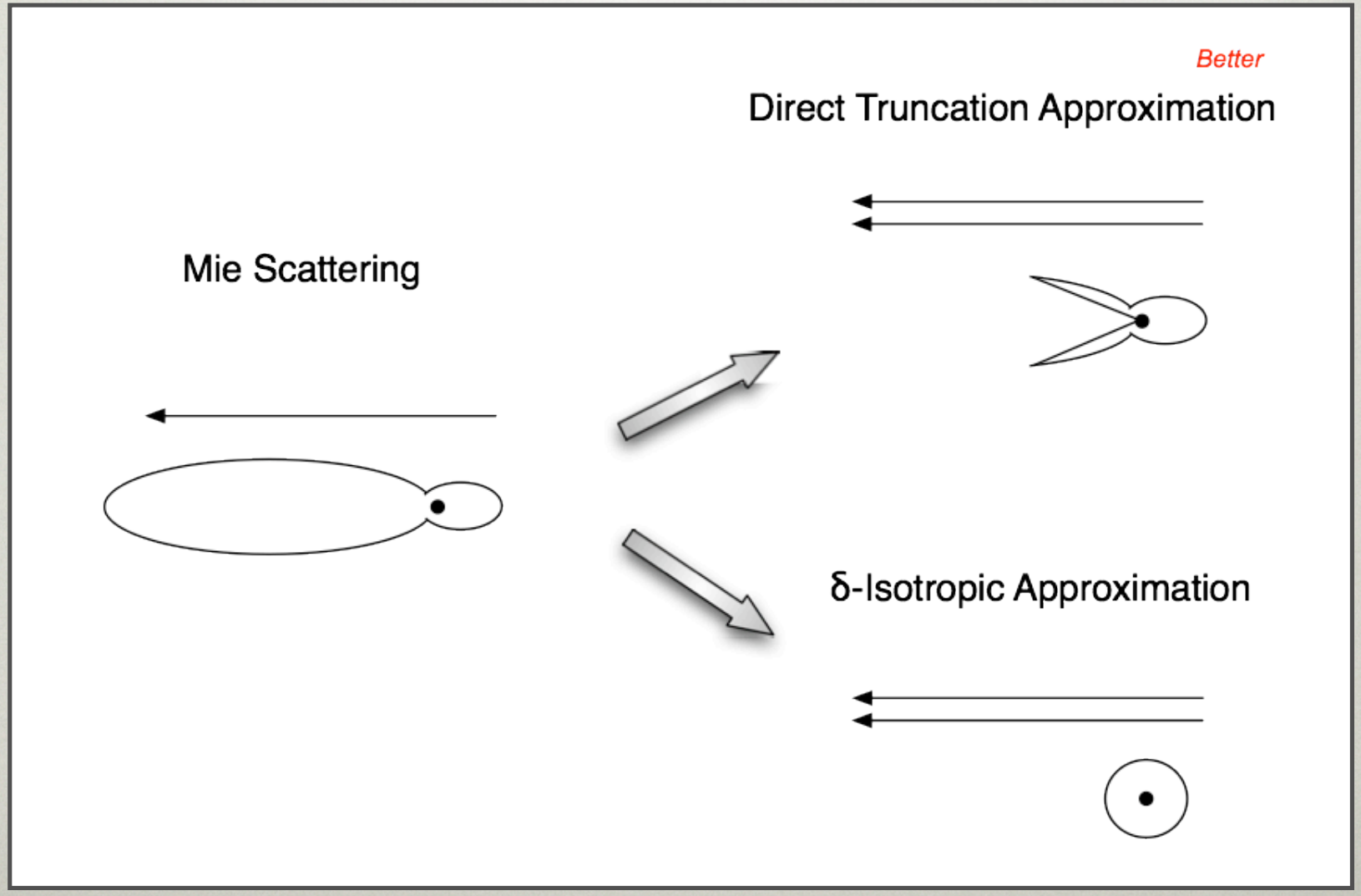




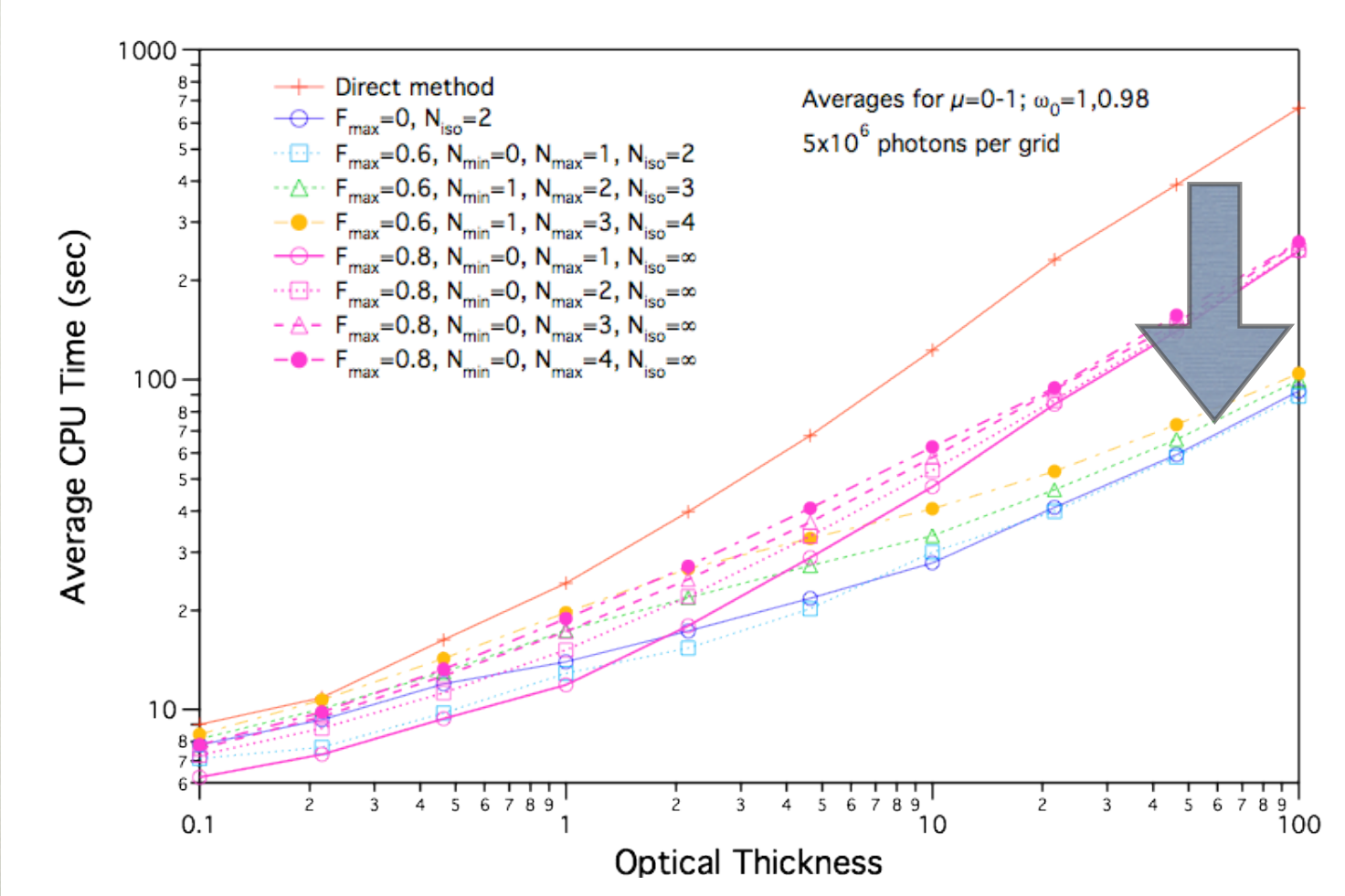


Appendix 2

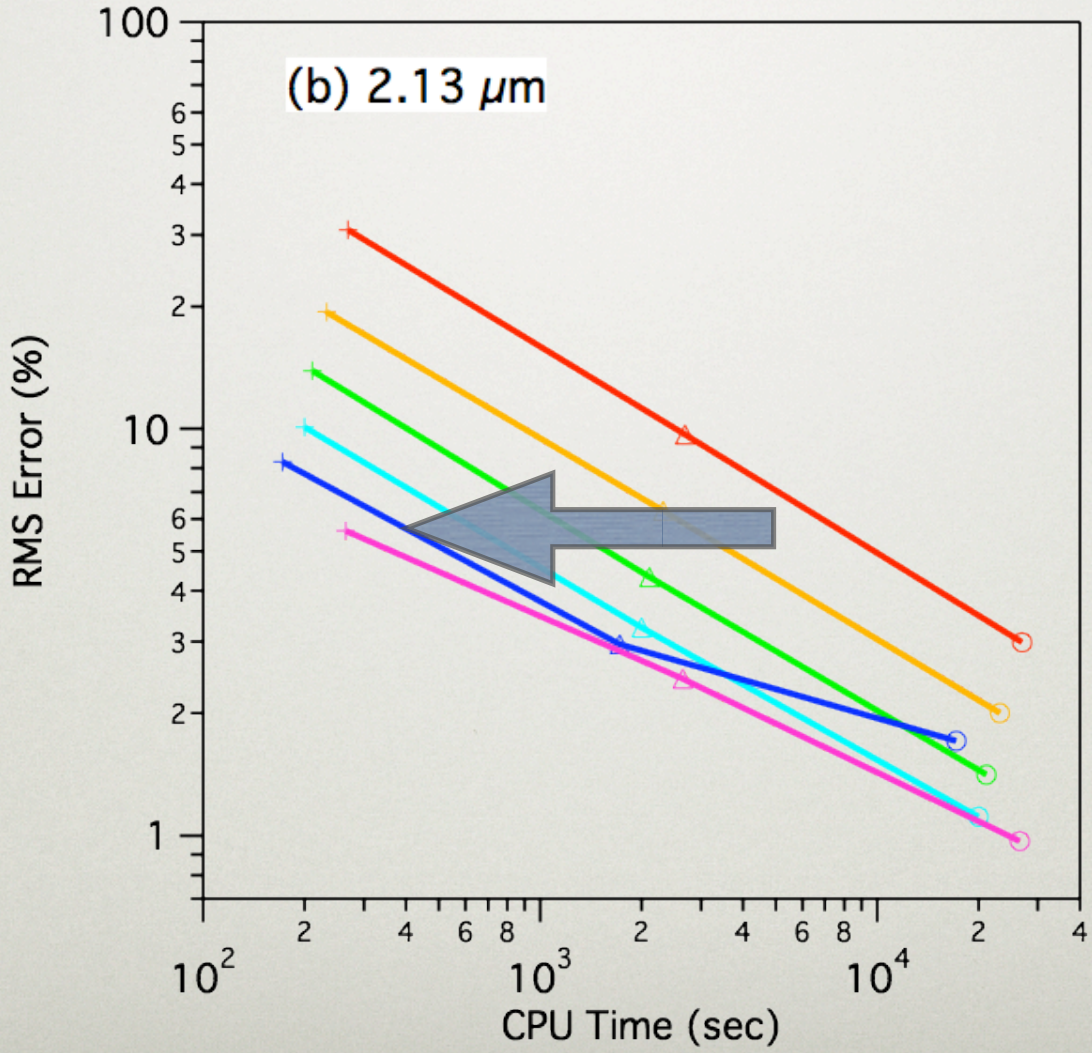
Truncation approximations of scattering phase functions

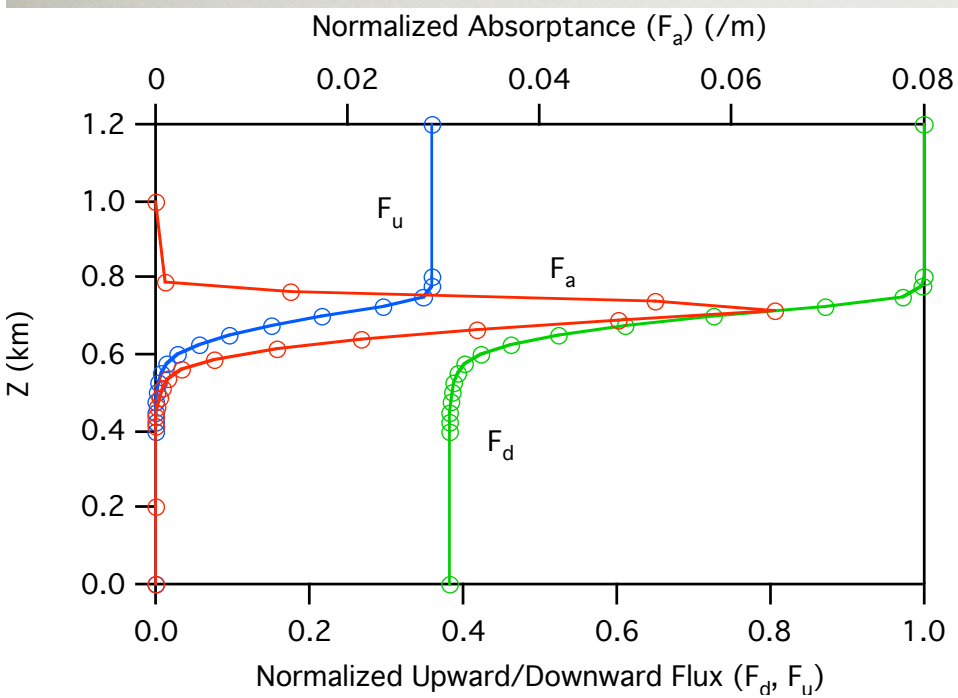


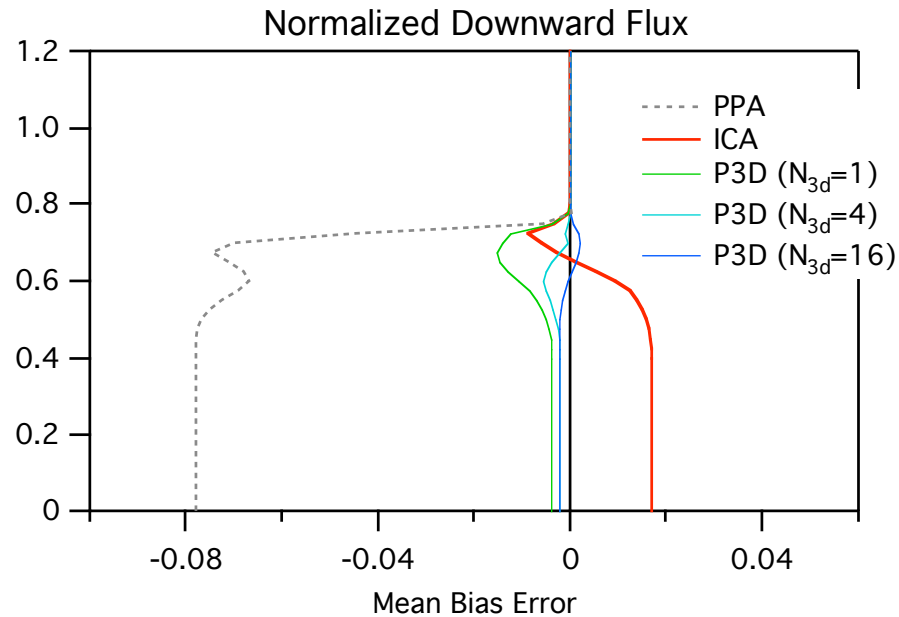
CPU time reduction by the truncation approximations

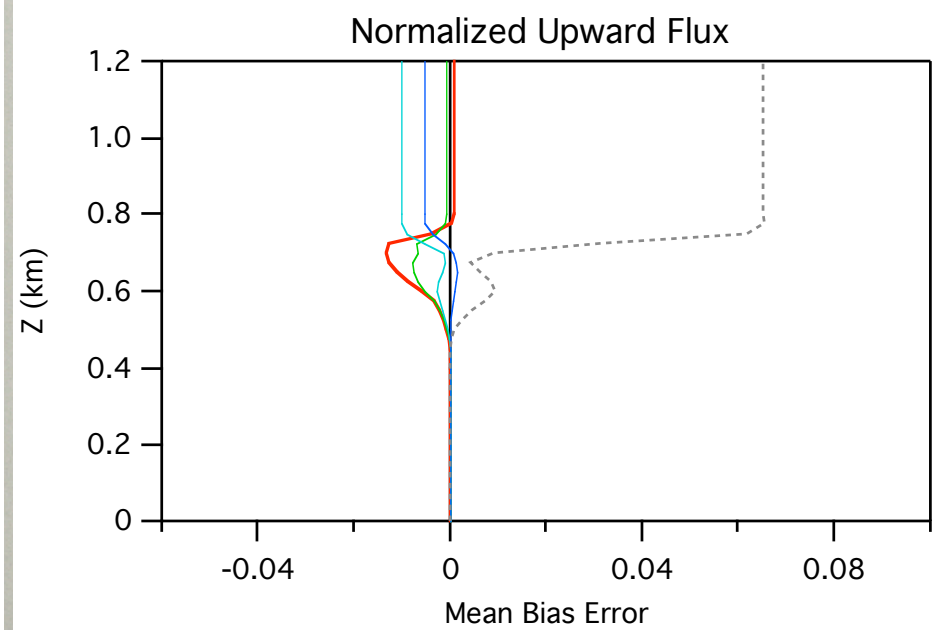


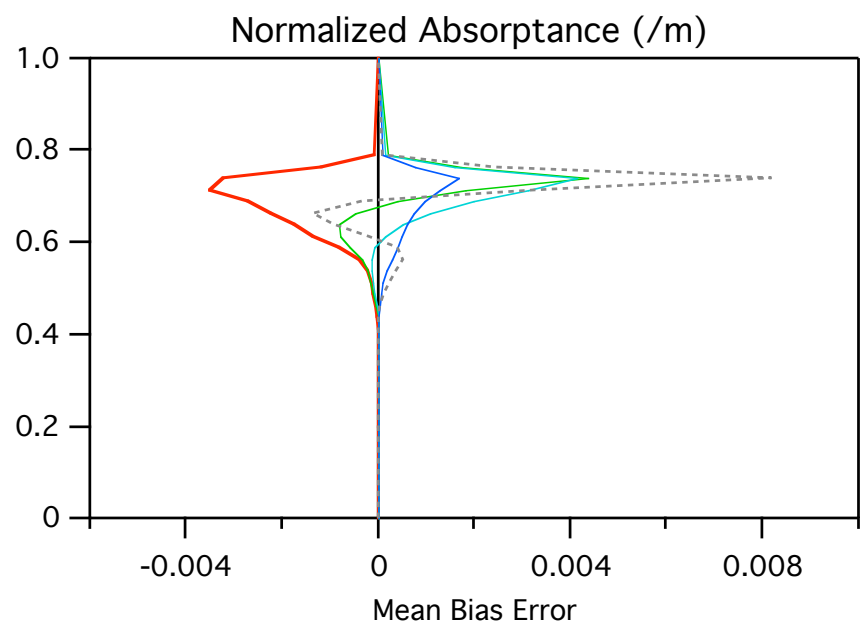
Performance improvements: Radiance

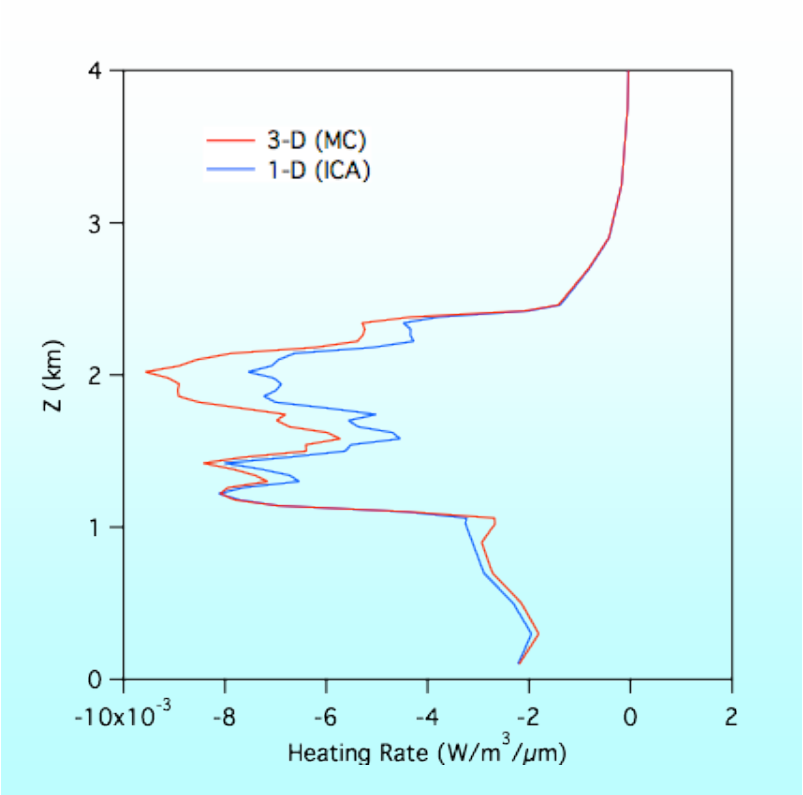


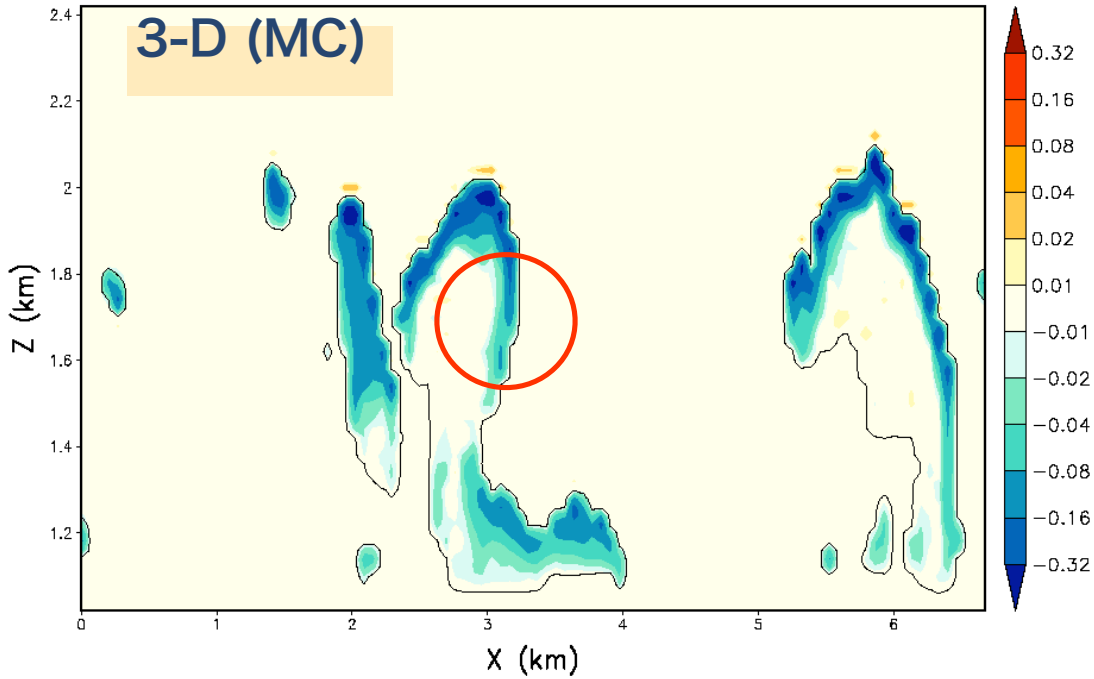

Normalized Absorptance (F_a) (/m)
0
0.02
0.04
0.06
0.08
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Z (km)
F_u
F_a
F_d
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Upward/Downward Flux (F_d, F_u)

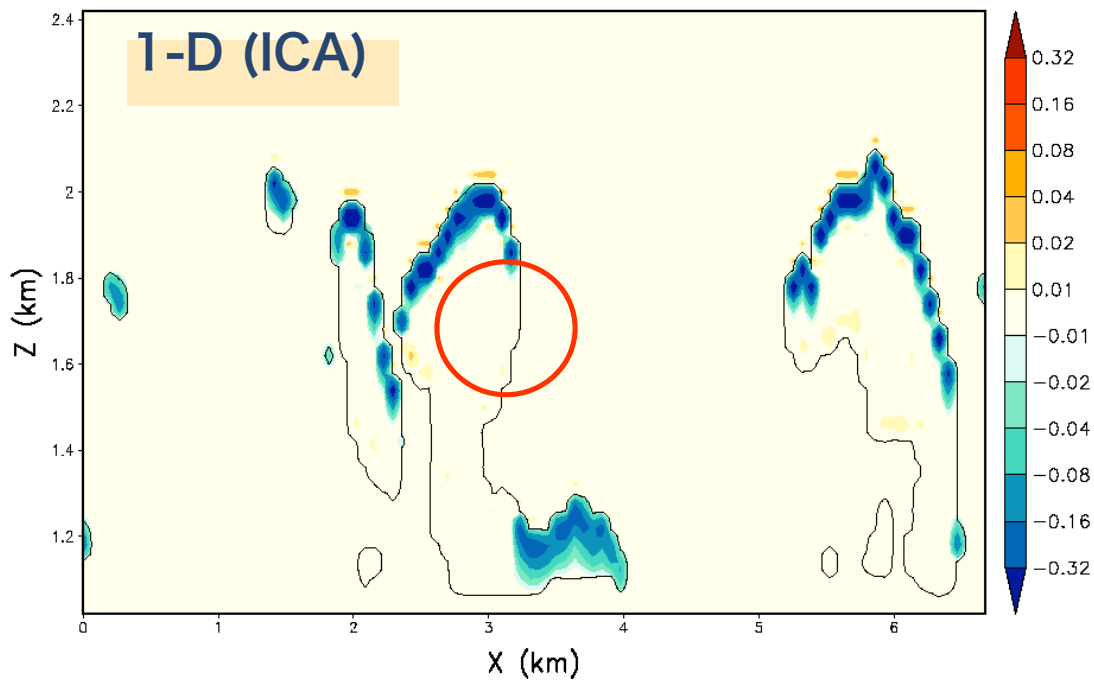

Normalized Downward Flux
1.2
1.0
0.8
0.6
0.4
0.2
0
PPA
ICA
P3D (N_{3d}=1)
P3D (N_{3d}=4)
P3D (N_{3d}=16)
-0.08
-0.04
0
0.04
Mean Bias Error


Normalized Upward Flux
1.2
1.0
0.8
0.6
0.4
0.2
0
Z (km)
-0.04
0
0.04
0.08
Mean Bias Error


Normalized Absorptance (/m)
1.0
0.8
0.6
0.4
0.2
0
-0.004
0
0.004
0.008
Mean Bias Error


3-D (MC)
1-D (ICA)
Z (km)
Heating Rate (W/m^3/μm)
-10x10^{-3}
-8
-6
-4
-2
0
2
0
1
2
3
4


3-D (MC)
Z (km)
X (km)
0.32
0.16
0.08
0.04
0.02
0.01
−0.01
−0.02
−0.04
−0.08
−0.16
−0.32


1-D (ICA)
Z (km)
X (km)
0.32
0.16
0.08
0.04
0.02
0.01
−0.01
−0.02
−0.04
−0.08
−0.16
−0.32

Major 3-D Radiative Effects

- Direct-beam effects (shadowing & side illumination), depending on solar angle
- Radiative diffusion of multiply-scattered light
- Enhanced heating

Formulas

The Russian Roulette Method

$$w' = \begin{cases} 0 & \text{if } \rho_w \geq w/W \\ W & \text{if } \rho_w < w/W \end{cases}$$

Directionality Parameter of a Photon Packet

$$\chi_n = \chi_{n-1} \left| g(n) \right|$$

Truncation Approximation

$$P(\Theta) \approx 2 f_\delta \delta(\Theta) + (1 - f_\delta)\hat{P}(\Theta)$$

$$\hat{\beta}_{\mathrm{e}} = \beta_{\mathrm{e}}(1 - f_\delta \omega)$$

$$\hat{\omega} = \omega(1 - f_\delta)/(1 - f_\delta \omega)$$

Scaling Transformation

$$\overline{\beta}_{\mathrm{e}} \Rightarrow \overline{\beta}'_{\mathrm{e}}$$

$$\overline{\omega} \Rightarrow \overline{\omega}' = 1 - (1 - \overline{\omega}) f_{\mathrm{e}}$$

$$P(\Theta) \Rightarrow P'(\Theta) = 2 f_{\mathrm{d}} \delta(\Theta) + (1 - f_{\mathrm{d}}) P(\Theta)$$

where

$$f_{\mathrm{e}} \equiv \overline{\beta}_{\mathrm{e}} / \overline{\beta}'_{\mathrm{e}} \qquad f_{\mathrm{d}} = \frac{1 - f_{\mathrm{e}}}{1 - (1 - \overline{\omega}) f_{\mathrm{e}}}$$

Unbiased Modification of the Local Estimate

$$\Psi \Rightarrow \Psi' = \begin{cases} \Psi_{\min} & \text{if } \rho_\Psi \leq \Psi/\Psi_{\min} \\ 0 & \text{if } \rho_\Psi > \Psi/\Psi_{\min} \end{cases}$$

$$T = \exp(-\tau)$$

$$\Rightarrow T' = \begin{cases} 1 & \text{if } \tau \leq \tau_{\text{free}} = -\ln(\rho_\tau) \\ 0 & \text{if } \tau > \tau_{\text{free}} \end{cases}$$

MLE Method: Final Form

1) $\pi\Psi \leq \zeta_{\min}$

$$\zeta' = \begin{cases} \zeta_{\min} & \text{if } \rho_\Psi \leq \pi\Psi/\zeta_{\min} \text{ and } \tau \leq \tau_{\text{free}} \\ 0 & \text{if } \rho_\Psi > \pi\Psi/\zeta_{\min} \text{ or } \tau > \tau_{\text{free}} \end{cases}$$

2) $\pi\Psi > \zeta_{\min}$

$$\zeta' = \begin{cases} \zeta & \text{if } \tau \leq \tau_{\max} \\ \zeta_{\min} & \text{if } \tau_{\max} < \tau \leq \tau_{\max} + \tau_{\text{free}} \\ 0 & \text{if } \tau > \tau_{\max} + \tau_{\text{free}} \end{cases}$$