APRP method (Taylor et al. 2007)

Extension to surface component

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Decomposition of shortwave flux change

S : Insolation / A : Planetary albedo / α : Surface albedo / $\widehat{Q_S^{\downarrow}}$: Ratio of incident surface flux to the insolation

$$SW_{TOA} = SW_{TOA}^{\downarrow} - SW_{TOA}^{\uparrow} = S(1 - A)$$

$$\Delta SW_{TOA,1\rightarrow 2} = (S_1 + \Delta S)(1 - A_1 - \Delta \mathrm{A}) - S_1(1 - A_1) = \Delta S(1 - A_1 - \Delta A) - S_1 \Delta A$$

$$\Delta SW_{TOA,2\rightarrow 1} = (S_2 - \Delta S)(1 - A_2 + \Delta \mathrm{A}) - S_2(1 - A_2) = -\Delta S(1 - A_2 + \Delta A) + S_2 \Delta A$$

$$\Delta SW_{TOA} = 0.5 * \left(\Delta SW_{TOA,1\rightarrow 2} - \Delta SW_{TOA,2\rightarrow 1}\right) = \Delta S(1 - A) - S\Delta A$$

$$A = 0.5 * (A_1 + A_2) \ , \ S = 0.5 * (S_1 + S_2)$$

$$SW_{SFC} = SW_{SFC}^{\downarrow} - SW_{SFC}^{\uparrow} = S\widehat{Q_S^{\downarrow}}(1 - \alpha)$$

$$\Delta SW_{SFC} = \Delta(S\widehat{Q_S^{\downarrow}})(1 - \alpha) - S\widehat{Q_S^{\downarrow}}\Delta\alpha$$

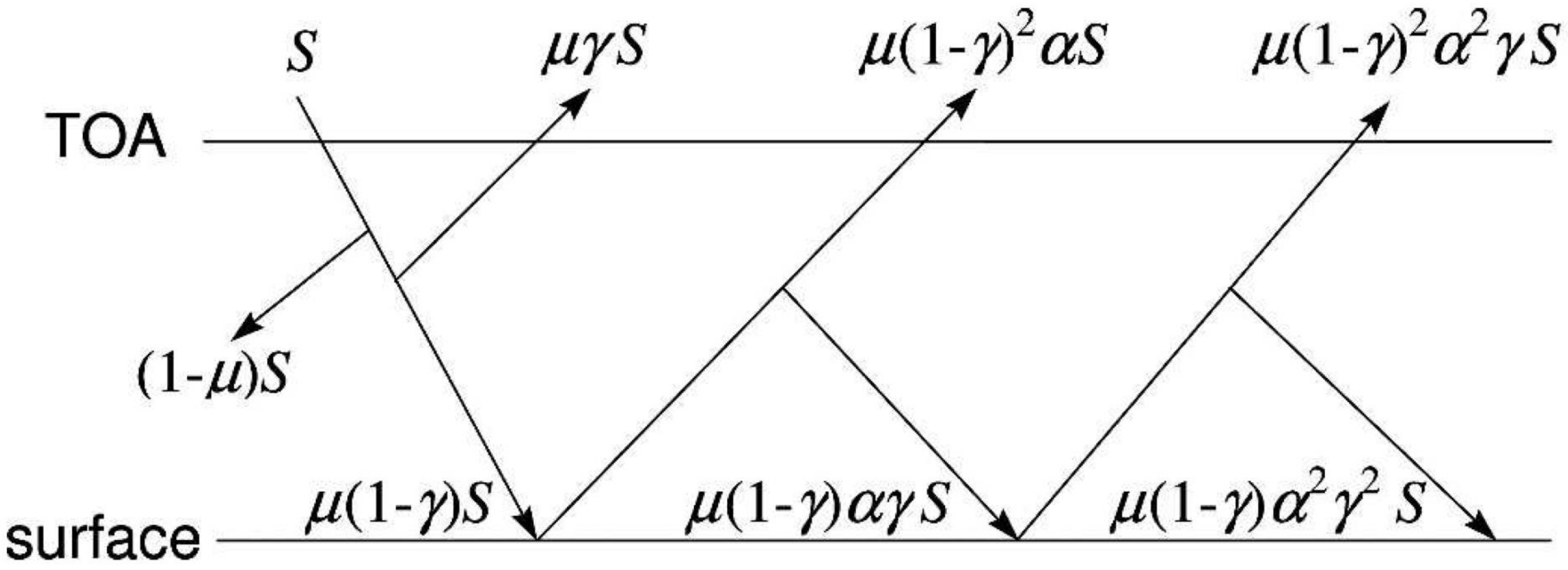
$$\Delta SW_{SFC} = \Delta S\widehat{Q_S^{\downarrow}}(1 - \alpha) + S\Delta\widehat{Q_S^{\downarrow}}(1 - \alpha) - S\widehat{Q_S^{\downarrow}}\Delta\alpha$$

$$\Delta SW_{TOA} = \Delta(S(1 - A)\ ) = (1 - A)\Delta S - S\Delta A$$

$$\Delta SW_{SFC} = \Delta(S\widehat{Q_S^{\downarrow}}(1 - \alpha)) = \widehat{Q_S^{\downarrow}}(1 - \alpha)\Delta S - S\widehat{Q_S^{\downarrow}}\Delta\alpha + S(1 - \alpha)\Delta\widehat{Q_S^{\downarrow}}$$

One-layer radiation model

Net TOA and SFC shortwave fluxes could be represented by three parameters (α, γ, μ) in this model



α : surface albedo

γ : atmospheric scattering

$1-\mu$: atmospheric absorptance

Assumption 1 : Atmospheric SW absorption occurs only at first pass

$$A(\alpha,\gamma,\mu) = \frac{SW_{TOA}^{\uparrow}}{SW_{TOA}^{\downarrow}} = \mu\gamma + \mu(1-\gamma^2)\alpha(1+\alpha\gamma+\alpha^2\gamma^2+\cdots) = \mu\gamma + \frac{\mu\alpha(1-\gamma)^2}{1-\alpha\gamma}$$

$$\widehat{Q_S^{\downarrow}}(\alpha,\gamma,\mu) = \frac{SW_{SFC}^{\downarrow}}{SW_{TOA}^{\downarrow}} = \mu(1-\gamma)(1+\alpha\gamma+\alpha^2\gamma^2+\cdots) = \frac{\mu(1-\gamma)}{1-\alpha\gamma}$$

One-layer radiation model

Assumption 2 : Non-cloud constituents in overcast sky will absorb and scatter same amount as in clear-sky

$$\mu_{oc} = \mu_{clr} * \mu_{cld}$$

$$1 - \gamma_{oc} = (1 - \gamma_{clr}) * (1 - \gamma_{cld})$$

$$A(\alpha, \gamma, \mu) = A(c, \alpha_{clr}, \alpha_{oc}, \mu_{clr}, \mu_{cld}, \gamma_{clr}, \gamma_{cld}) = (1 - c) * A_{clr}(\alpha_{clr}, \gamma_{clr}, \mu_{clr}) + c * A_{oc}(\alpha_{oc}, \gamma_{oc}, \mu_{oc})$$

$$\widehat{Q_S^{\downarrow}}(\alpha, \gamma, \mu) = \widehat{Q_S^{\downarrow}}(c, \alpha_{clr}, \alpha_{oc}, \mu_{clr}, \mu_{cld}, \gamma_{clr}, \gamma_{cld}) = (1 - c) * \widehat{Q_S^{\downarrow}}_{clr}(\alpha_{clr}, \gamma_{clr}, \mu_{clr}) + c * \widehat{Q_S^{\downarrow}}_{oc}(\alpha_{oc}, \gamma_{oc}, \mu_{oc})$$

$$\Delta A_t = 0.5 * \left(A(t_2, o_1) - A(t_1, o_1)\right) + 0.5 * \left(A(t_2, o_2) - A(t_1, o_2)\right)$$

$$\Delta A = \Delta A_c + \Delta A_{\alpha_{clr}} + \Delta A_{\alpha_{oc}} + \Delta A_{\mu_{clr}} + \Delta A_{\mu_{cld}} + \Delta A_{\gamma_{clr}} + \Delta A_{\gamma_{cld}}$$

$$\Delta\widehat{Q_S^{\downarrow}} = \Delta\widehat{Q_S^{\downarrow}}_c + \Delta\widehat{Q_S^{\downarrow}}_{\alpha_{clr}} + \Delta\widehat{Q_S^{\downarrow}}_{\alpha_{oc}} + \Delta\widehat{Q_S^{\downarrow}}_{\mu_{clr}} + \Delta\widehat{Q_S^{\downarrow}}_{\mu_{cld}} + \Delta\widehat{Q_S^{\downarrow}}_{\gamma_{clr}} + \Delta\widehat{Q_S^{\downarrow}}_{\gamma_{cld}}$$

$$\Delta SW_{TOA} = (1 - A)\Delta S - S\Delta A$$

$$\Delta SW_{SFC} = \widehat{Q_S^{\downarrow}}(1 - \alpha)\Delta S - S\widehat{Q_S^{\downarrow}}\Delta\alpha + S(1 - \alpha)\Delta\widehat{Q_S^{\downarrow}}$$

If we get blue variables, we can decompose net SW change into change due to each variables!

Adjustment of parameters to model output

Input : $rsds, rsus, rsut, rsdt, rsutcs, rsdscs, rsuscs, clt$

$R = (1 - clt) * R_{clr} + clt * R_{oc}$, $R = rsut, rsds, rsus$

$$\alpha_{clr} = \frac{rsuscs}{rsds} \quad A_{clr} = \frac{rsutcs}{rsdt} \quad \widehat{Q_S^{\downarrow}}_{clr} = \frac{rsdscs}{rsdt} \quad 1 - \mu_{clr} = 1 - A_{clr} - \widehat{Q_S^{\downarrow}}_{clr}(1 - \alpha_{clr}) \quad \widehat{Q_S^{\downarrow}}_{clr} = \frac{\mu_{clr}(1 - \gamma_{clr})}{1 - \alpha_{clr}\gamma_{clr}}$$

$$\alpha_{oc} = \frac{rsusoc}{rsds} \quad A_{oc} = \frac{rsutcs}{rsdt} \quad \widehat{Q_S^{\downarrow}}_{oc} = \frac{rsdsoc}{rsdt} \quad 1 - \mu_{oc} = 1 - A_{oc} - \widehat{Q_S^{\downarrow}}_{oc}(1 - \alpha_{oc}) \quad \widehat{Q_S^{\downarrow}}_{oc} = \frac{\mu_{clr}(1 - \gamma_{oc})}{1 - \alpha_{clr}\gamma_{oc}}$$

$$\mu_{oc} = \mu_{clr} * \mu_{cld} \quad 1 - \gamma_{oc} = (1 - \gamma_{clr}) * (1 - \gamma_{cld})$$

$$\Delta A = \Delta A_c + \Delta A_{\alpha_{clr}} + \Delta A_{\alpha_{oc}} + \Delta A_{\mu_{clr}} + \Delta A_{\mu_{cld}} + \Delta A_{\gamma_{clr}} + \Delta A_{\gamma_{cld}}$$

$$\Delta \widehat{Q_S^{\downarrow}} = \Delta \widehat{Q_S^{\downarrow}}_c + \Delta \widehat{Q_S^{\downarrow}}_{\alpha_{clr}} + \Delta \widehat{Q_S^{\downarrow}}_{\alpha_{oc}} + \Delta \widehat{Q_S^{\downarrow}}_{\mu_{clr}} + \Delta \widehat{Q_S^{\downarrow}}_{\mu_{cld}} + \Delta \widehat{Q_S^{\downarrow}}_{\gamma_{clr}} + \Delta \widehat{Q_S^{\downarrow}}_{\gamma_{cld}}$$

$$\Delta SW_{TOA} = (1 - A)\Delta S - S(\Delta A_{clt} + \Delta A_{\alpha_{clr}} + \Delta A_{\alpha_{oc}} + \Delta A_{\mu_{clr}} + \Delta A_{\mu_{cld}} + \Delta A_{\gamma_{clr}} + \Delta A_{\gamma_{cld}})$$

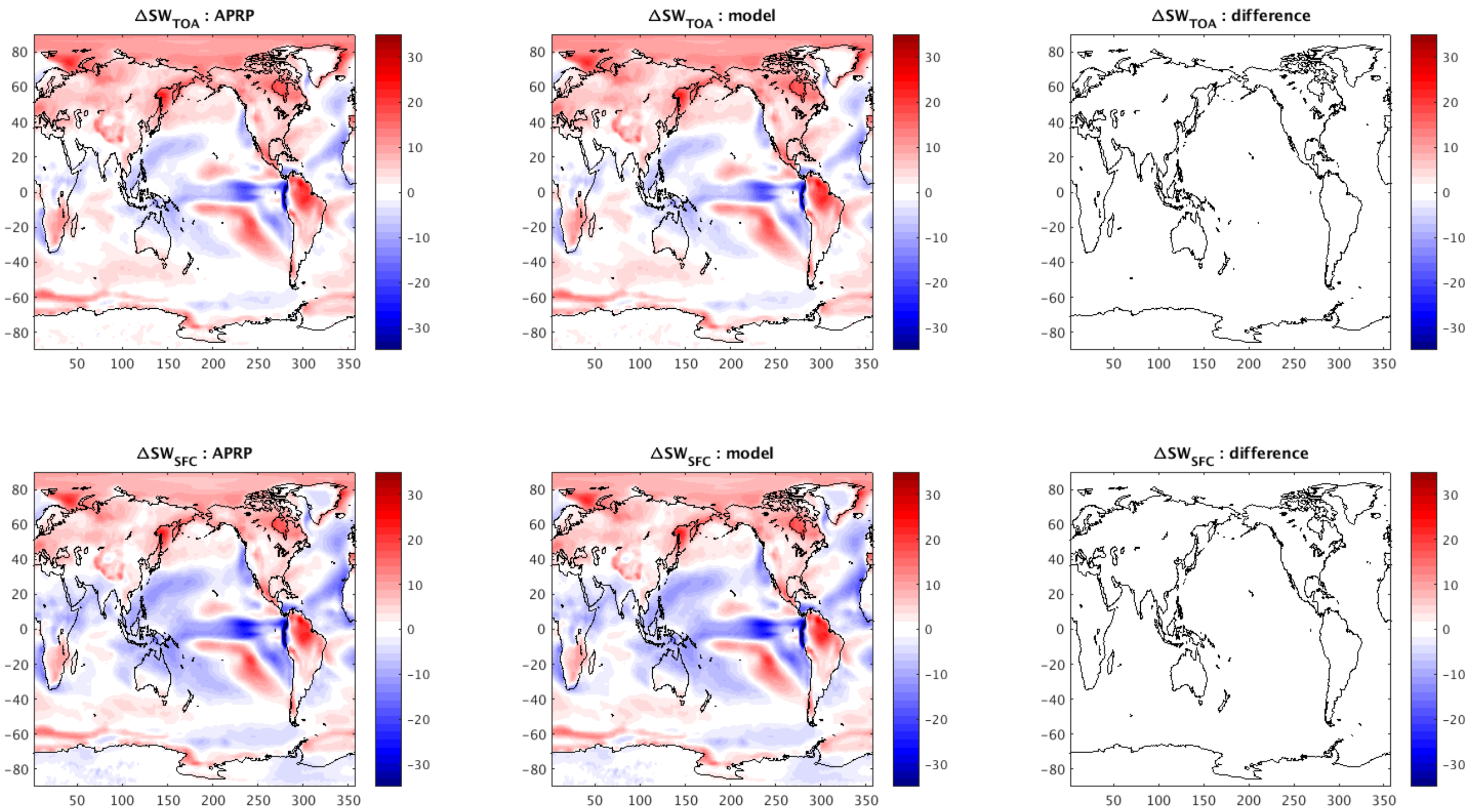
$$\Delta SW_{SFC} = \widehat{Q_S^{\downarrow}}(1 - \alpha)\Delta S - S\widehat{Q_S^{\downarrow}}\Delta\alpha + S(1 - \alpha)(\Delta \widehat{Q_S^{\downarrow}}_{clt} + \Delta \widehat{Q_S^{\downarrow}}_{\alpha_{clr}} + \Delta \widehat{Q_S^{\downarrow}}_{\alpha_{oc}} + \Delta \widehat{Q_S^{\downarrow}}_{\mu_{clr}} + \Delta \widehat{Q_S^{\downarrow}}_{\mu_{cld}} + \Delta \widehat{Q_S^{\downarrow}}_{\gamma_{clr}} + \Delta \widehat{Q_S^{\downarrow}}_{\gamma_{cld}})$$

Attribution of SW change to each radiative properties

$$\Delta SW_{TOA} = (1 - A)\Delta S - S(\Delta A_{\alpha_{oc}} + \Delta A_{\alpha_{clr}}) - S(\Delta A_{clt} + \Delta A_{\mu_{cld}} + \Delta A_{\gamma_{cld}}) - S(\Delta A_{\mu_{clr}} + \Delta A_{\gamma_{clr}})$$

$$\Delta SW_{SFC} = \widehat{Q_S^{\downarrow}}(1 - \alpha)\Delta S - S\widehat{Q_S^{\downarrow}}\Delta\alpha + S(1 - \alpha)\left(\Delta\widehat{Q_S^{\downarrow}}_{\alpha_{oc}} + \Delta\widehat{Q_S^{\downarrow}}_{\alpha_{clr}}\right) + S(1 - \alpha)\left(\Delta\widehat{Q_S^{\downarrow}}_{clt} + \Delta\widehat{Q_S^{\downarrow}}_{\mu_{cld}} + \Delta\widehat{Q_S^{\downarrow}}_{\gamma_{cld}}\right) + S(1 - \alpha)(\Delta\widehat{Q_S^{\downarrow}}_{\mu_{clr}} + \Delta\widehat{Q_S^{\downarrow}}_{\gamma_{clr}})$$

Insolation effect | Surface albedo effect | Cloud effect | Non-cloud effect



The variations of one-layer model in APRP method

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Introduction

- Motivation

Let's attribute change in shortwave flux (ΔSW) to each climate agents (surface albedo, cloud, clear-sky constituents)

- Partial Radiative Perturbation (PRP) method [*Wetherald and Manabe, 1988; Colman and McAvaney, 1997;*]

model specific radiation code, most accurate

- Radiative kernel technique [*Soden and held 2006*]

model specific pre-calculation, not accurate for non-linear change

- Approximate Partial Radiative Perturbation (APRP) method [*Taylor et al., 2007*]

one-layer model tuned to mimic model radiation code, can explain non-linear change

reasonable match with PRP method for slab ocean experiments (2co2, LGM)

<u>can be utilized for multi-model analysis or experiments with different radiation parameterization</u>

Physical basis for APRP method [*Winton, 2005*]

- Essential ingredients for correctly representing atmosphere-surface interaction of SW flux

Shielding: The atmosphere shields the surface by reflecting and absorbing a certain fraction of the downward radiation. The shielding effect of the atmosphere is characterized by its transmissivity to downward radiation

Multiple reflection: Radiation reaching the surface may undergo several reflections between the clouds and surface before being absorbed or escaping from the surface. The albedo of the surface and of the atmosphere to upward radiation both contribute to multiple reflection

Atmospheric compensation: Upward radiation from the surface may be absorbed by the atmosphere before it can escape to space. The absorptivity of the atmosphere to upward radiation is its most important quality for this atmospheric compensation effect

- Estimation of radiative parameters using model modification

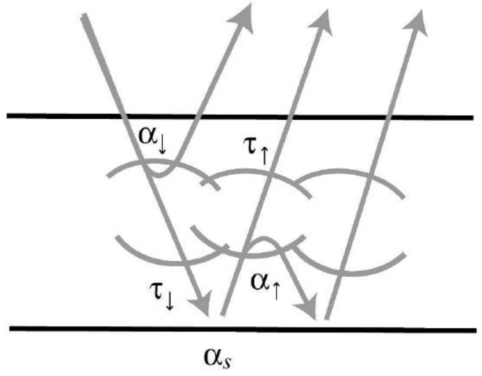
$$S_{T\uparrow} = \alpha_{\downarrow} S_{T\downarrow} + \tau_{\uparrow} S_{B\uparrow} \quad (1)$$

$$S_{B\downarrow} = \tau_{\downarrow} S_{T\downarrow} + \alpha_{\uparrow} S_{B\uparrow} \quad (2)$$

$$S_{B\uparrow} = \alpha_S S_{B\downarrow}, \quad (3)$$

$$S_{T\uparrow}(\alpha_S = 0) = \alpha_{\downarrow} S_{T\downarrow} \quad (4)$$

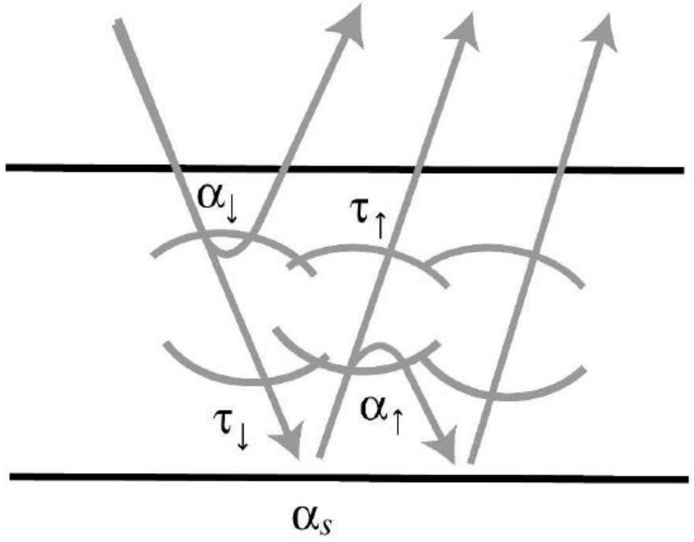
$$S_{B\downarrow}(\alpha_S = 0) = \tau_{\downarrow} S_{T\downarrow}. \quad (5)$$



By setting surface albedo as 0, atmospheric transmissivity and the reflectivity could be measured for each grid and time. So the results are relatively accurate in this study

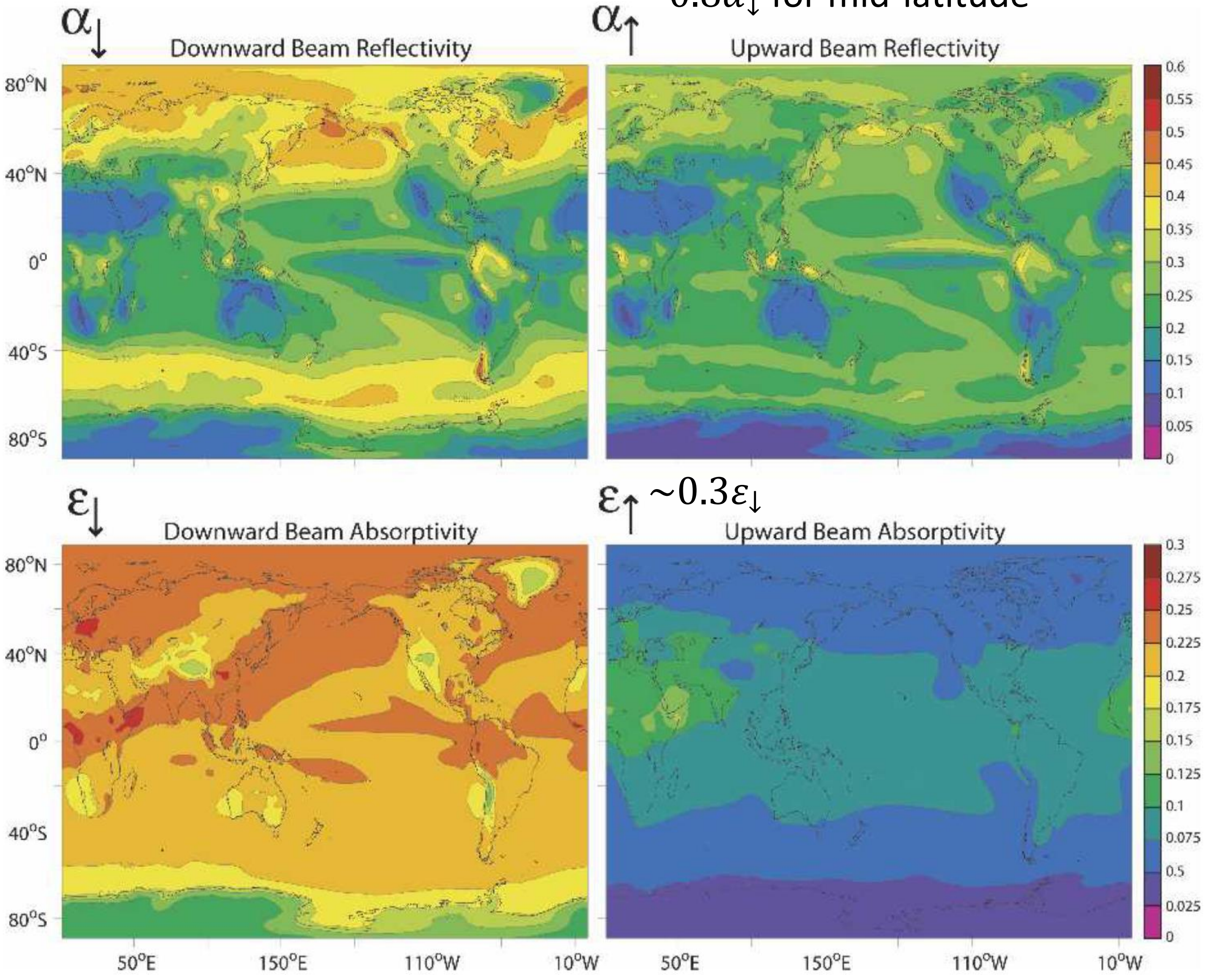
Physical basis for APRP method [*Winton, 2005*]

- Estimations of atmospheric radiative properties



$\sim 0.8\alpha_\downarrow$ for mid-latitude

$\sim 0.3\varepsilon_\downarrow$



- Discussions

1) Downward radiation is partly direct and partly diffusive, while the upward shortwave is diffusive → radiative properties to the upward and downward beam is different.

2) Atmospheric absorption occurs in specific spectral bands → Second absorption of reflected SW is small

3) Difference in the vertical distribution of absorption and reflection can affect the result

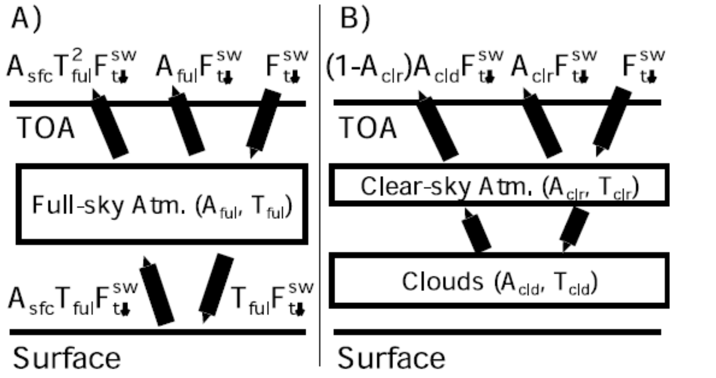
One-layer model to mimic the radiation code

- One-layer SW radiation model : *Yokohata et al., 2005 / Taylor et al., 2007 / Donohoe et al., 2011*

In these studies, planetary albedo change (ΔSW_{TOA}) is attributed to each radiative properties (α, μ, γ) change. However, change in surface SW flux (ΔSW_{SFC}) is not diagnosed.

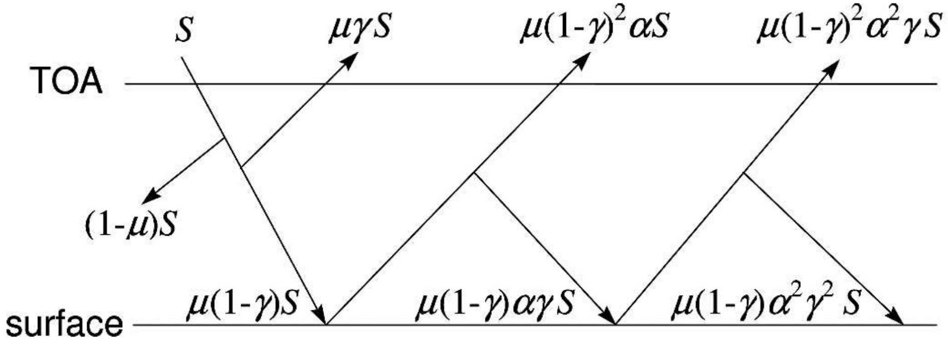
Especially, T07 consider the cloud effect, and reasonably attribute the SW change to cloud, surface albedo, and non-cloud constituents.

Yokohata et al., 2005



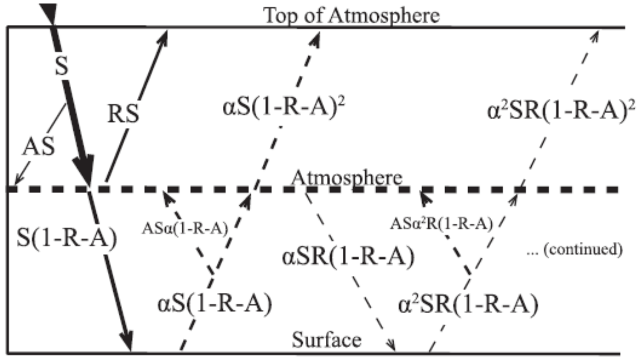
- ✓ Single reflection and double absorptions
- ✓ Separation for cloud effect
- ✓ Same treatment for upward and downward beam

Taylor et al., 2007



- ✓ Multiple reflections and single absorption
- ✓ Separation for cloud effect
- ✓ Same treatment for upward and downward beam

Donohoe et al., 2011



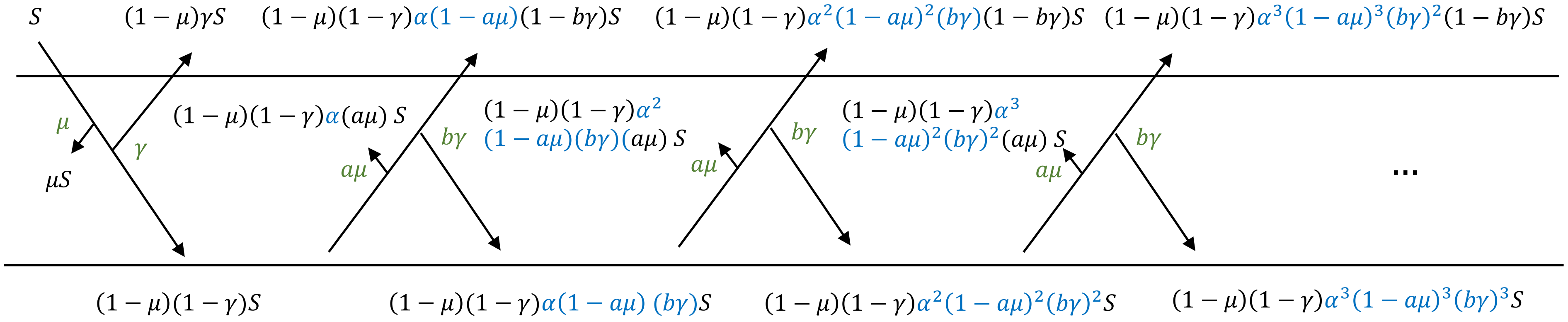
- ✓ Multiple reflections and absorptions
- ✓ No separation for cloud effect
- ✓ Same treatment for upward and downward beam

From *Winton, 2005*, radiation model has to accounts for **shielding, multiple reflection, and atmospheric compensation** (5~10%).

→ **How about the model with (multiple reflections and absorptions) + (separation for cloud effect) + (different treatment for upward and downward beam) + (extension to the surface component)? → two versions!**

One-layer radiation model (in sequence, variation of *Taylor et al., 2007*)

Absorption and reflection in sequence



a : ratio of upward beam absorptivity to downward beam absorptivity

b : ratio of upward beam reflectivity to downward beam reflectivity

W05 : a≈0.3, b≈0.8 / **T07 : a=0, b=1**

① : $A = (1-\mu)\gamma + (1-\mu)(1-\gamma)(1-a\mu)(1-b\gamma)\alpha[1+(1-a\mu)\alpha(b\gamma)+(1-a\mu)^2\alpha^2(b\gamma)^2+\cdots] = (1-\mu)\gamma + \frac{(1-\mu)(1-\gamma)(1-a\mu)(1-b\gamma)}{1-(1-a\mu)\alpha(b\gamma)}\alpha$

② : $SA = \mu + (1-\mu)(1-\gamma)\alpha(a\mu)[1+(1-a\mu)\alpha(b\gamma)+(1-a\mu)^2\alpha^2(b\gamma)^2+\cdots] = \mu + \frac{(1-\mu)(1-\gamma)(a\mu)}{1-(1-a\mu)\alpha(b\gamma)}\alpha$

③ : $Q_s = (1-\mu)(1-\gamma)[1+(1-a\mu)\alpha(b\gamma)+(1-a\mu)^2\alpha^2(b\gamma)^2+\cdots] = \frac{1}{1-(1-a\mu)\alpha(b\gamma)}(1-\mu)(1-\gamma)$

μ : ② & ③ → $1 - A - Q_s(1-\alpha) = \mu + Q_s\alpha(a\mu)$ → $\mu = \frac{1-A-Q_s(1-\alpha)}{1+a\alpha Q_s}$

γ : ③ → $Q_s[1-(1-a\mu)\alpha(b\gamma)] = (1-\mu)(1-\gamma)$ → $\gamma = \frac{1-\mu-Q_s}{1-\mu-(1-a\mu)\alpha b Q_s}$

$R = (1-clt) * R_{clr} + clt * R_{oc}$

$\mu_{oc} = \mu_{clr} * \mu_{cld}$

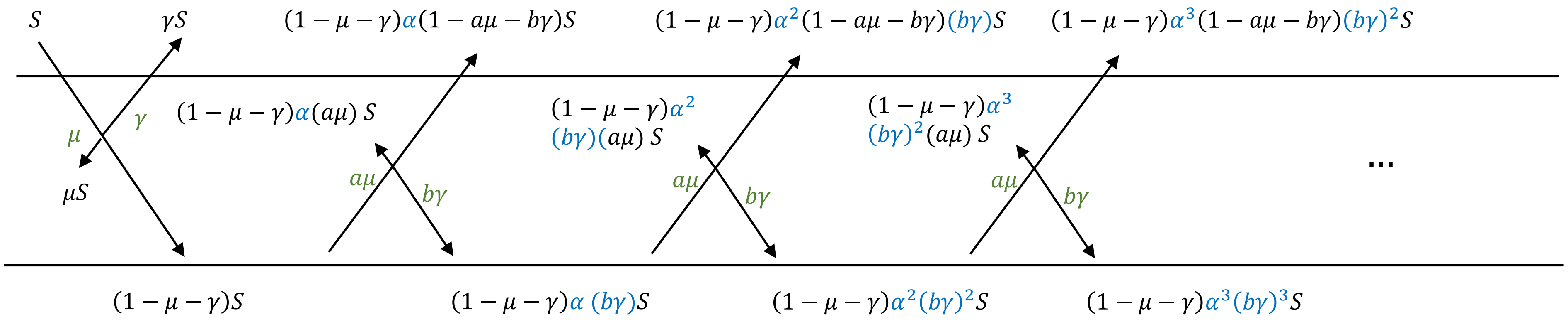
$1-\gamma_{oc} = (1-\gamma_{clr}) * (1-\gamma_{cld})$

$A = (1-clt) * A_{clr} + clt * A_{oc}$

$Q_s = (1-clt) * Q_s + clt * Q_s$

One-layer radiation model (at the same time, variation of *Donohoe et al., 2011*)

Absorption and reflection at the same time



a : ratio of upward beam absorptivity to downward beam absorptivity

b : ratio of upward beam reflectivity to downward beam reflectivity

W05 : a≈0.3, b≈0.8 / **D11 : a=1, b=1**

① : $A = \gamma + (1-\mu-\gamma)(1-a\mu-b\gamma)\alpha[1+\alpha(b\gamma)+\alpha^2(b\gamma)^2+\cdots] = \gamma + \frac{(1-\mu-\gamma)(1-a\mu-b\gamma)}{1-\alpha(b\gamma)}\alpha$

② : $SA = \mu + (1-\mu-\gamma)\alpha(a\mu)\,[1+\alpha(b\gamma)+\alpha^2(b\gamma)^2+\cdots] = \mu + \frac{(1-\mu-\gamma)(a\mu)}{1-\alpha(b\gamma)}\alpha$

③ : $Q_s = (1-\mu-\gamma)\,[1+\alpha(b\gamma)+\alpha^2(b\gamma)^2+\cdots] = \frac{1}{1-\alpha(b\gamma)}(1-\mu-\gamma)$

μ : ② & ③ → $1 - A - Q_s(1-\alpha) = \mu + Q_s\alpha(a\mu)$ → $\mu = \frac{1-A-Q_s(1-\alpha)}{1+a\alpha Q_s}$

γ : ③ → $Q_s[1-\alpha(b\gamma)] = (1-\mu-\gamma)$ → $\gamma = \frac{1-\mu-Q_s}{1-b\alpha Q_s}$

$R = (1-clt) * R_{clr} + clt * R_{oc}$

$\mu_{oc} = \mu_{clr} * \mu_{cld}$

$1-\gamma_{oc} = (1-\gamma_{clr}) * (1-\gamma_{cld})$

$A = (1-clt) * A_{clr} + clt * A_{oc}$

$Q_s = (1-clt) * Q_s + clt * Q_s$