云辐射参数化研究

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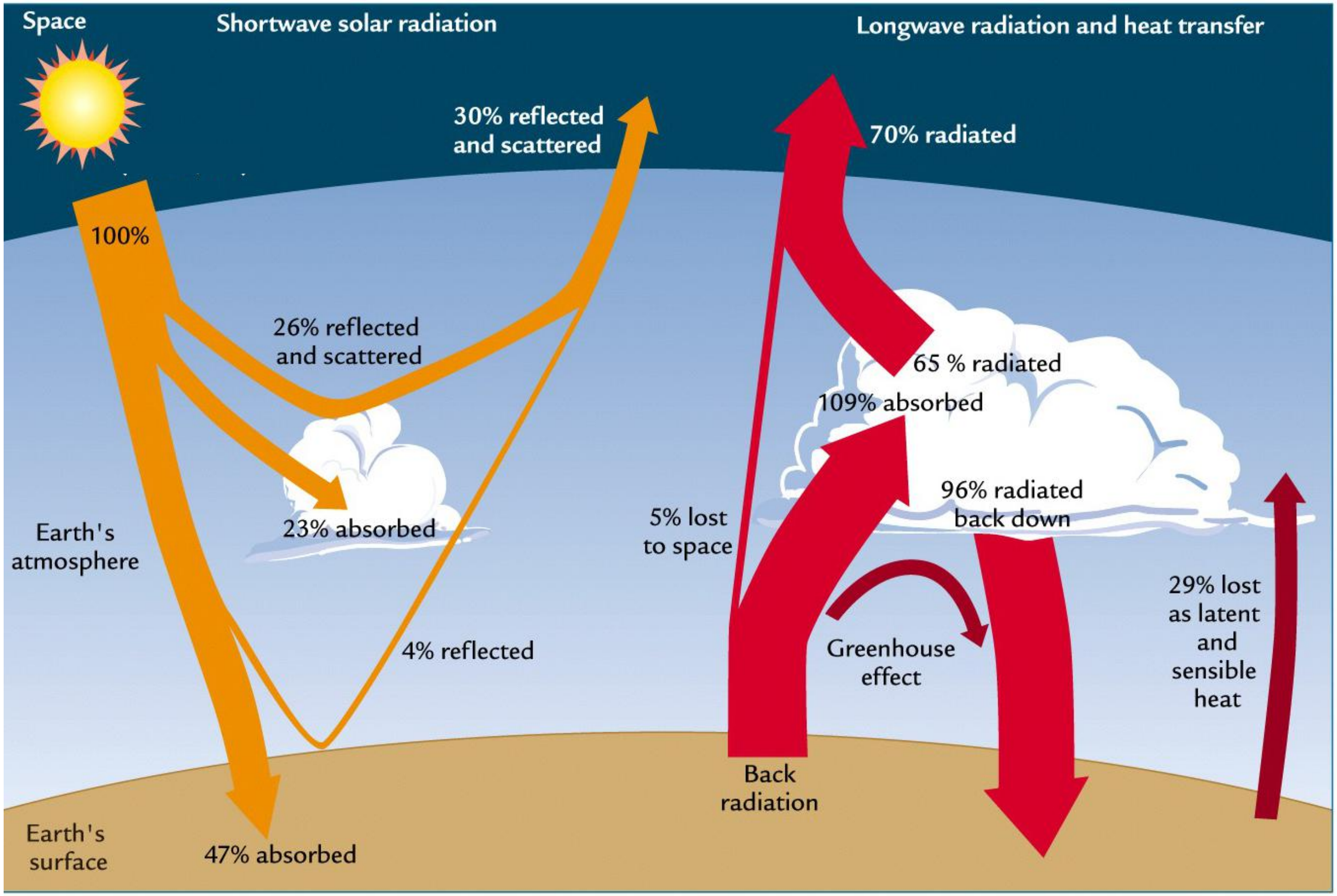
Introduction

Cloud Radiative transfer (RT) process is one of the basic physical processes of the earth–atmosphere system, which plays an important role in the climate change and remote sensing.



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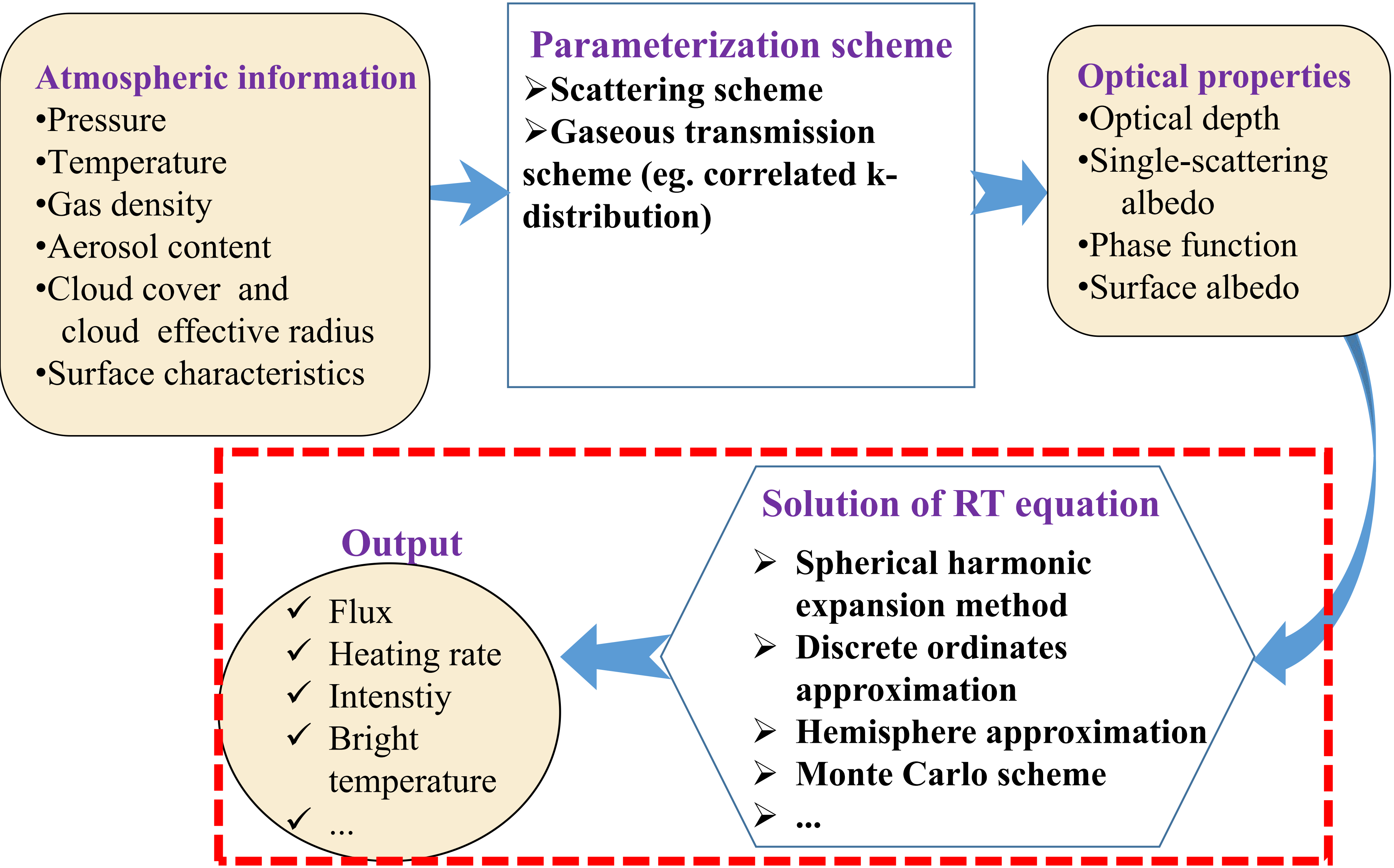
Framework of Radiative transfer simulation



Cloud radiative transfer for solar radiation

Introduction

The radiative transfer equation is an integro-differential equation. The exact solution of the radiative transfer equation in a scattering and absorbing media is impossible to be obtained in a computationally efficient manner even for the plane-parallel case, thus, approximate methods are necessary.

Solar radiative transfer equation

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - \frac{\omega}{2}\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' - \frac{\omega}{4\pi}F_0 e^{-\tau/\mu_0} P(\mu,-\mu_0)$$

single-scattering albedo (ω)

cosine of zentih angle (μ)

radiative intensity ($I(\tau,\mu)$)

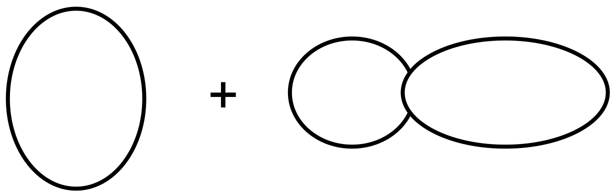
azimuthal in-dependent phase function ($P(\mu,\mu')$)

Cloud radiative transfer for solar radiation

The δ-two-stream approximations provide a simple answer to radiative transfer, especially the δ-Eddington approximation and δ-two-stream discrete ordinates method (DOM), are widely used.

δ-Eddington approximation

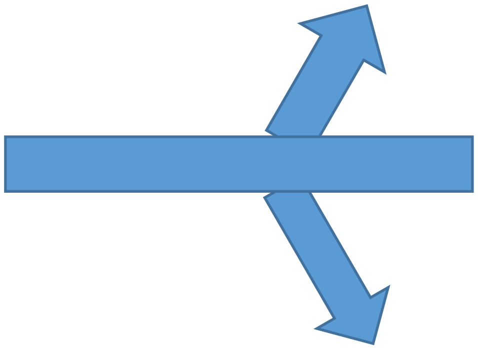
$$I(\tau, \mu) = I_0(\tau) + I_1(\tau)\mu$$



δ-two-stream discrete ordinates method (DOM)

$$\int_{-1}^{1} F(\mu)d\mu = \sum_{i=-n}^{n} w_i F(\mu_i)$$

$$I(\tau, \mu) = I_{-1}(\tau, \mu_{-1}) + I_{+1}(\tau, \mu_{+1})$$



However, the cloud heating might have been underestimated by as much as 10% under the cloudy-sky condition, which indicates that a four-stream or higher order approximation scheme is necessary in order to obtain the accurate solar cloud absorption in weather and climate models.

Cloud radiative transfer for solar radiation

1. Adding method of four stream DOM (4DDA)

Single layer solution for four stream discrete ordinate method (DOM) (Liou et al.1988)

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - \frac{\omega}{2}\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' - \frac{\omega}{4\pi} F_0 e^{-\tau/\mu_0} P(\mu,-\mu_0)$$

$$\mu_i \frac{dI_i}{d\tau} = I_i - \frac{\omega}{2}\sum_{l=0}^{3}\omega_\ell P_l(\mu_i)\sum_{j=-2}^{2} a_j I_j P_l(\mu_j) - \frac{\omega}{4\pi}F_0 \sum_{l=0}^{3}\omega_\ell P_l(\mu_i)P_l(-\mu_0)e^{-\tau/\mu_0}, i = \pm 1, \pm 2$$

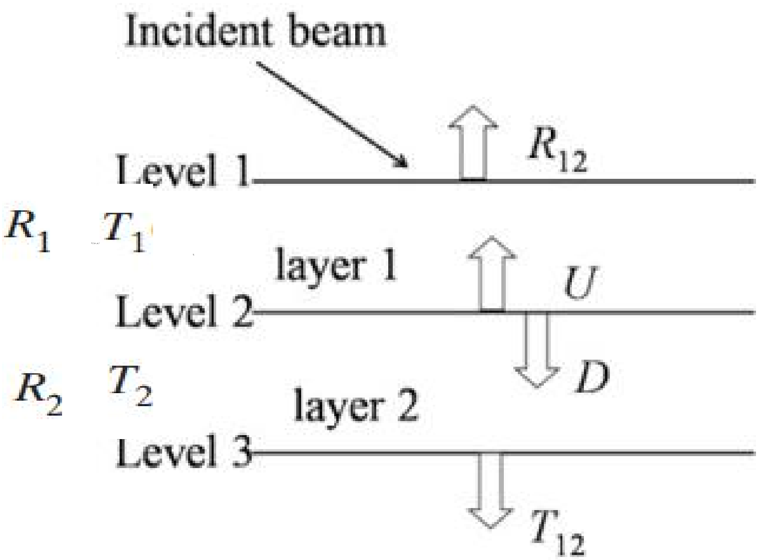
solution

$$\begin{bmatrix} I_2 \\ I_1 \\ I_{-1} \\ I_{-2} \end{bmatrix} = \begin{bmatrix} \varphi_2^+ e^{-k_2\tau} & \varphi_1^+ e^{-k_1\tau} & \varphi_1^- e^{-k_1(\tau_0-\tau)} & \varphi_2^- e^{-k_2(\tau_0-\tau)} \\ \Phi_2^+ e^{-k_2\tau} & \Phi_1^+ e^{-k_1\tau} & \Phi_1^- e^{-k_1(\tau_0-\tau)} & \Phi_2^- e^{-k_2(\tau_0-\tau)} \\ \Phi_2^- e^{-k_2\tau} & \Phi_1^- e^{-k_1\tau} & \Phi_1^+ e^{-k_1(\tau_0-\tau)} & \Phi_2^+ e^{-k_2(\tau_0-\tau)} \\ \varphi_2^- e^{-k_2\tau} & \varphi_1^- e^{-k_1\tau} & \varphi_1^+ e^{-k_1(\tau_0-\tau)} & \varphi_2^+ e^{-k_2(\tau_0-\tau)} \end{bmatrix} \mathbf{G} + \begin{bmatrix} Z_2^+ \\ Z_1^+ \\ Z_1^- \\ Z_{-2}^- \end{bmatrix} e^{-f_0\tau}$$

Cloud radiative transfer for solar radiation

Adding method of Four stream DOM (4DDA):

a) two layers



The four principles of invariance governing the reflection and transmission of light beam,

$$U(\mu,\mu_0) = R_2(\mu,\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + 2\int_0^1 R_2(\mu,\mu')D(\mu',\mu_0)\mu'\,d\mu'$$

$$D(\mu,\mu_0) = T_1(\mu,\mu_0) + 2\int_0^1 R_1^*(\mu,\mu')U(\mu',\mu_0)\mu'\,d\mu'$$

$$R_{1,2}(\mu,\mu_0) = R_1(\mu,\mu_0) + U(\mu,\mu_0)\exp\left(-\frac{\tau_1}{\mu}\right) + 2\int_0^1 T_1^*(\mu,\mu')U(\mu',\mu_0)\mu'\,d\mu'$$

$$T_{1,2}(\mu,\mu_0) = T_2(\mu,\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + D(\mu,\mu_0)\exp\left(-\frac{\tau_2}{\mu}\right) + 2\int_0^1 T_2(\mu,\mu')D(\mu',\mu_0)\mu'\,d\mu'$$

Cloud radiative transfer for solar radiation

Using the two node Gaussian quadrature to decompose the integrations

$$\mathbf{U}(\mu_0) = \mathbf{R}_2(\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + \overline{\mathcal{R}}_2\mathbf{D}(\mu_0)$$

$$\mathbf{D}(\mu_0) = \mathbf{T}_1(\mu_0) + \overline{\mathcal{R}}_1^*\mathbf{U}(\mu_0)$$

$$\mathbf{R}_{1,2}(\mu_0) = \mathbf{R}_1(\mu_0) + \overline{\mathcal{T}}_1^*\mathbf{U}(\mu_0)$$

$$\mathbf{T}_{1,2}(\mu_0) = \mathbf{T}_2(\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + \overline{\mathcal{T}}_2\mathbf{D}(\mu_0)$$

We get the solution

$$\mathbf{U}(\mu_0) = [\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*]^{-1}\left[\mathbf{R}_2(\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)\right]$$

$$\mathbf{D}(\mu_0) = \mathbf{T}_1(\mu_0) + \overline{\mathcal{R}}_1^*[\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*]^{-1}\times\left[\mathbf{R}_2(\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)\right]$$

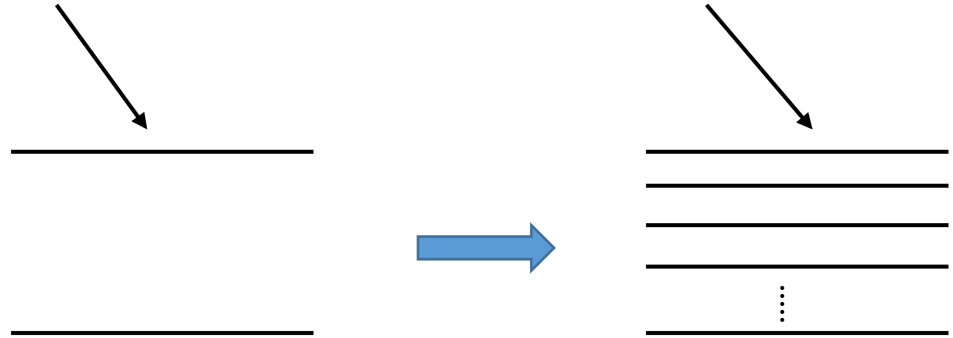
$$\mathbf{R}_{1,2}(\mu_0) = \mathbf{R}_1(\mu_0) + \overline{\mathcal{T}}_1^*[\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*]^{-1}\times\left[\mathbf{R}_2(\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)\right]$$

$$\mathbf{T}_{1,2}(\mu_0) = \mathbf{T}_2(\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + \overline{\mathcal{T}}_2\mathbf{T}_1(\mu_0) + \overline{\mathcal{T}}_2\overline{\mathcal{R}}_1^*[\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*]^{-1}$$

$$\times\left[\mathbf{R}_2(\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)\right]$$

Cloud radiative transfer for solar radiation

b) multi-layer



Applied to an atmospheric slab extending from the layer 1 to layer k,

$$\mathbf{U}_{k+1}(\mu_0) = [\mathbf{E} - \bar{\mathbf{R}}_{k+1,N}\bar{\mathbf{R}}^*_{1,k}]^{-1}[\mathbf{R}_{k+1,N}(\mu_0)e^{-\tau_{1,k}/\mu_0} + \bar{\mathbf{R}}_{k+1,N}\mathbf{T}_{1,k}(\mu_0)]$$

$$\mathbf{D}_{k+1}(\mu_0) = \mathbf{T}_{1,k}(\mu_0) + \bar{\mathbf{R}}^*_{1,k}[\mathbf{E} - \bar{\mathbf{R}}_{k+1,N}\bar{\mathbf{R}}^*_{1,k}]^{-1}[\mathbf{R}_{k+1,N}(\mu_0)e^{-\tau_{1,k}/\mu_0} + \bar{\mathbf{R}}_{k+1,N}\mathbf{T}_{1,k}(\mu_0)]$$

Finally, the upward and downward fluxes at level k +1 (lower boundary of the layer k) are

$$F^{\uparrow}_{k+1} = \mu_0 F_0 \boldsymbol{\mu} \cdot \mathbf{U}_{k+1}(\mu_0) \qquad F^{\downarrow}_{k+1} = \mu_0 F_0 \boldsymbol{\mu} \cdot \mathbf{D}_{k+1}(\mu_0) + \mu_0 F_0 e^{-\tau_{1,k}/\mu_0}$$

Zhang et al J. Atmos. Sci., 2013a

Zhang et al J. Atmos. Sci., 2016

Cloud radiative transfer for solar radiation

2. Adding method of four SHM (4SDA)

Single layer solution for four stream spherical harmonic expansion method (SHM) (Li et al.1996)

The intensity can be separated out the angle-dependent factor by assuming

$$I(\tau,\mu)=\sum_{l=0}^{3} I_l(\tau)P_l(\mu)$$

Substituting the above formula into RT equation and using the orthogonality relation of the Legendre function,

$$\frac{d}{d\tau}\begin{bmatrix} I_0(\tau) \\ I_1(\tau) \\ I_2(\tau) \\ I_3(\tau) \end{bmatrix} = \begin{bmatrix} 0 & a_1 & 0 & -\frac{2}{3}a_2 \\ a_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{3}a_3 \\ -\frac{2}{3}a_0 & 0 & -\frac{1}{3}a_2 & 0 \end{bmatrix} \begin{bmatrix} I_0(\tau) \\ I_1(\tau) \\ I_2(\tau) \\ I_3(\tau) \end{bmatrix} + \begin{bmatrix} \frac{2}{3}b_3 - b_1 \\ -b_0 \\ -\frac{1}{3}b_3 \\ \frac{2}{3}b_0 - \frac{1}{3}b_2 \end{bmatrix} e^{-\tau/\mu_0}$$

Cloud radiative transfer for solar radiation

According to the orthogonality of $P_1(\mu)$ and $P_3(\mu)$ in $0 \le \mu \le 1$ or $-1 \le \mu \le 0$, we can get

$$F^-(\tau) = 2\pi \int_0^{-1} I(\tau,\mu) P_1(\mu)\, d\mu = 2\pi \left[\frac{1}{2} I_0(\tau) - I_1(\tau) + \frac{5}{8} I_2(\tau) \right]$$

$$\mathcal{F}^-(\tau) = 2\pi \int_0^{-1} I(\tau,\mu) P_3(\mu)\, d\mu = 2\pi \left[-\frac{1}{8} I_0(\tau) + \frac{5}{8} I_2(\tau) - I_3(\tau) \right]$$

$$F^+(\tau) = 2\pi \int_0^{1} I(\tau,\mu) P_1(\mu)\, d\mu = 2\pi \left[\frac{1}{2} I_0(\tau) + I_1(\tau) + \frac{5}{8} I_2(\tau) \right]$$

$$\mathcal{F}^+(\tau) = 2\pi \int_0^{1} I(\tau,\mu) P_3(\mu)\, d\mu = 2\pi \left[-\frac{1}{8} I_0(\tau) + \frac{5}{8} I_2(\tau) + I_3(\tau) \right]$$

Therefore, we can get the solution

$$\begin{bmatrix} F^-(\tau) \\ \mathcal{F}^-(\tau) \\ F^+(\tau) \\ \mathcal{F}^+(\tau) \end{bmatrix} = \begin{bmatrix} \varphi_1^- e_1 & \varphi_1^+ e_3 & \varphi_2^- e_2 & \varphi_2^+ e_4 \\ \Phi_1^- e_1 & \Phi_1^+ e_3 & \Phi_2^- e_2 & \Phi_2^+ e_4 \\ \varphi_1^+ e_1 & \varphi_1^- e_3 & \varphi_2^+ e_2 & \varphi_2^- e_4 \\ \Phi_1^+ e_1 & \Phi_1^- e_3 & \Phi_2^+ e_2 & \Phi_2^- e_4 \end{bmatrix} \mathbf{G} + \begin{bmatrix} Z_1^- \\ Z_2^- \\ Z_1^+ \\ Z_2^+ \end{bmatrix} \exp(-f_0 \tau)$$

Cloud radiative transfer for solar radiation

a) two layer

The four principles of invariance governing the reflection and transmission of light beam

$$U(\mu,\mu_0) = R_2(\mu,\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + 2\int_0^1 R_2(\mu,\mu')D(\mu',\mu_0)\mu'\,d\mu'$$

$$D(\mu,\mu_0) = T_1(\mu,\mu_0) + 2\int_0^1 R_1^*(\mu,\mu')U(\mu',\mu_0)\mu'\,d\mu'$$

$$R_{1,2}(\mu,\mu_0) = R_1(\mu,\mu_0) + U(\mu,\mu_0)\exp\left(-\frac{\tau_1}{\mu}\right) + 2\int_0^1 T_1^*(\mu,\mu')U(\mu',\mu_0)\mu'\,d\mu'$$

$$T_{1,2}(\mu,\mu_0) = T_2(\mu,\mu_0)\exp\left(-\frac{\tau_1}{\mu_0}\right) + D(\mu,\mu_0)\exp\left(-\frac{\tau_2}{\mu}\right) + 2\int_0^1 T_2(\mu,\mu')D(\mu',\mu_0)\mu'\,d\mu'$$

4DDA

$$U(\mu,\mu_0) = R_2(\mu,\mu_0)e^{-\tau_1/\mu_0} + 2\int_0^1 R_2(\mu,\mu')D(\mu',\mu_0)\mu'\,d\mu'$$

$$D(\mu,\mu_0) = T_1(\mu,\mu_0) + 2\int_0^1 R_1^*(\mu,\mu')U(\mu',\mu_0)\mu'\,d\mu'$$

$$R_{1,2}(\mu,\mu_0) = R_1(\mu,\mu_0) + 2\int_0^1 \tilde{T}_1^*(\mu,\mu')U(\mu',\mu_0)\mu'\,d\mu'$$

$$T_{1,2}(\mu,\mu_0) = T_2(\mu,\mu_0)e^{-\tau_1/\mu_0} + 2\int_0^1 \tilde{T}_2(\mu,\mu')D(\mu',\mu_0)\mu'\,d\mu'$$

4SDA

$$\int_0^1 P_1(\mu)P_3(\mu)d\mu = 0$$

orthogonality

Cloud radiative transfer for solar radiation

We multiple $2P_1(u)du$ in both sides of the above equation and do integration from 0 to 1. Also we multiple $2P_3(u)du$ in both sides of the above equation and do integration from 0 to 1. Then, we can obtain

$$\mathbf{U}(\mu_0) = \mathbf{R}_2(\mu_0)e^{-\tau_1/\mu_0} + \overline{\mathcal{R}}_2\mathbf{D}(\mu_0)$$

$$\mathbf{D}(\mu_0) = \mathbf{T}_1(\mu_0) + \overline{\mathcal{R}}_1^*\mathbf{U}(\mu_0)$$

$$\mathbf{R}_{1,2}(\mu_0) = \mathbf{R}_1(\mu_0) + \overline{\mathcal{T}}_1^*\mathbf{U}(\mu_0)$$

$$\mathbf{T}_{1,2}(\mu_0) = \mathbf{T}_2(\mu_0)e^{-\tau_1/\mu_0} + \overline{\mathcal{T}}_2\mathbf{D}(\mu_0)$$

We get the solution

$$\mathbf{U}(\mu_0) = (\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*)^{-1}[\mathbf{R}_2(\mu_0)e^{-\tau_1/\mu_0} + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)]$$

$$\mathbf{D}(\mu_0) = \mathbf{T}_1(\mu_0) + \overline{\mathcal{R}}_1^*(\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*)^{-1} \times [\mathbf{R}_2(\mu_0)e^{-\tau_1/\mu_0} + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)]$$

$$\mathbf{R}_{1,2}(\mu_0) = \mathbf{R}_1(\mu_0) + \overline{\mathcal{T}}_1^*(\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*)^{-1} \times [\mathbf{R}_2(\mu_0)e^{-\tau_1/\mu_0} + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)]$$

$$\mathbf{T}_{1,2}(\mu_0) = \mathbf{T}_2(\mu_0)e^{-\tau_1/\mu_0} + \overline{\mathcal{T}}_2\mathbf{T}_1(\mu_0) + \overline{\mathcal{T}}_2\overline{\mathcal{R}}_1^*(\mathbf{E} - \overline{\mathcal{R}}_2\overline{\mathcal{R}}_1^*)^{-1} \times [\mathbf{R}_2(\mu_0)e^{-\tau_1/\mu_0} + \overline{\mathcal{R}}_2\mathbf{T}_1(\mu_0)]$$

Cloud radiative transfer for solar radiation

b) multi-layer

$$\mathbf{U}_{k+1}(\mu_0) = [\mathbf{E} - \overline{\mathcal{R}}_{k+1,N}\overline{\mathcal{R}}^*_{1,k}]^{-1} \times \left[\mathbf{R}_{k+1,N}(\mu_0)\exp\left(-\frac{\tau_{1,k}}{\mu_0}\right) + \overline{\mathcal{R}}_{k+1,N}\mathbf{T}_{1,k}(\mu_0)\right]$$

$$\mathbf{D}_{k+1}(\mu_0) = \mathbf{T}_{1,k}(\mu_0) + \overline{\mathcal{R}}^*_{1,k}[\mathbf{E} - \overline{\mathcal{R}}_{k+1,N}\overline{\mathcal{R}}^*_{1,k}]^{-1} \times \left[\mathbf{R}_{k+1,N}(\mu_0)\exp\left(-\frac{\tau_{1,k}}{\mu_0}\right) + \overline{\mathcal{R}}_{k+1,N}\mathbf{T}_{1,k}(\mu_0)\right]$$

Then, the flux is

$$F^{\uparrow}_{k+1} = \mu_0 F_0 \boldsymbol{\mu} \cdot \mathbf{U}_{k+1}(\mu_0)$$

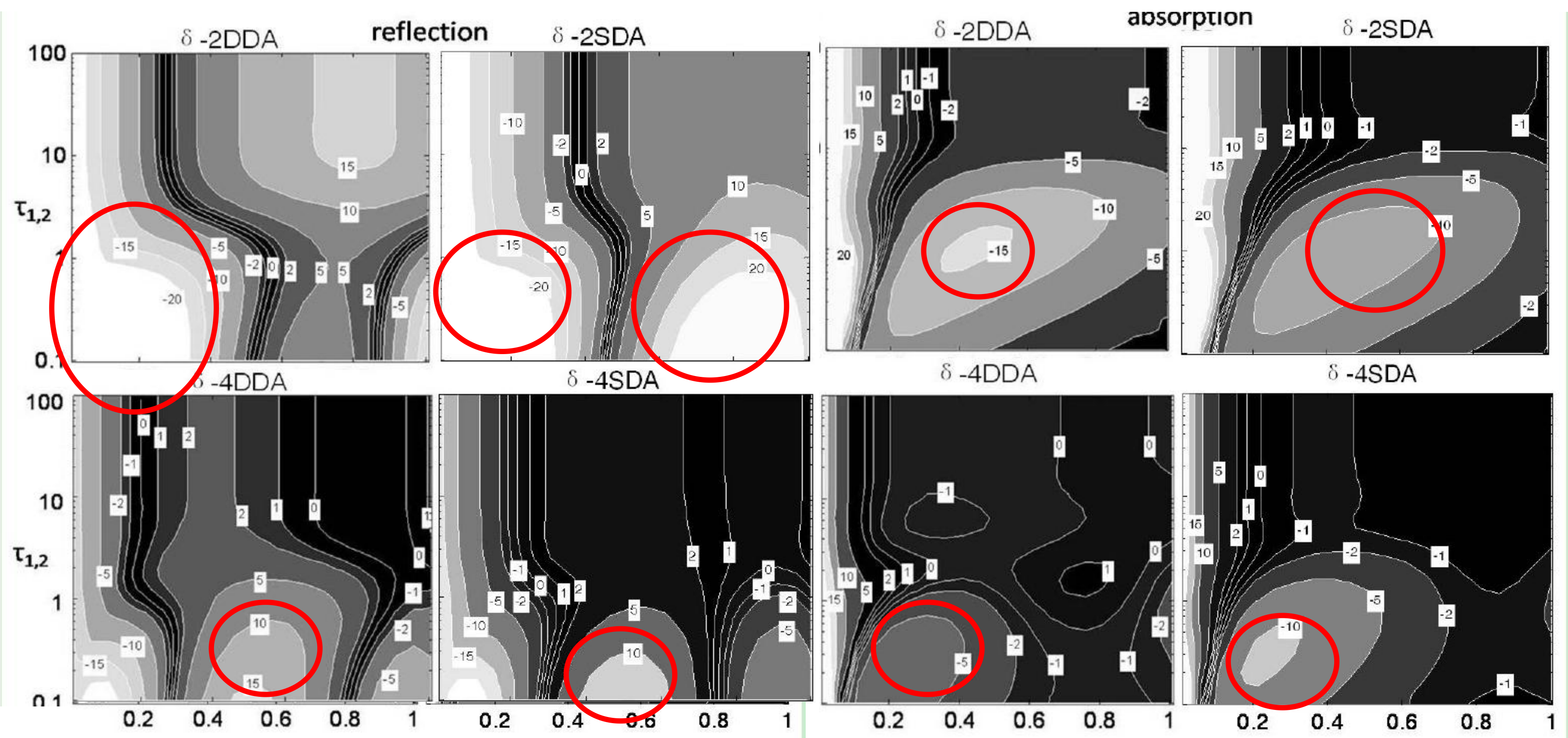
$$F^{\downarrow}_{k+1} = \mu_0 F_0 \boldsymbol{\mu} \cdot \mathbf{D}_{k+1}(\mu_0) + \mu_0 F_0 \exp\left(-\frac{\tau_{1,k}}{\mu_0}\right)$$

Zhang et al J. Atmos. Sci., 2013b

Cloud radiative transfer for solar radiation

Comparison results and discussion

a. Double layer $\omega_1 = \omega_2 = 0.9 \quad g_1 = 0.837$ and $g_2 = 0.861$



Cloud radiative transfer for solar radiation

Comparison of upward flux at TOA and downward flux at the surface (W m^{-2}) for the four adding schemes. The aerosol optical depth 0.1.

μ_0	δ-128S	δ-2DDA		δ-2SDA		δ-4DDA		δ-4SDA	
				$F^{\uparrow}$ (TOA)					
1.0	260.88	261.85	(0.97)	266.28	(5.40)	259.34	(−1.54)	260.71	(−0.17)
0.5	154.93	154.05	(0.88)	155.95	(1.02)	155.02	(0.09)	155.85	(0.92)
0.25	96.54	92.30	(−4.24)	92.96	(−3.58)	95.63	(−0.91)	96.11	(−0.43)
				$F^{\downarrow}$ (surface)					
1.0	1157.96	1157.71	(−0.25)	1150.55	(−7.41)	1159.42	(1.46)	1157.44	(−0.52)
0.5	522.60	526.07	(3.47)	522.78	(0.18)	522.10	(−0.50)	522.00	(−0.60)
0.25	221.32	228.83	(7.51)	227.50	(6.18)	222.47	(1.15)	222.82	(1.50)

The results of efficiency for δ-2DDA and δ-4DDA are shown. The inverse matrix method used in the Fu–Liou model (Liou et al. 1988; Fu 1991; Fu et al. 1997) is also used to solve layer connection in δ-two-stream DOM scheme (denoted as δ-2DOM) and in δ-four-stream DOM scheme (denoted as δ-4DOM). Normalized to the δ-2DOM method. Gaseous transmission and cloud absorption are included in 'radiation model', but not in 'algorithm only'.

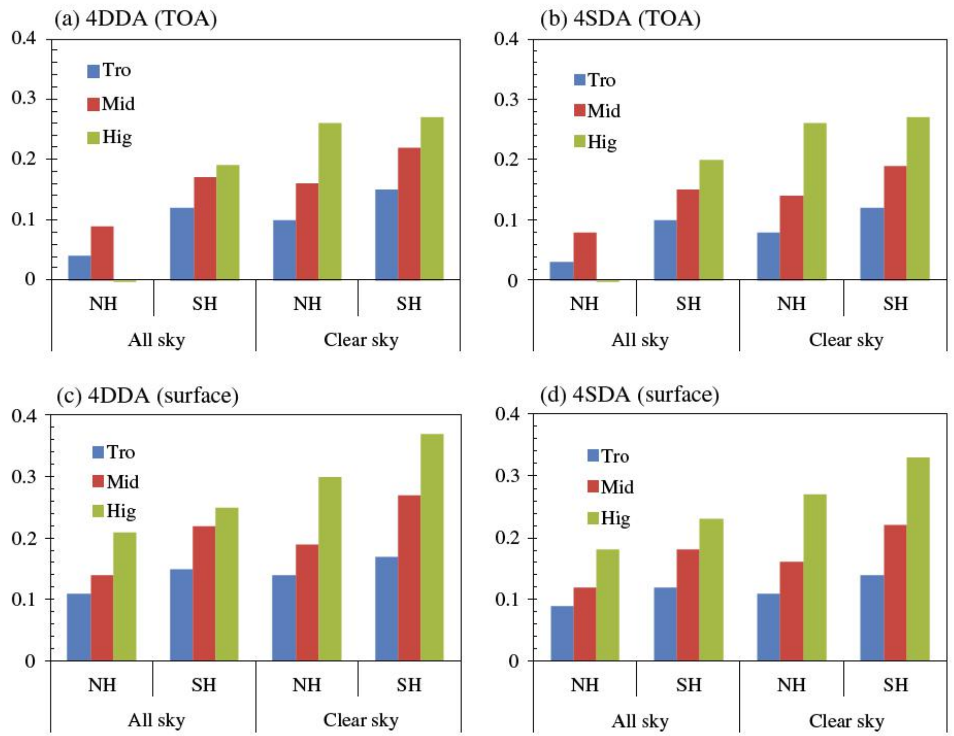
Radiative transfer timing	δ-2DDA	δ-4DDA	δ-2DOM	δ-4DOM
Algorithm only	0.96	2.2	1.0	6.6
Radiation model	1.0	1.8	1.0	4.2

Atmospheric General Circulation Model of the Beijing Climate Center (BCC_AGCM2.0.1)

Table 1. Global annual means of simulated total aerosol shortwave DREs for the year 2000 (unit: W m^{-2}).

	All sky			Clear sky		
	TOA	ATM	SFC	TOA	ATM	SFC
Base	−2.01	2.19	−4.20	−4.49	2.21	−6.69
δ-4DDA	−2.21 (10%)	2.59 (18%)	−4.80 (14%)	−5.21 (16%)	2.74 (24%)	−7.95 (19%)
δ-4SDA	−2.17 (8%)	2.51 (15%)	−4.68 (12%)	−5.10 (14%)	2.61 (18%)	−7.71 (15%)

TOA, ATM, and SFC represent top of the atmosphere, atmosphere, and surface, respectively. Values in parentheses are relative differences in aerosol shortwave DREs between two- and four-stream algorithms.



Zhang Hua, Zhili Wang*, Feng Zhang, Xianwen Jing, 2015, International Journal of Climatology

Cloud radiative transfer for Infrared radiation

Introduction

- Solving the radiative transfer equation (RTE) is a key issue when dealing with radiative processes. For infrared radiation, an absorption approximation (AA) is used in most current climate models (Oreopoulos et al. 2012) .
- Studies have shown that AA leads to larger errors in cloudy sky cases. Conversely, if scattering is considered, we need to use the discrete-ordinates method (DOM) and the calculation process is complicated.
- The aim of this study was to develop 4DDA and VIM to establish a more efficient infrared radiative transfer method for a scattering medium, whose accuracy would be comparable to that of DOM.

Cloud radiative transfer for Infrared radiation

Infrared radiative transfer equation

single-scattering albedo

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - (1-\omega)B(\tau) - \frac{\omega}{2}\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu'$$

cosine of zentih angle

radiative intensity

the Planck function at optical depth τ

azimuthal in-dependent phase function

It's an integro-differential equation and it has no exact solution.

Cloud radiative transfer for Infrared radiation

1.Absorption Approximation (AA)

In absorption approximation (AA), the scattering phase function P is simplified as a δ function, and the infrared RTE becomes

$$\mu\frac{dI(\tau,\mu)}{d\tau}=(1-\omega)I(\tau,\mu)-(1-\omega)B(\tau)$$

So the upward intensity at $\tau=0$ is

$$I(0,\mu)=I(\tau_0,\mu)e^{-(1-\omega)\tau_0/\mu}+\frac{1-\omega}{\mu\beta+1-\omega}[B_0-B_1e^{-(1-\omega)\tau_0/\mu}]$$

And the downward intensity at $\tau=\tau_1$ is

$$I(\tau_1,-\mu)=I(0,-\mu)e^{-(1-\omega)\tau_1/\mu}+\frac{1-\omega}{\mu\beta-1+\omega}[B_0e^{-(1-\omega)\tau_1/\mu}-B_1]$$

Variational Iteration Method (VIM)

For a general nonlinear system:

a nonlinear term

$$L\upsilon(x) + N\upsilon(x) = h(x)$$

a linear term   an inhomogeneous term

If $\upsilon(x)$ is found in n-th iteration, the (n+1)-th-order n solution is

a restricted variation, which equals to 0 after variation

$$\upsilon^{n+1}(x) = \upsilon^{n}(x) + \int_0^x \lambda(\zeta)[L\upsilon^{n}(\zeta) + N\tilde{\upsilon}^{n}(\zeta) - h(\zeta)]d\zeta$$

a general Lagrange multiplier, which can be identified by using variational theory

Cloud radiative transfer for Infrared radiation

For the infrared RTE

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - (1-\omega)B(\tau) - \frac{\omega}{2}\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu'$$

The functional reiteration can be deduced as

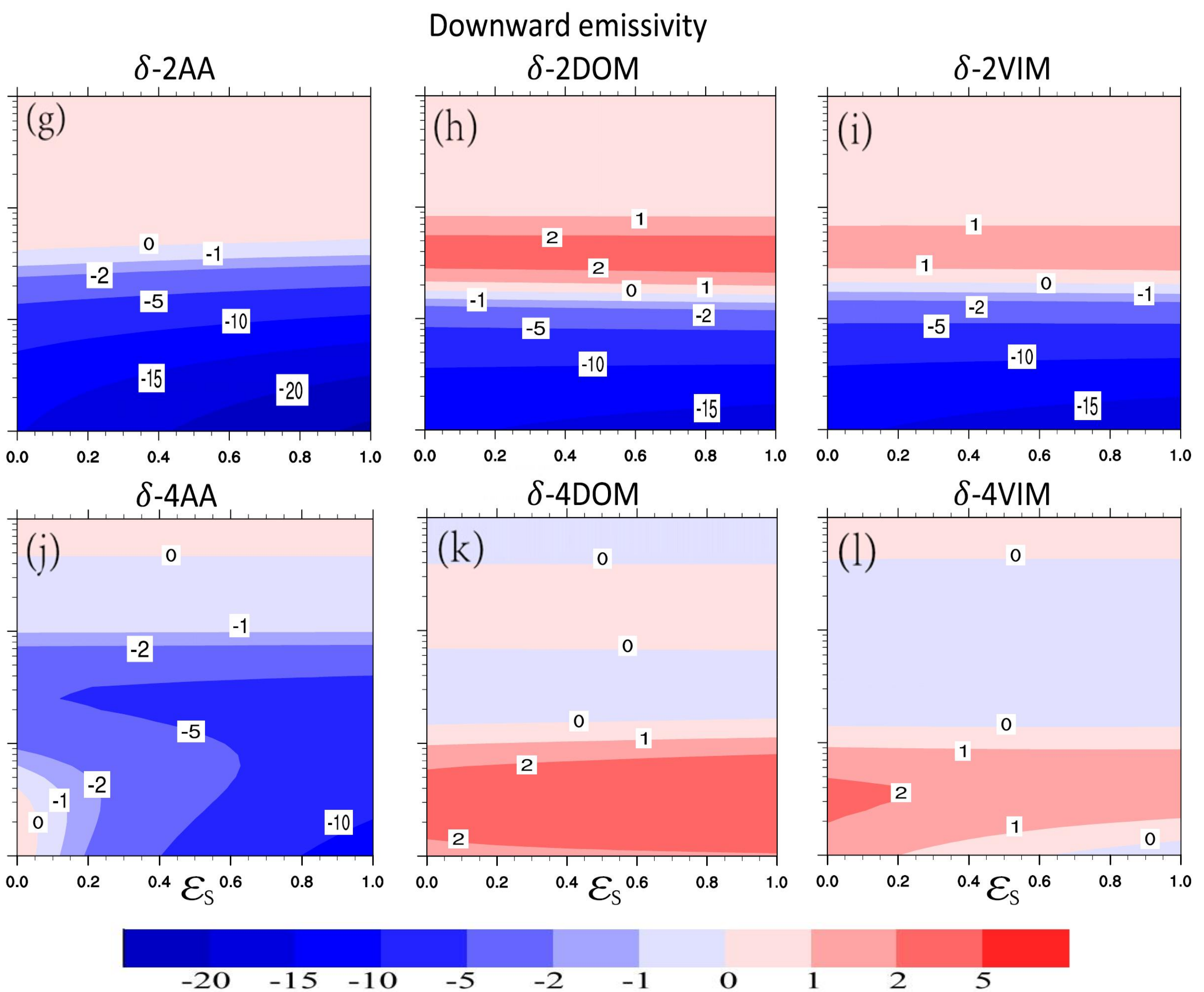
$$I^{n+1}(s,\pm\mu) = I^{n}(s,\pm\mu) + \int_{\tau_s}^{\tau} \lambda^{\pm}(s)[\frac{dI^{n}(s,\pm\mu)}{ds} \mp \frac{I^{n}(s,\pm\mu)}{\mu} \pm \frac{1-\omega}{\mu}B(s)$$
$$\pm \frac{\omega}{2\mu}\int_{-1}^{1} \widetilde{I}^{n}(s,\mu')P(\pm\mu,\mu')d\mu']ds$$

The AA expression can be used as the initial 0th-order solution, and the scattering effect is included in the first-order solution

Cloud radiative transfer for Infrared radiation

a. Single Medium

ω=0.7105, g=0.9044

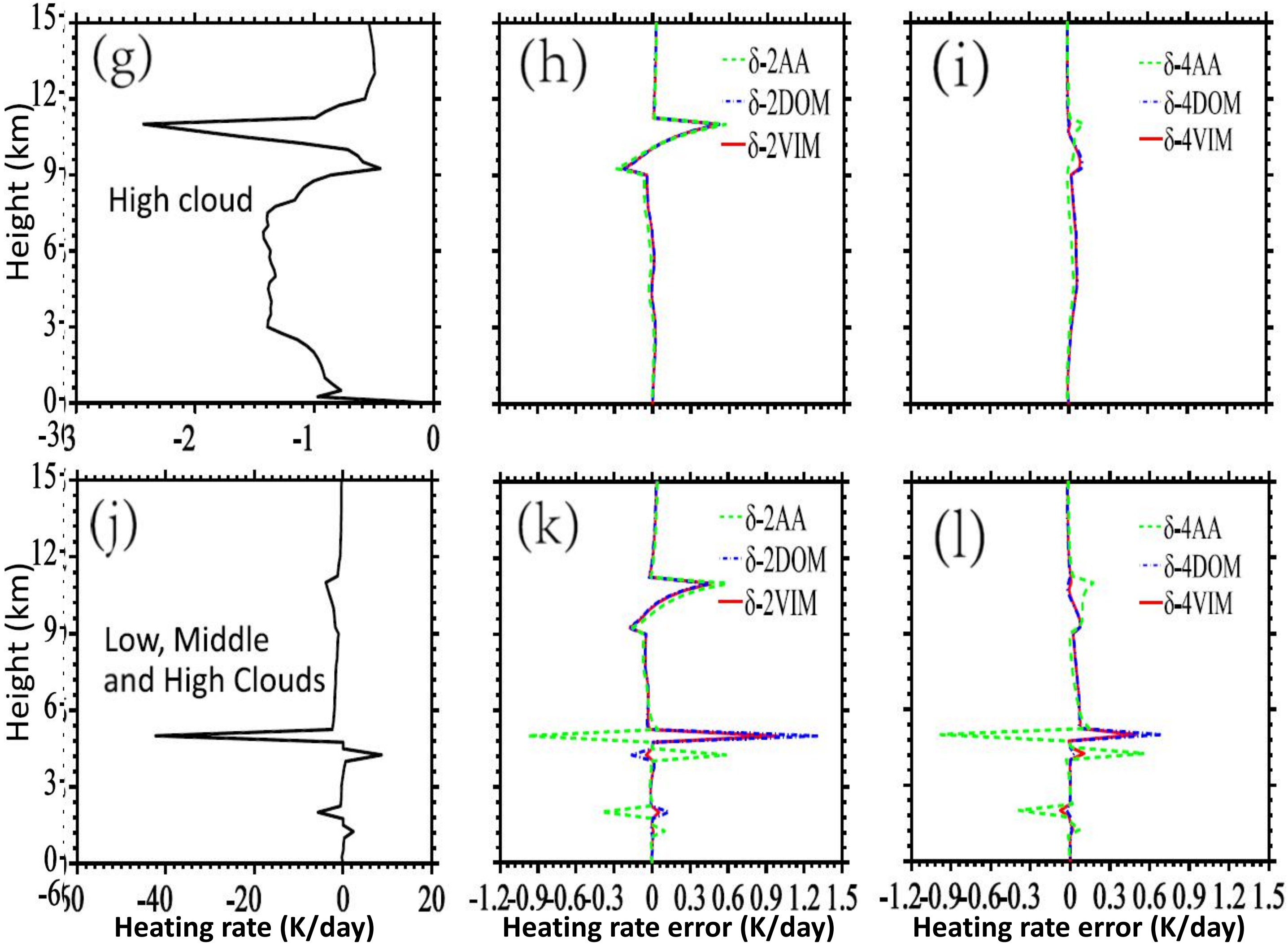


δ-2VIM is similar to δ-2DOM in the small optical depth but more accurate than δ-2DOM in the large optical depth.

δ-4VIM and δ-4DOM are much more accurate than δ-4AA.

Cloud radiative transfer for Infrared radiation

b. Multilayer atmosphere



Cloud radiative transfer for Infrared radiation

Efficiency

Computing times of various infrared radiative transfer methods (normalized by the computing time of δ-2AA)

	δ-2AA	δ-2DOM	δ-2VIM	δ-4AA	δ-4DOM	δ-4VIM
Algorithm only	1.00	2.22	2.04	1.44	14.82	5.36
Radiation model	1.00	1.41	1.38	1.11	5.90	2.27

δ-2VIM is slightly faster than δ-2DOM

δ-4VIM is more than twice as fast as δ-4DOM

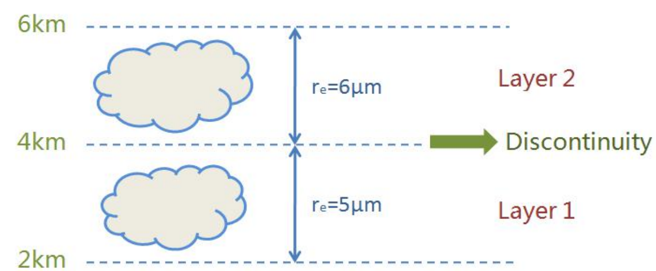
Zhang et al. J. Atmos. Sci., 2017

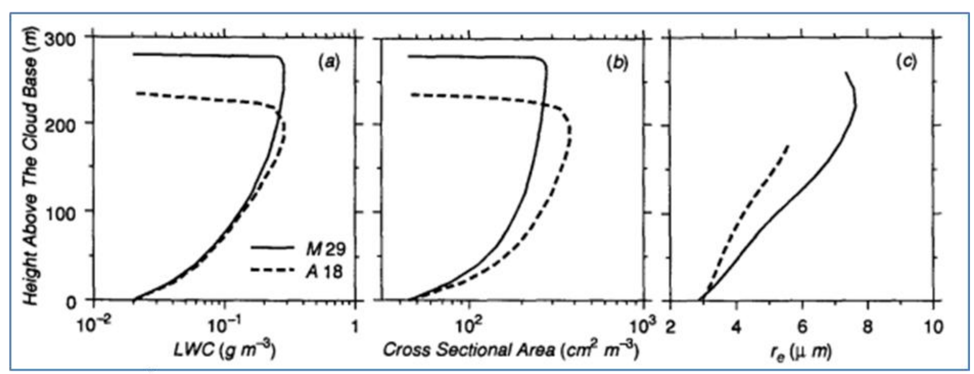
Vertically internally inhomogeneous Cloud

- 已有大量观测表明，云的微物理结构随距离云底的高度增加呈较大的变化。对于典型的对流云而言，其云水含量在云底分布最少，随着距离云底高度的增加而增加，在接近云顶处达到最大；而通常在对流云上层观测到的云滴大小比云的下层大。

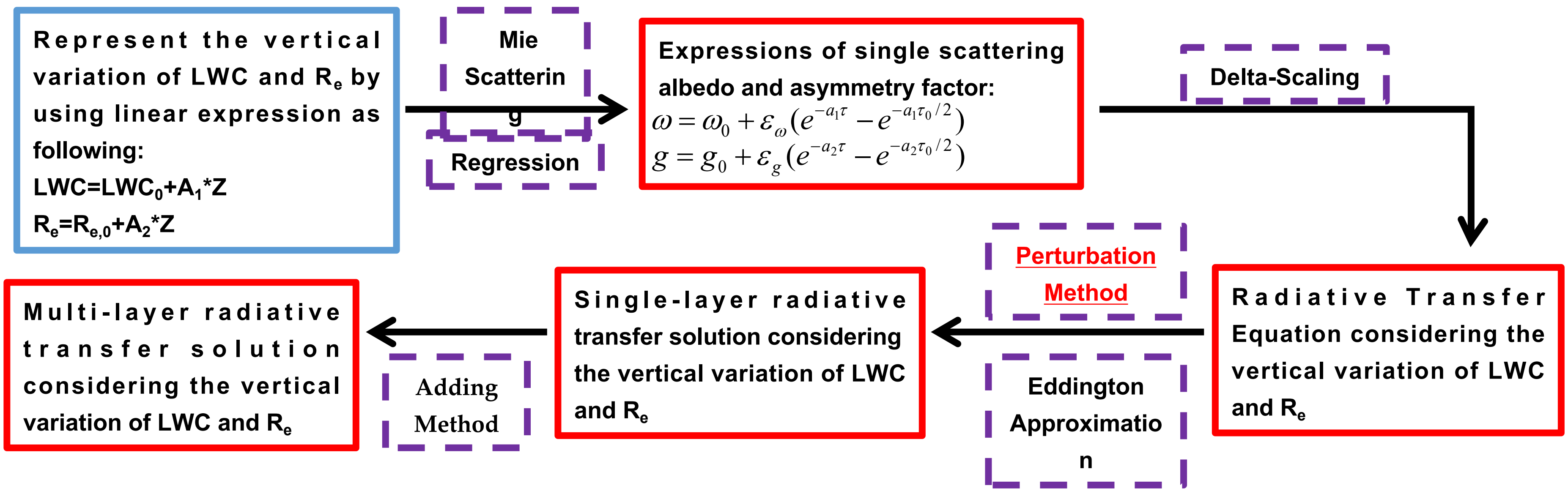
- 现有模式中将网格尺度的云微物理特性进行不连续分层的做法破坏了云微物理特性变化的连续性，从而导致模式层交界处的云微物理特性存在突变。

Li et al.,1994;
Duan et al., 2010





Vertically internally inhomogeneous Cloud



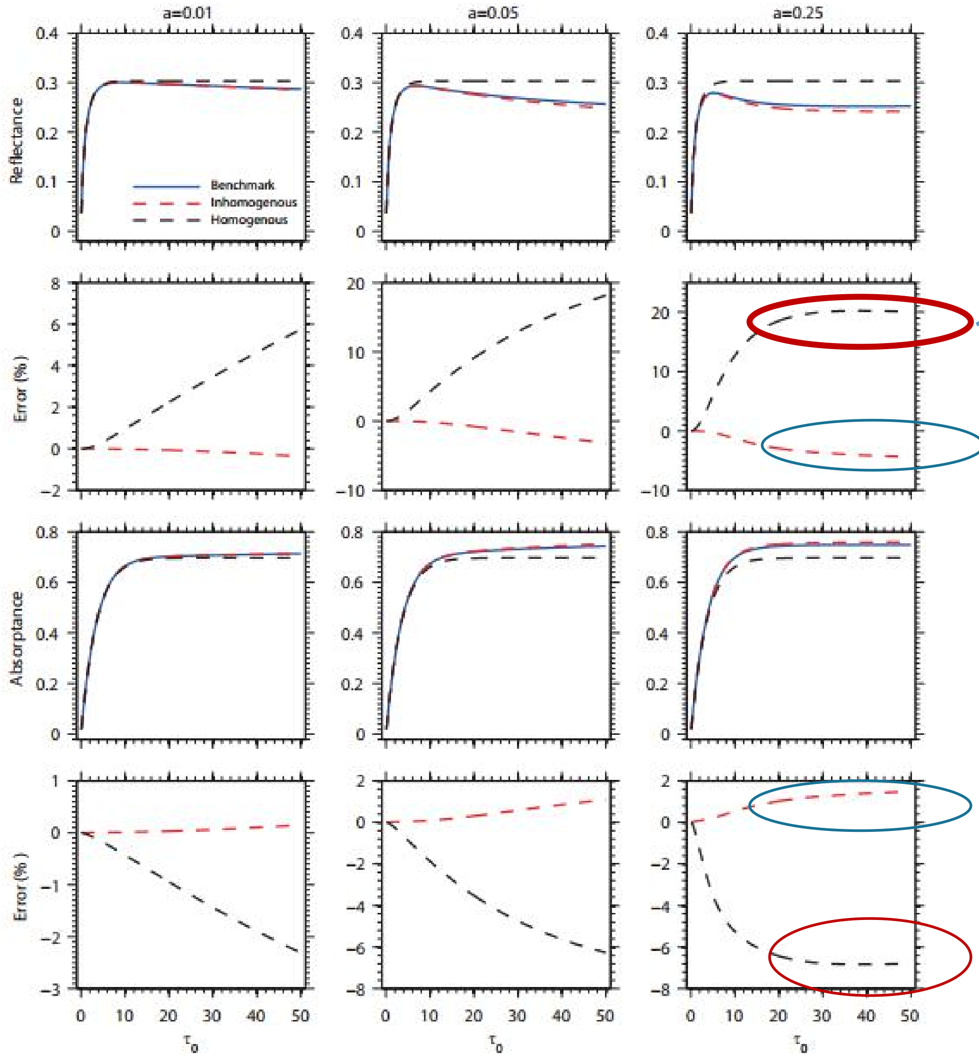
$$F^+ = F_0^+ + \varepsilon_\omega F_1^+ + \varepsilon_g F_2^+ ,$$

$$F^- = F_0^- + \varepsilon_\omega F_1^- + \varepsilon_g F_2^- .$$

$$\frac{dF^+}{d\tau} = \left[\gamma_1^0 + \gamma_1^1 \varepsilon_\omega \left(e^{-a\tau} - e^{-a\tau_0/2}\right) + \gamma_1^2 \varepsilon_g \left(\mathrm{e}^{-b\tau} - e^{-b\tau_0/2}\right)\right]\left(F_0^+ + F_1^+ \varepsilon_\omega + F_2^+ \varepsilon_g\right)$$
$$- \left[\gamma_2^0 + \gamma_2^1 \varepsilon_\omega \left(e^{-a\tau} - e^{-a\tau_0/2}\right) + \gamma_2^2 \varepsilon_g \left(e^{-b\tau} - e^{-b\tau_0/2}\right)\right]\left(F_0^- + F_1^- \varepsilon_\omega + F_2^- \varepsilon_g\right)$$
$$- \left[\hat{\omega}\gamma_3^0 + \gamma_3^0 \varepsilon_\omega (\mathrm{e}^{-a\tau} - \mathrm{e}^{-a\tau_0/2}) + \hat{\omega}\gamma_3^2 \varepsilon_g (\mathrm{e}^{-b\tau} - \mathrm{e}^{-b\tau_0/2})\right] F_s e^{-\tau/\mu_0}$$

Vertically internally inhomogeneous Cloud

1. Idealized medium



homogeneous solutions

inhomogeneous solutions

$$g(\tau) = 0.75$$

$$\omega(\tau) = 0.9 - 0.05(e^{-a\tau} - e^{-a\tau_0/2}).$$

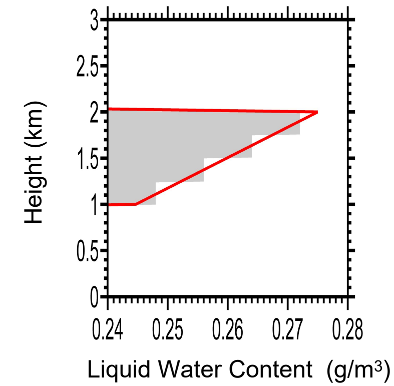
Zhang et al. J. Atmos. Sci., 2018

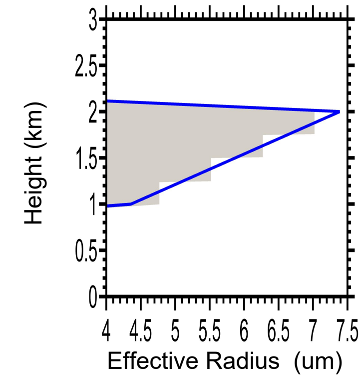
Vertically internally inhomogeneous Cloud

The accuracy and efficiency of the new radiative transfer scheme :

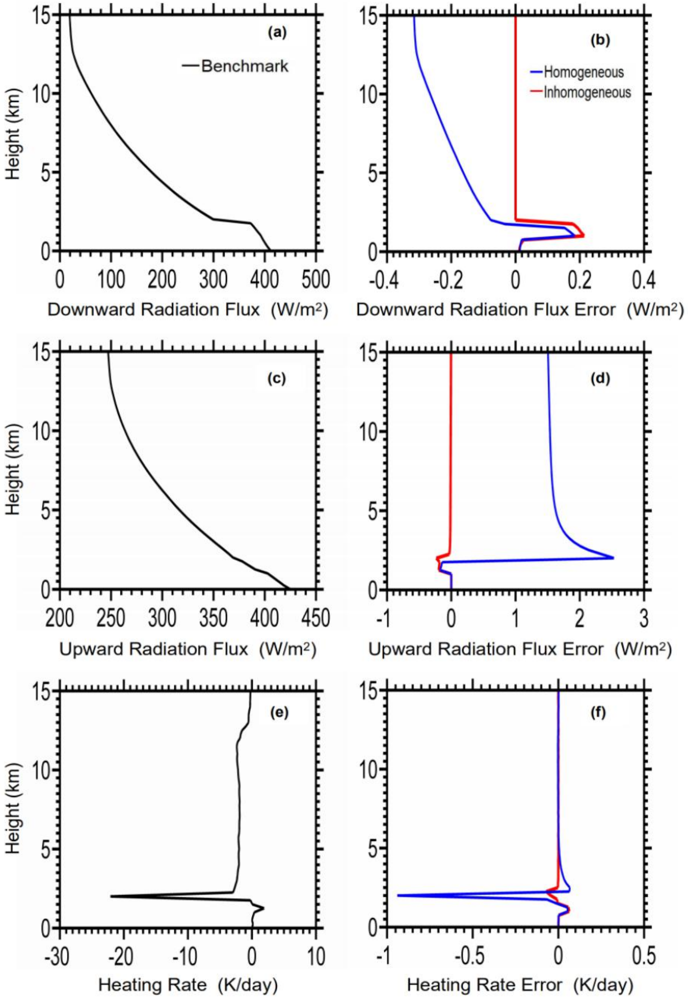
Simulating Description

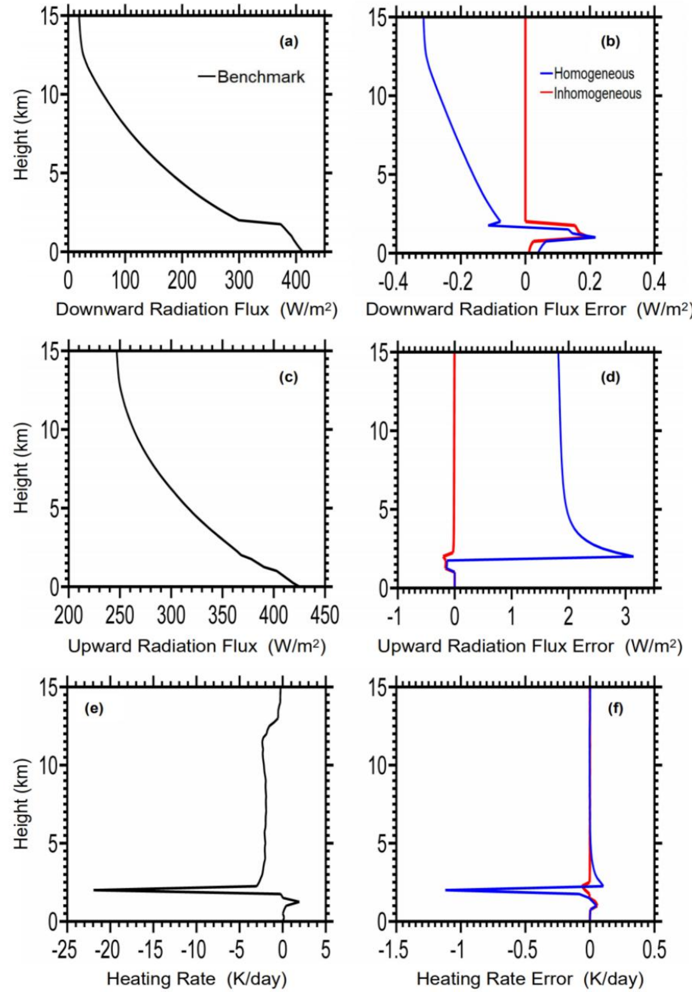
Name	Benchmark	Homogeneous	Inhomogeneous
Atmospheric Profile	The midlatitude winter atmosphere with a subdivision of 400 layers each of which having a geometrical thickness of 0.25 km.		
Cloud Location	1 - 2 km		
Vertical Resolution of Cloudy Area	100 layer	4 layer	4 layer
LWC within Cloud ($g\ m^{-3}$)	0.245+0.00003z where z varies 0 - 1000 m	0.248, 0.256, 0.264, 0.272	0.245+0.00003z where z varies 0 - 1000 m
R_e within Cloud (um)	4.39+0.003z where z varies 0 - 1000 m	4.77, 5.52, 6.27, 7.02	4.39+0.003z where z varies 0 - 1000 m





Vertically internally inhomogeneous Cloud

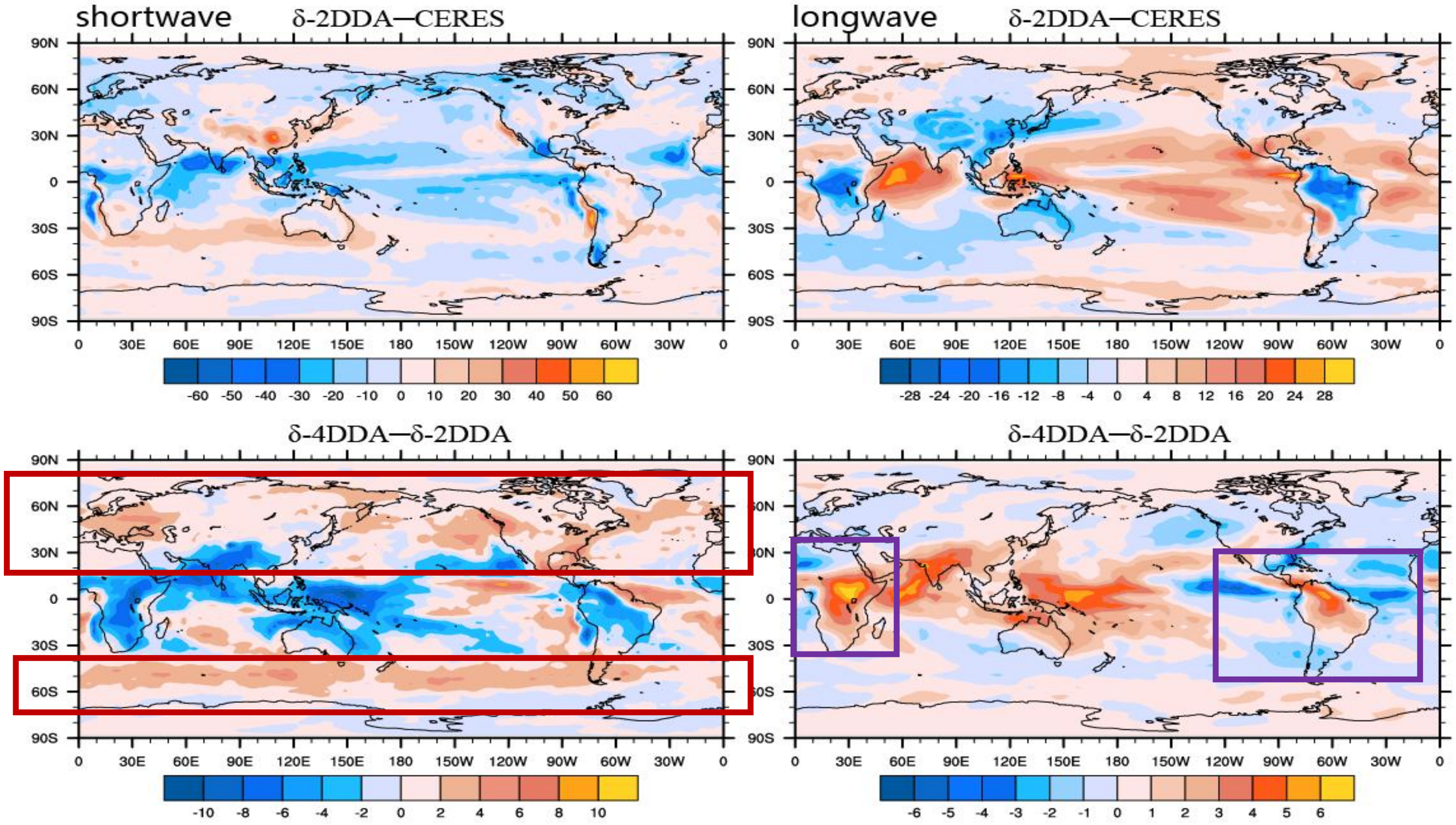




Shi, Zhang*al Optics Express. 2019

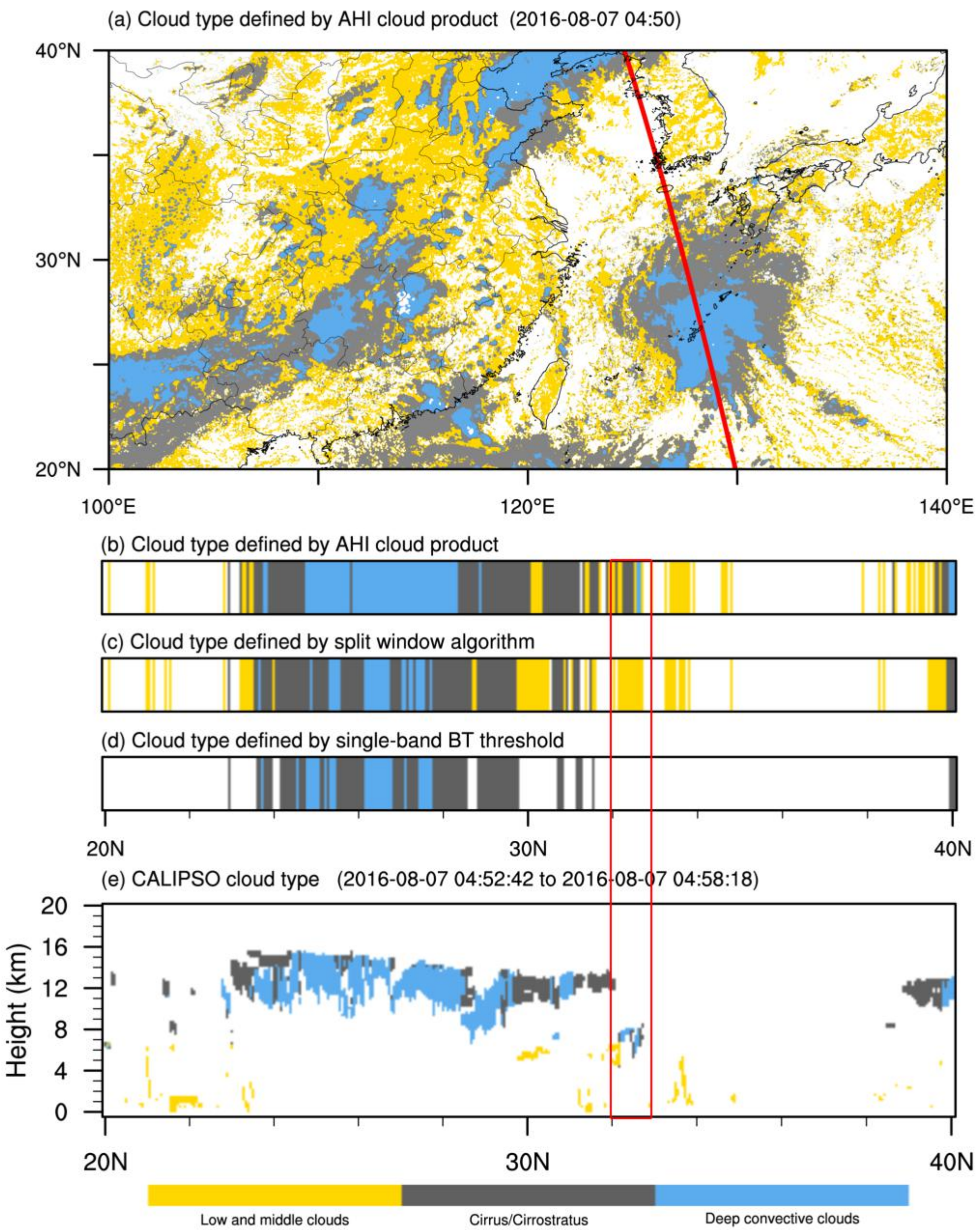
Impact of four-stream adding method on cloud radiative effects in climate model

- BCC_AGCM2.0.1
- Run Time: 1975-2010, last 30 years for analysis



Yang, Zhang*al JQSRT., 2019

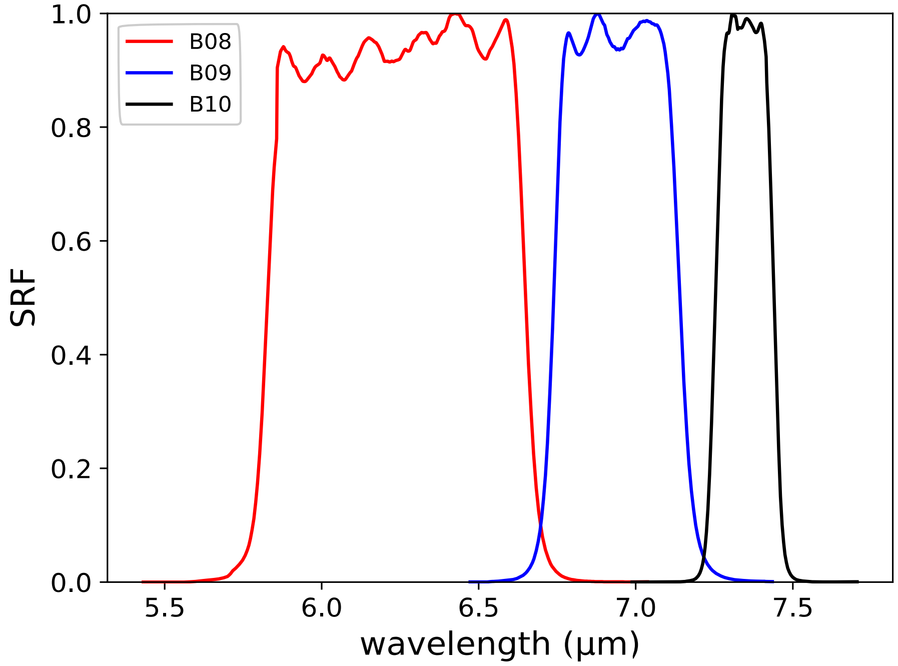
DCS identification



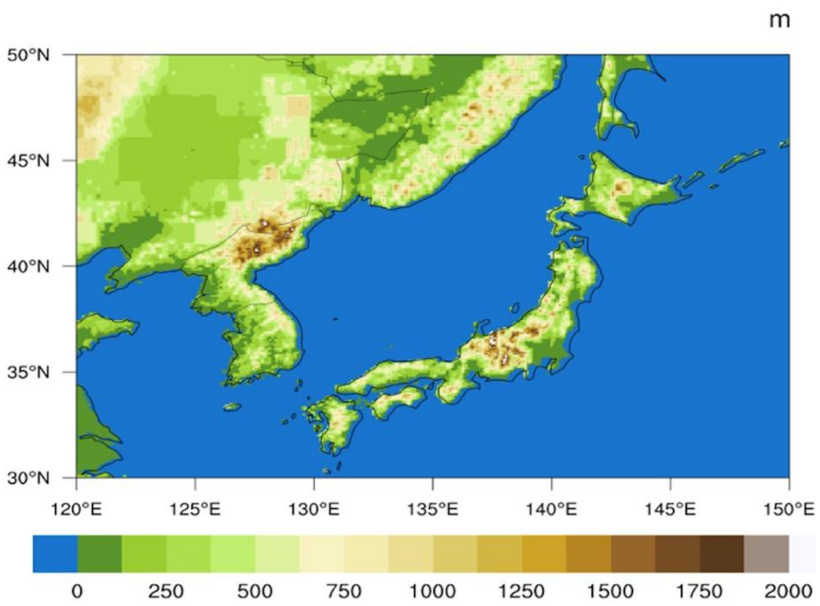
Cloud type map from AHI cloud product based on ISCCP at 04:50 UTC on 7 August 2016 over region (20°N-40°N, 100°W-140°W) with CALIPSO orbit indicated by the red line.

Li，Zhang* et al.,
Submitted to Climate Dynamics

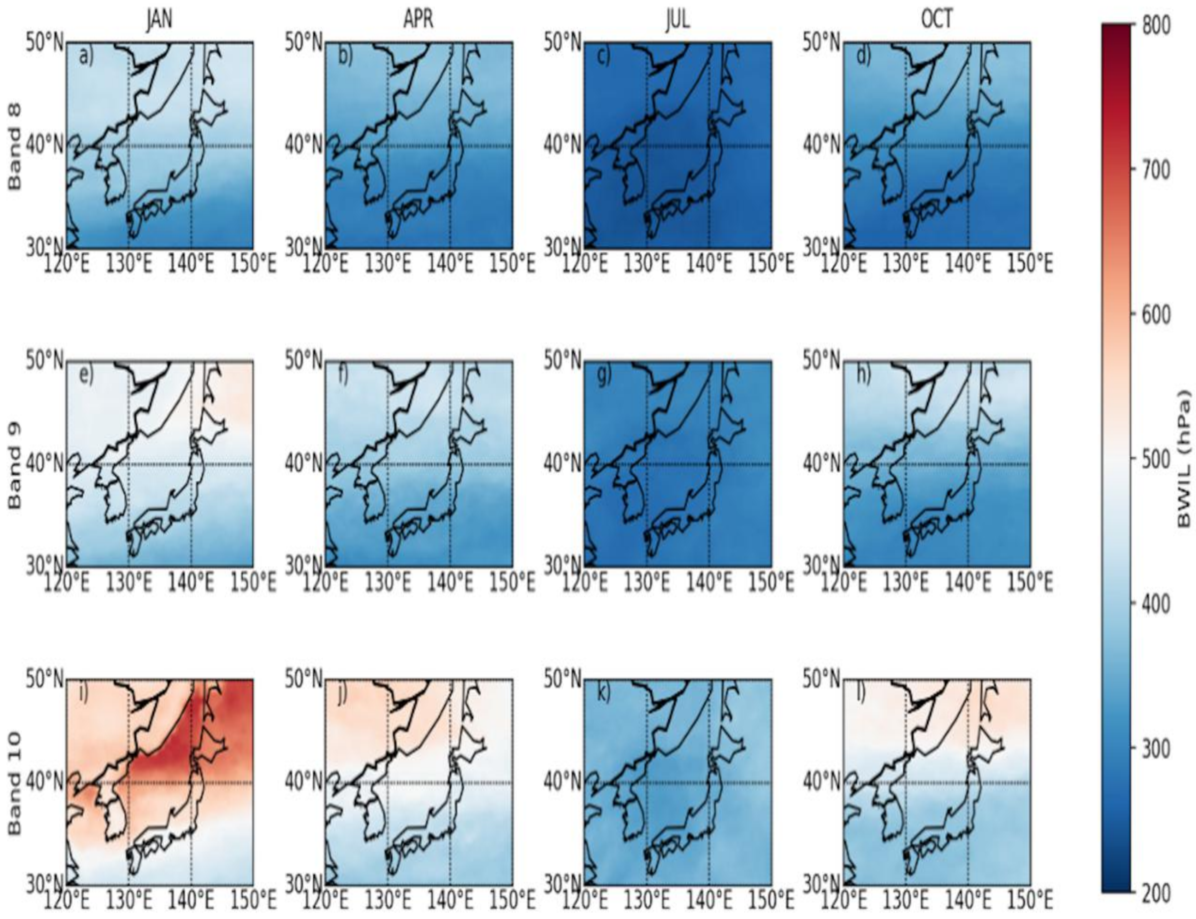
Best Water Vapor Information Layer



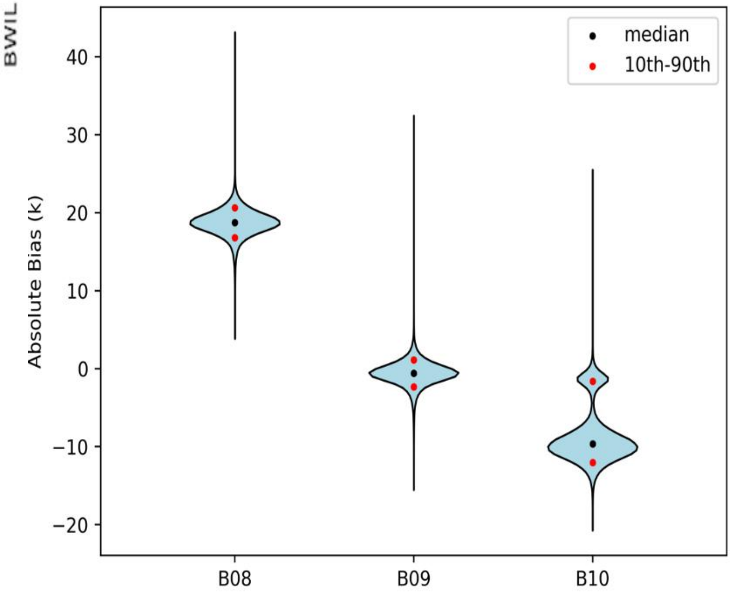
SRFs of the water vapor absorption IR bands for AHI.



Elevation distribution over the typical region of Ea
Asia. Units are m.



The mean height of BWIL over the typical region of East Asia in January, April, July and October



The violin plot of absolute biases between the AHI observations and simulated brightness temperatures for Band 8, Band 9 and Band 10.

Wu You, Feng Zhang*, et al, Sensors,2020

THANKS!

Zhang Feng

Email:fengzhang@fudan.edu.cn

Homepage:https://atmsci.fudan.edu.cn/60/f3/c14809a221427/page.htm