Nonisotropic Aerosol Scattering Effects on Longwave Irradiance

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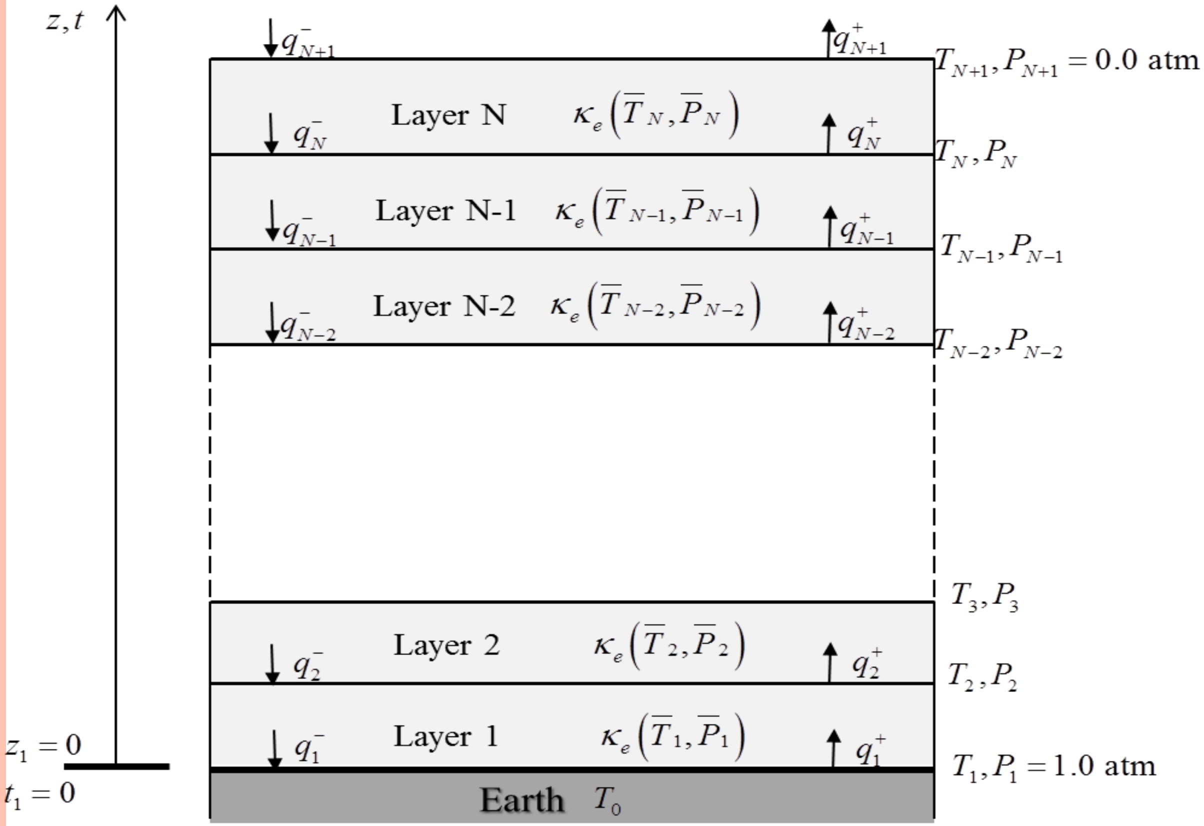
Introduction

- Solving thermal radiative heat transfer problem in atmosphere in order to
  - Modeling climate change
  - Design solar concentrated power plants
  - Predict solar energy
- Analytical atmospheric model: isotropic assumption
- This study:
  - Monte Carlo approach
  - Mie scattering
  - Scale anisotropic effects

ATMOSPHERIC MODEL

- 18-layer model



N	Upper boundary $z_N(m)$	Average $T_N(K)$
18	120000	275
17	32700	230
16	23500	220
15	18500	216
14	15100	217
13	12600	226
12	10500	238
11	8640	249
10	7050	259
9	5700	267
8	4490	273
7	3450	279
6	2550	284
5	1790	288
4	1160	290
3	664	292
2	300	293
1	68.1	294
Earth	0	294

Atmospheric Model

- Pressure and temperature in each layer

$$\sigma_n = \frac{2N - 2n + 1}{2N}$$

$$\bar{P}_n = {\sigma_n}^2 (3 - 2\sigma_n)$$

$$P_n = \frac{1}{N} \sum_{j=n}^{N} dP_j = \frac{1}{N} \sum_{j=n}^{N} 6(\sigma_j - \sigma_j^2)$$

$$\bar{T}_n = \frac{T_n (P_n - \bar{P}_n) + T_n + T_{n+1} (\bar{P}_n - P_{1+n})}{P_n - P_{n+1}}$$

- AFGL profiles used for temperature and pressure profile
- HITRAN molecular spectral data for seven gases used to calculate absorption coefficients.

Mathematical model

- Radiative transfer equation (Boltzmann equation) in a scattering medium:

$$\mu \frac{\partial I(\kappa,\mu)}{\partial \kappa} + I(\kappa,\mu) = (1-\tilde{\rho}) I_b(T) + \frac{\tilde{\rho}}{2} \int_{-1}^{1} P(\mu,\mu') I(\kappa,\mu') d\mu'$$

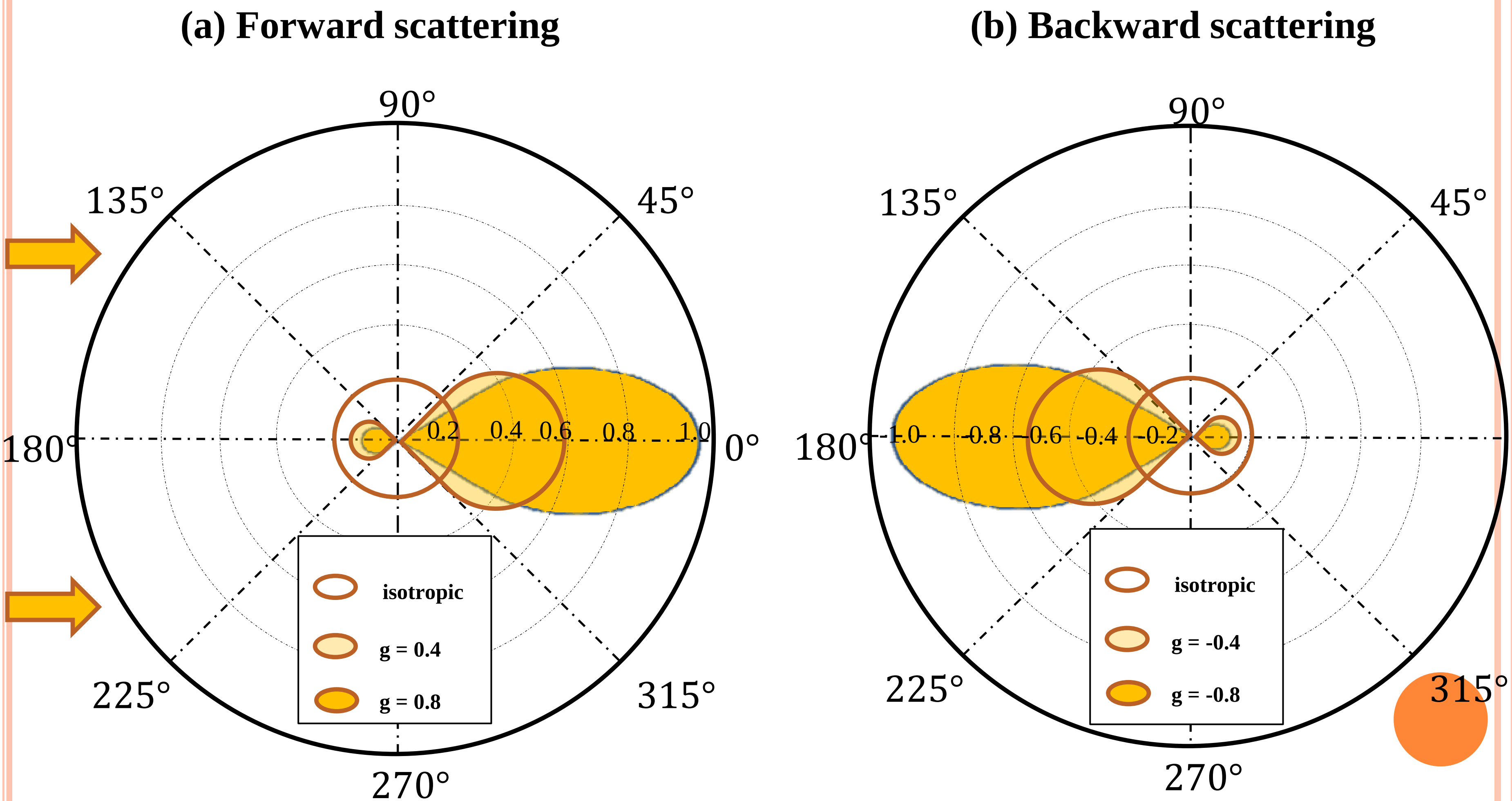
- For plane-parallel , isotropic scattering layers, radiosity, J and irradiance, G can be used:

$$J = (1-\tilde{\rho})\pi I_b - \tilde{\rho}\pi \mathrm{I}$$

$$G = \int_0^s e^{-t_{s'}} J(s') ds'$$

- Calculate J and G in each layer by solving a matrix constructed by transfer factors and modified transfer factors

ANISOTROPIC SCATTERING



Anisotropic scattering

- Mie theory:
  - Used to calculate absorption and scattering coefficients
  - Used to determine phase functions
    - Simplified phase function: Henyey-Greenstein

$$P(\cos\theta) = \frac{1-g^2}{2(1+g^2-2g\cos\theta)^{3/2}} \qquad \theta \in [0,\pi]$$

  - Scale gross error of final results
- P-1 approximation scaling
  - Scale initial inputs (absorption and scattering coefficients and albedo) to an isotropic scattering medium:

$$\hat{\kappa} = (1-\tilde{\rho}g)\kappa$$

$$\hat{\tilde{\rho}} = \frac{\tilde{\rho}(1-g)}{1-\tilde{\rho}g}$$

Method – Monte Carlo

Choose number of bundles n for simulation

Start a new bundle
(Determine position and direction)

Method – monte carlo

- Initialization:
  - Initial angle:
    - Surface: $\theta = \cos^{-1}(\sqrt{\xi_\theta})$ $\varphi = 2\pi\xi_\varphi$
    - Volume: $\theta = \cos^{-1}(2\xi_\theta - 1)$ $\varphi = 2\pi\xi_\varphi$
  - Initial position: random position within an layer
  - Optical depth: $\tau_0 = -\log(1-\xi)$ since $I \propto e^{-\tau}$
  - Energy contained in each bundle:
    - $E_{bs} = \frac{\varepsilon\sigma T_s^4}{N}$
    - $E_{bg} = \frac{4\kappa_a \Delta z}{N} \int_{\Delta\nu} I_{b\nu}(\nu, T) d\nu$

Where, $I_{b\nu}(\nu, T) = \frac{2hc^2\nu^3}{e^{hc\nu/(\kappa_B T g)}-1}$

Method – Monte Carlo

Choose number of bundles n for simulation

↓

Start a new bundle
(Determine position and direction)

↓

Determine distance to next collision d_c

Method – monte carlo

- Initialization:
  - Initial angle:
    - Surface: $\theta = \cos^{-1}(\sqrt{\xi_\theta})$ $\varphi = 2\pi\xi_\varphi$
    - Volume: $\theta = \cos^{-1}(2\xi_\theta - 1)$ $\varphi = 2\pi\xi_\varphi$
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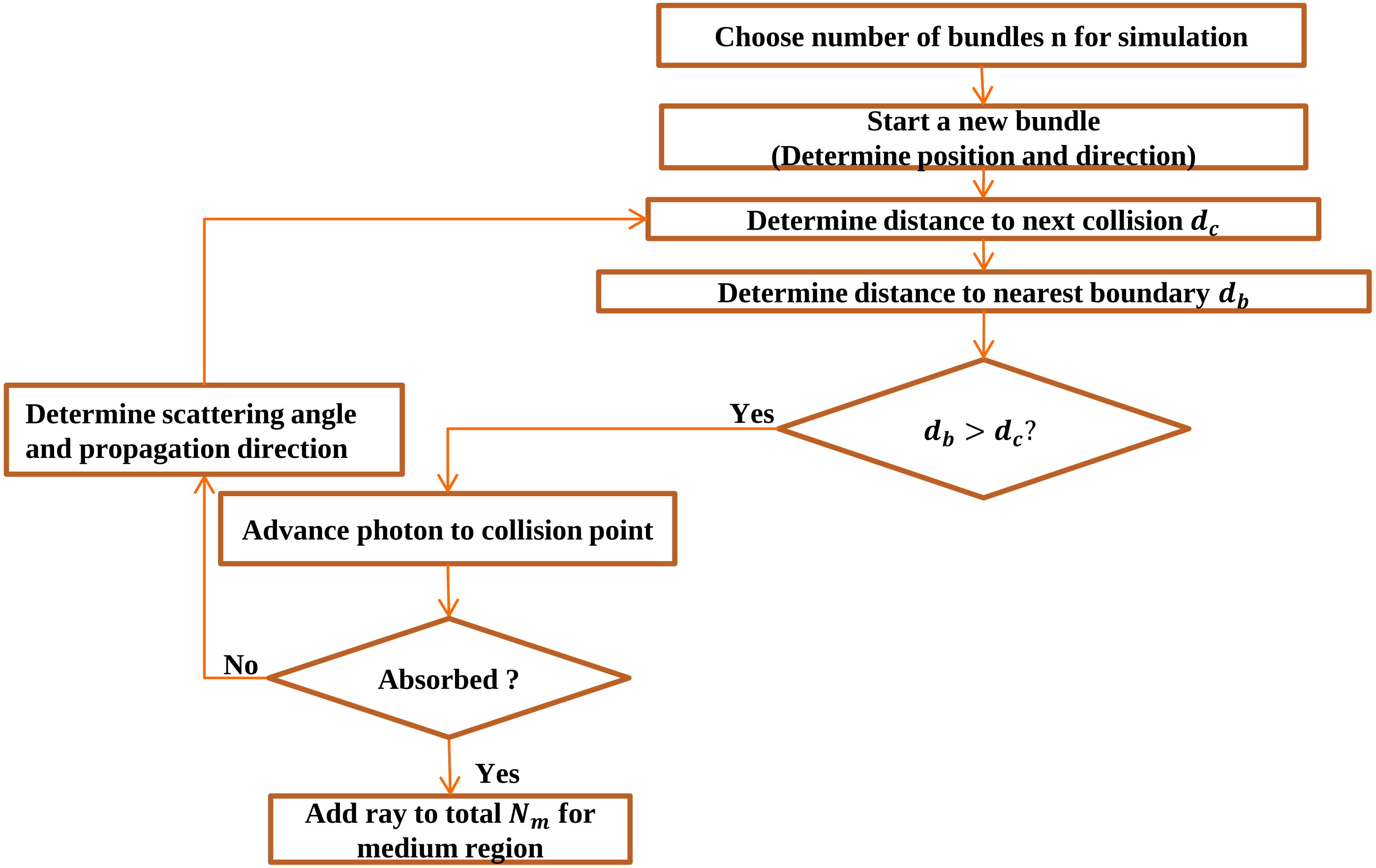
    - $E_{bg} = \frac{4\kappa_a \Delta z}{N} \int_{\Delta\nu} I_{b\nu}(\nu, T) d\nu$
- Tracing
  - Determine position of interaction
    - $d_c = -\frac{\log(1-\xi)}{\kappa_e}$

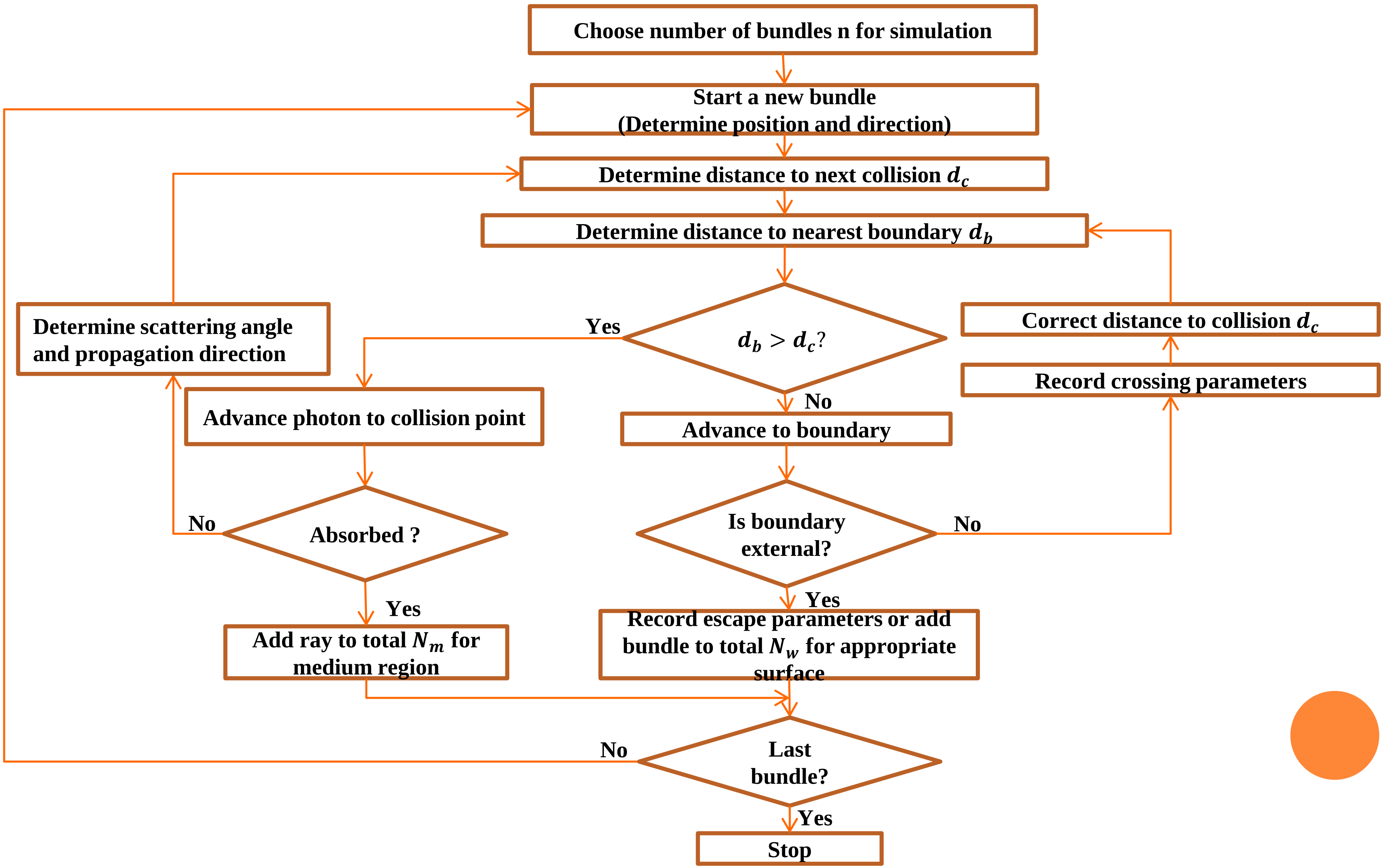
Method – Monte Carlo



Method – monte carlo

- Tracing
  - Determine position of interaction
    - $d_c = -\frac{\log(1-\xi)}{\kappa_e}$
  - Determine which particle to interact:
    - According to relative ratio of extinction coefficients
  - Determine particle destiny:
    - Absorbed: $\xi < (1-\alpha)$
    - Scattered: $\xi \geq (1-\alpha)$
    - $\alpha = \frac{\kappa_s}{\kappa_e}$ is single albedo

Method – Monte Carlo



Method – monte carlo scattering

Scattering angle:

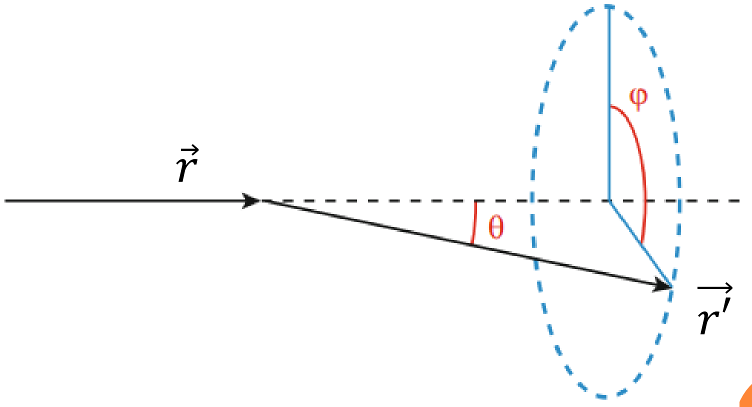
$$\cos\boldsymbol{\theta} = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{g}}\left\{\mathbf{1} + \boldsymbol{g}^2 - \left[\frac{\mathbf{1} - \boldsymbol{g}^2}{\mathbf{1} - \boldsymbol{g} + \mathbf{2}\boldsymbol{g}\boldsymbol{\xi}}\right]^2\right\}$$

New Direction:

$$\boldsymbol{r}'_x = \boldsymbol{r}_x \cos\boldsymbol{\theta} - \frac{\sin\boldsymbol{\theta}}{\sqrt{\mathbf{1} - \boldsymbol{r}_z^2}}(\boldsymbol{r}_x\boldsymbol{r}_z \cos\boldsymbol{\varphi} + \mathbf{r}_y \sin\boldsymbol{\varphi})$$

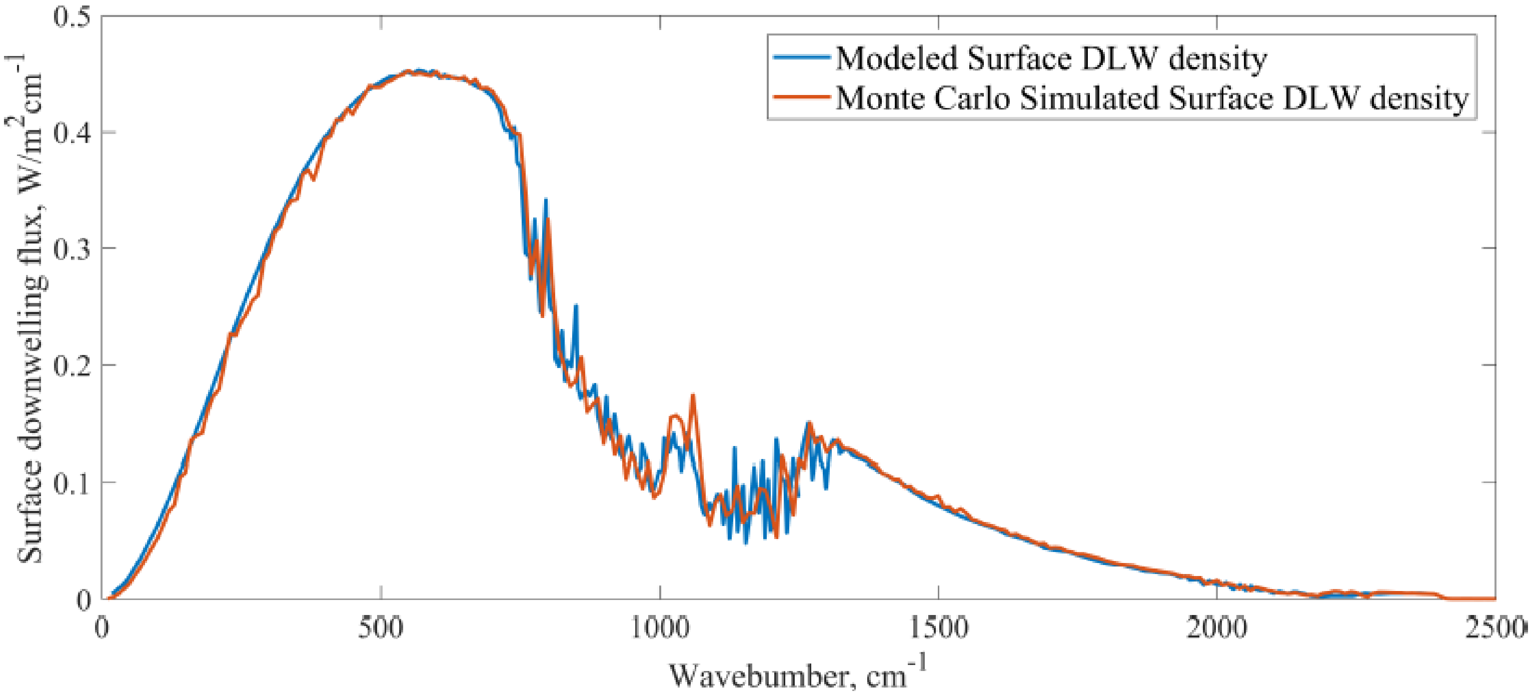
$$\boldsymbol{r}'_y = \boldsymbol{r}_y\, \boldsymbol{cos}\,\boldsymbol{\theta} - \frac{\boldsymbol{sin}\,\boldsymbol{\theta}}{\sqrt{\mathbf{1} - \boldsymbol{r}_z^2}}(\boldsymbol{r}_y\boldsymbol{r}_z\, \boldsymbol{cos}\,\boldsymbol{\varphi}) -)\boldsymbol{r}_x\, \boldsymbol{sin}\,\boldsymbol{\varphi})$$

$$\boldsymbol{r}'_z = \boldsymbol{r}_z\, \boldsymbol{cos}\,\boldsymbol{\theta} + \sqrt{\mathbf{1} - \boldsymbol{r}_z^2}\sin\boldsymbol{\theta}\cos\boldsymbol{\varphi}$$



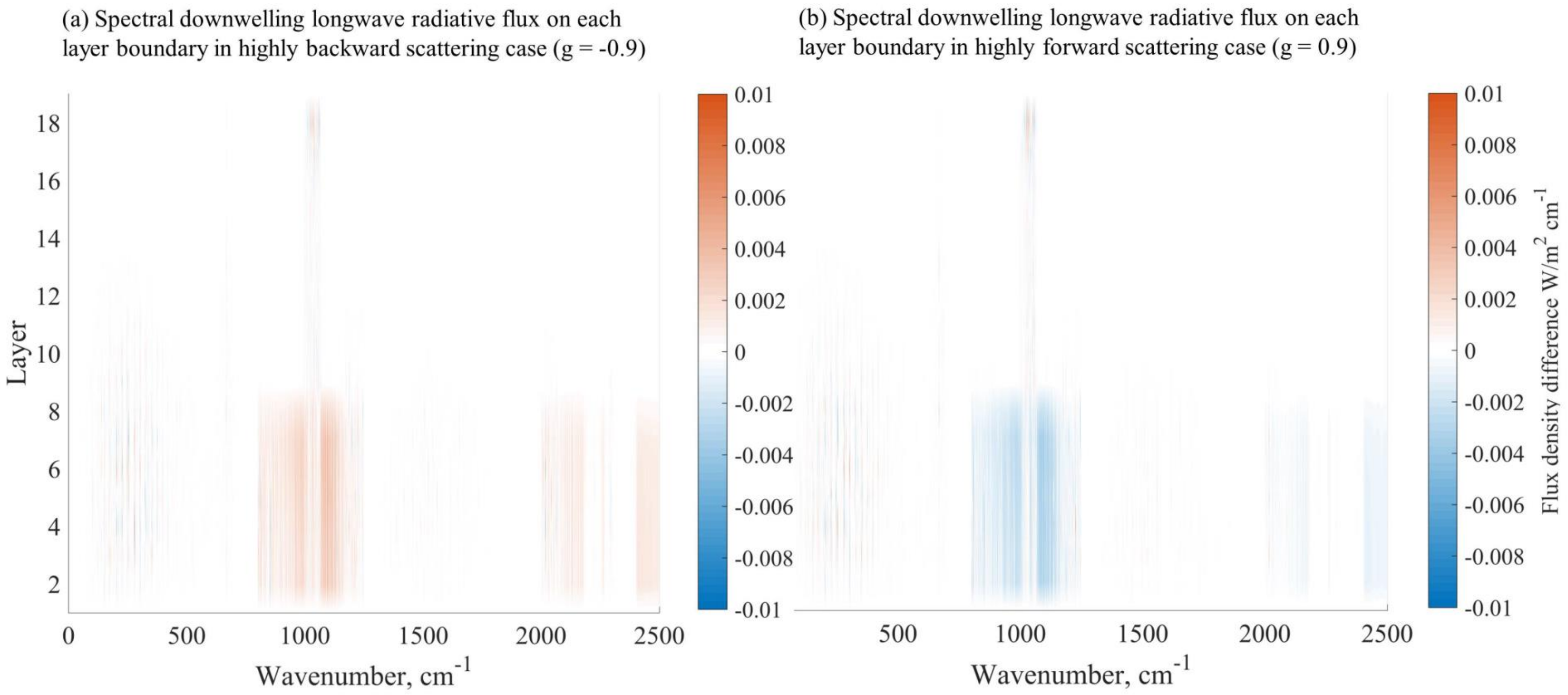
Results – model validation

- Compare aerosol-free case
  - Simulation result and ICRCCM model result



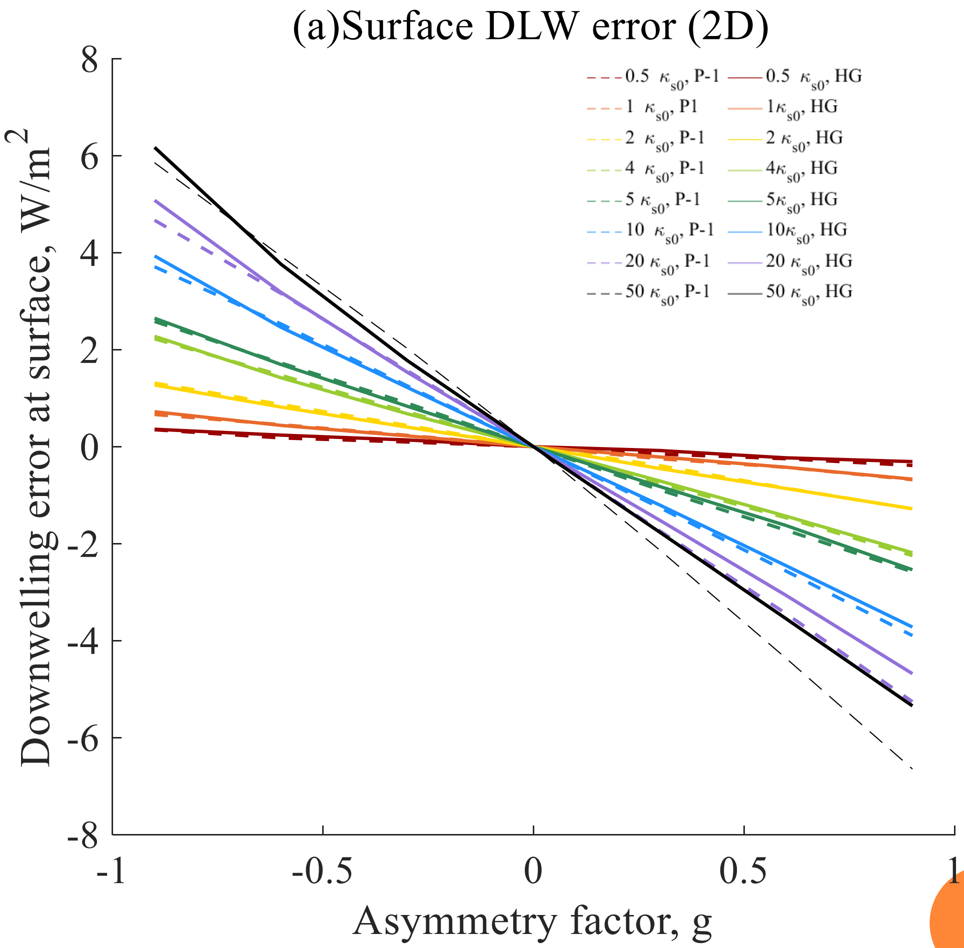
RESULTS – SPECTRAL DIFFERENCE

- The difference of spectral DLW radiative flux density on each layer boundary between a highly forward/backward scattering case, and an isotropic case.



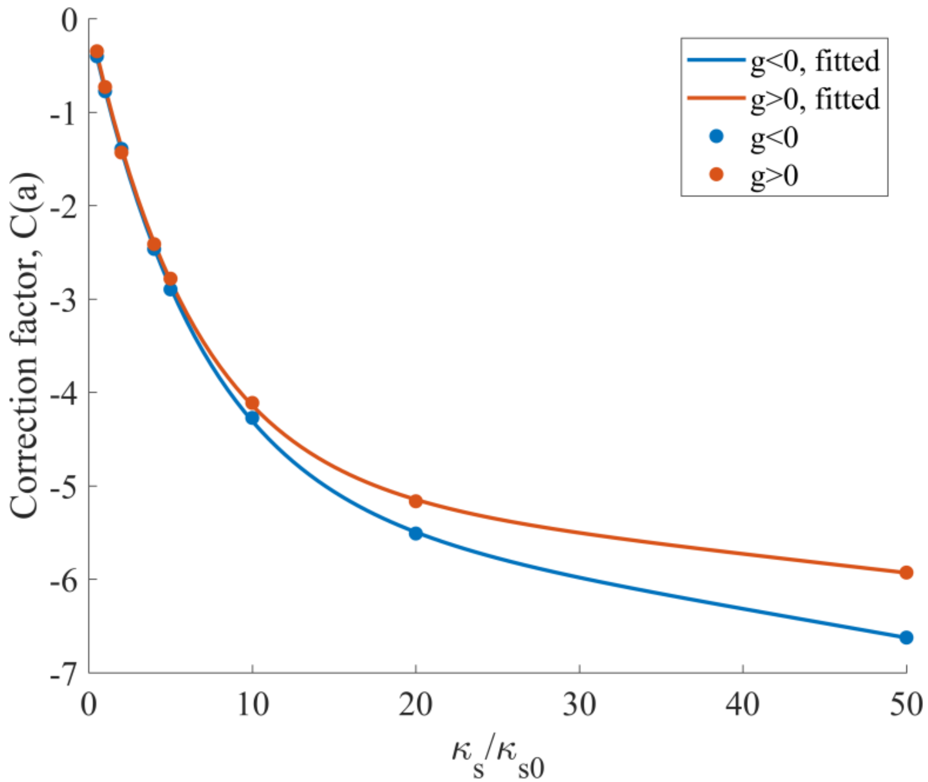
RESULTS

- Downwelling longwave radiation flux errors (W/m2) from isotropic case that vary with asymmetry factor, g and relative aerosol amount



Results

$$C(a) = \frac{\mathrm{DLW}^* - \mathrm{DLW}}{g} = \begin{cases} -5.02e^{0.00335a} + 5.03e^{-0.157a} & \text{for } g \geq 0 \\ -5.27e^{0.00461a} + 5.24e^{-0.147a} & \text{for } g < 0 \end{cases}$$



Conclusion

- With specific aerosol concentration and temperature profile, effect can be scaled to isotropic scattering case to assist analytical calculation.

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- P-1 scaling gives pretty good approximation when aerosol concentration is small.