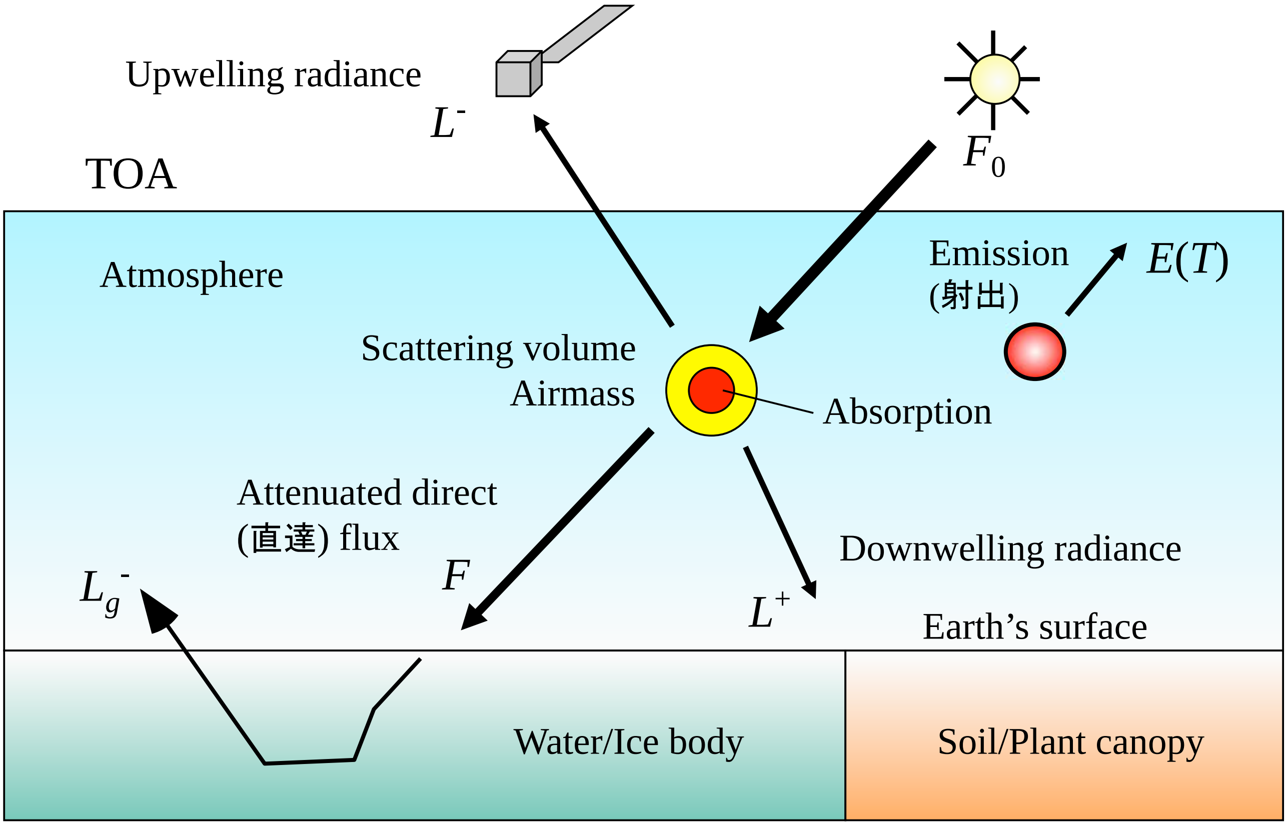
3. Transfer equation (放射伝達方程式)

Transfer of radiation

Extraterrestrial irradiance
Solar insolation



Upwelling radiance

L^-

TOA

F_0

Atmosphere

Emission
(射出)

$E(T)$

Scattering volume
Airmass

Absorption

Attenuated direct
(直達) flux

F

L_g^-

L^+

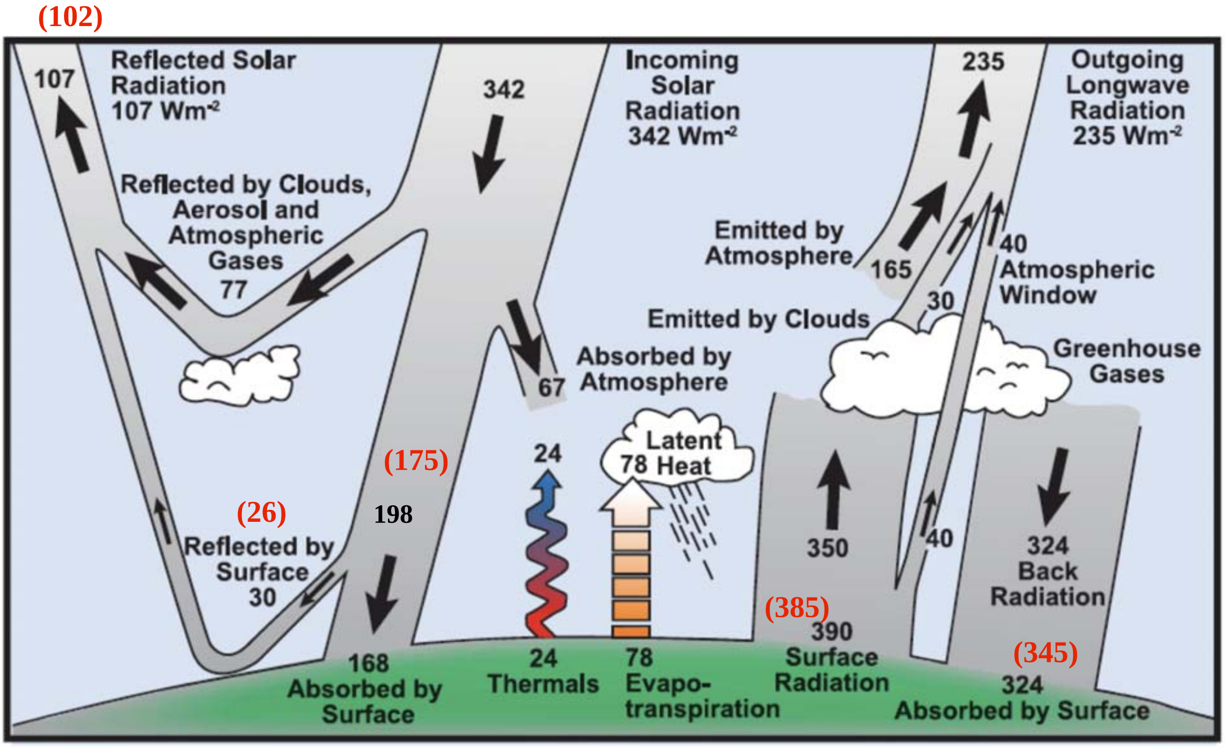
Downwelling radiance

Earth’s surface

Water/Ice body

Soil/Plant canopy

Radiation budget (放射収支) of the atmosphere



FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

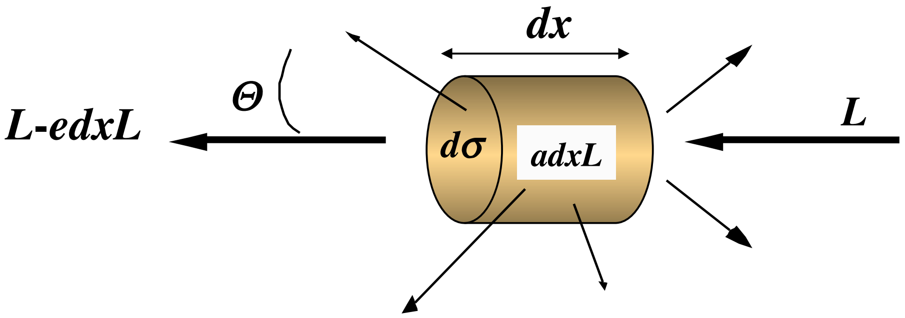
IPCC-AR4 (2007) **BSRN (A. Ohmura)**

The radiation transfer equation

放射伝達方程式

- **Optical thickness: $d\tau = -edz$**
- **Single scattering albedo: $\omega = s/e$**
- **Scattering angle: Θ**

$$dL(\Omega) = \underbrace{-edxL(\Omega)}_{\text{Extinction 消散項}} + \underbrace{\underbrace{sdx\int_{4\pi} P(\Omega,\Omega')L(\Omega')d\Omega'}_{\text{Scattering 散乱項}} + \underbrace{adxB(T)}_{\text{Emission 射出項}}}_{J \quad \text{Source 光源項}}$$



Radiative transfer equation for a plane parallel atmosphere

平行平面大気の放射伝達方程式
光学的厚さ
一次散乱アルベド
散乱角

- **Optical thickness: $d\tau = -e dz$**
- **Single scattering albedo: $\omega = s/e$**
- **Scattering angle: Θ**

$$d\zeta = dz/\mu$$

$$\mu \frac{dL(\tau,\mu,\phi)}{d\tau} = -L(\tau,\mu,\phi) + \omega \int_{-1}^{1} d\mu' \int_{0}^{2\pi} d\phi' P(\mu,\mu',\phi-\phi') L(\tau,\mu',\phi') + (1-\omega) B(T)$$

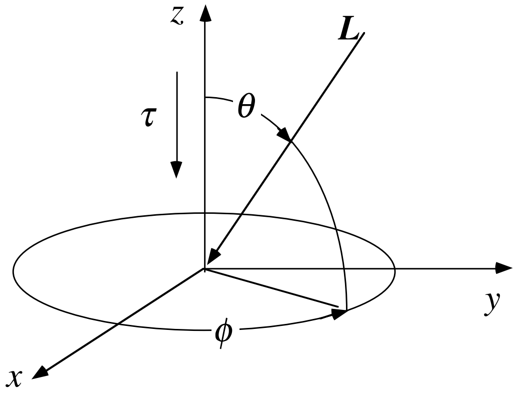
$$\mu = \cos\theta$$

$$\Omega(\mathbf{e}) = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$\cos\Theta = \Omega\cdot\Omega'$$

$$= \cos\theta\cos\theta' + \sin\theta\sin\theta'\cos(\phi-\phi')$$

$$= \mu\mu' + \sqrt{1-\mu^2}\sqrt{1-\mu'^2}\cos(\phi-\phi')$$



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4. Transfer of Thermal Radiation

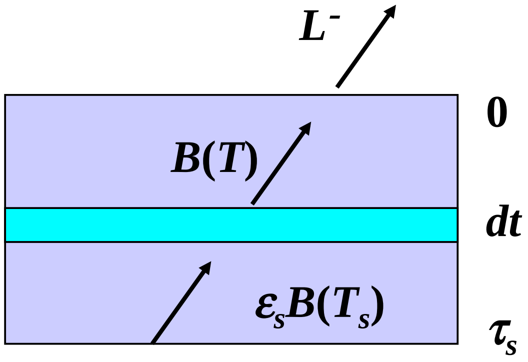
Transfer of thermal radiation

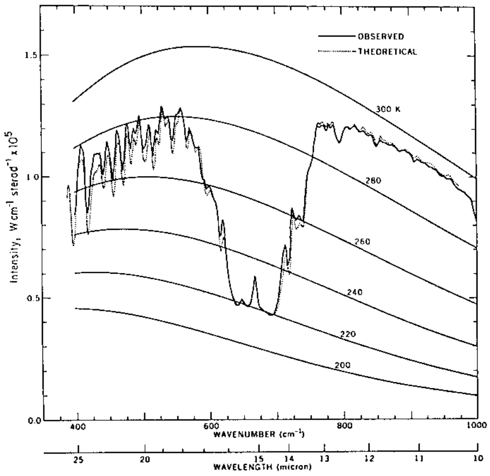
- ω=0 for λ > 4 μm in cases other than cloudy atmosphere
- TOA radiance and black body radiances at various temperature(Goody and Yung, 1989)

$$\pm\mu\frac{dL\pm(\tau,\mu,\phi)}{d\tau} = -L\pm(\tau,\mu,\phi) + B(T)$$

$$L^{-}(0) = [\varepsilon_s B(T_s) + (1-\varepsilon_s)F^{+}(\tau_s)/\pi]e^{-\tau_s/\mu} + \int_0^{\tau_s} B(T(t))e^{-t/\mu}dt/\mu$$

$$L^{+}(0) = \int_0^{\tau_s} B(T(t))e^{-(\tau_s-t)/\mu}dt/\mu$$





Remote sensing of temperature

- **Weighting function**

$$L_{path}^{-} \approx \int_0^{\tau_s} B(T(t))e^{-t/\mu}dt/\mu = \int_0^{\tau_s} B(T)W(P)dP$$

$$dt = -a(T)dz = a(T)\frac{dP}{\rho g}$$

$$PV = nRT, \quad \rho = \frac{M_{air}n}{V} = \frac{M_{air}P}{RT}$$

$$a = k\frac{N}{V} = k\frac{CN_{air}}{V} = k\frac{CN_{air}P}{nRT} = k\frac{CN_A P}{RT}$$

$$dt = \frac{a}{\rho g}dP = k\frac{CN_A P}{RT}\frac{RT}{M_{air}Pg}dP = \beta P dP$$

$$\beta = \frac{\hat{k}}{P}\frac{CN_A}{M_{air}gP} \approx \hat{k}\frac{CN_A}{M_{air}g}, \quad if\ k = \hat{k}P$$

$$t = \int_0^{p} \beta P dP \approx \frac{\beta P^2}{2}, \quad if\ \beta = const$$

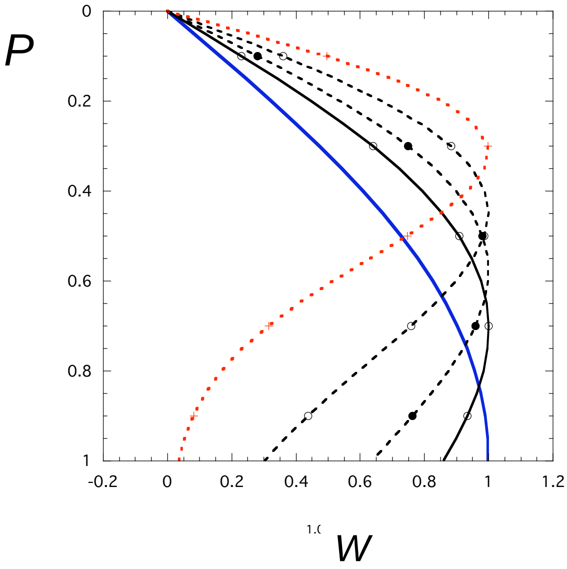
$$W(P) = e^{-\beta P^2/2}\beta P$$

$$P_{\max} = 1/\sqrt{\beta}, \quad W_{\max} = e^{-1/2}\sqrt{\beta}$$

$$\beta = k\frac{CN_A}{M_{air}gP} \approx \hat{k}\frac{CN_A}{M_{air}g}$$

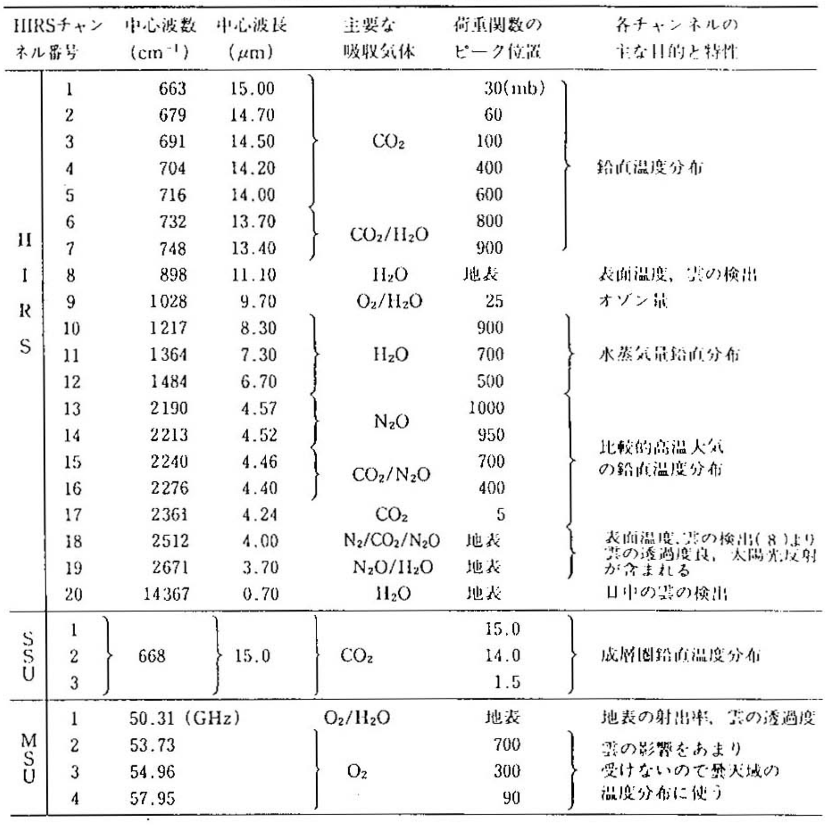
2006.9 途中間違え、結論に影響無し

β= 1, 2, 3, 5, 10



Tiros Operational Vertical Sounder/HIRS

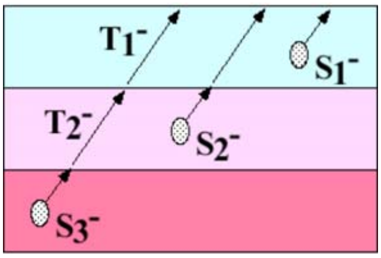
表 2.9 NOAA搭載TOVSの諸元

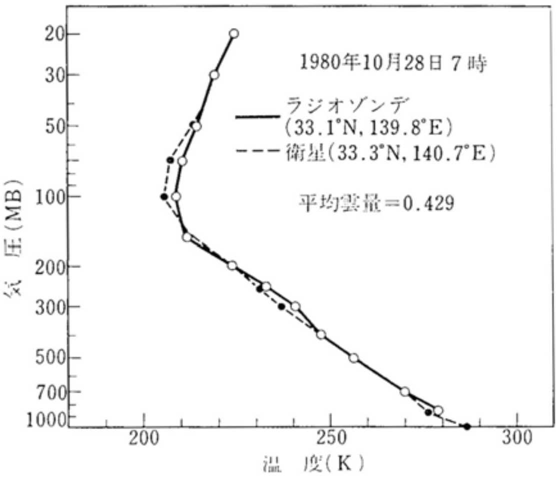


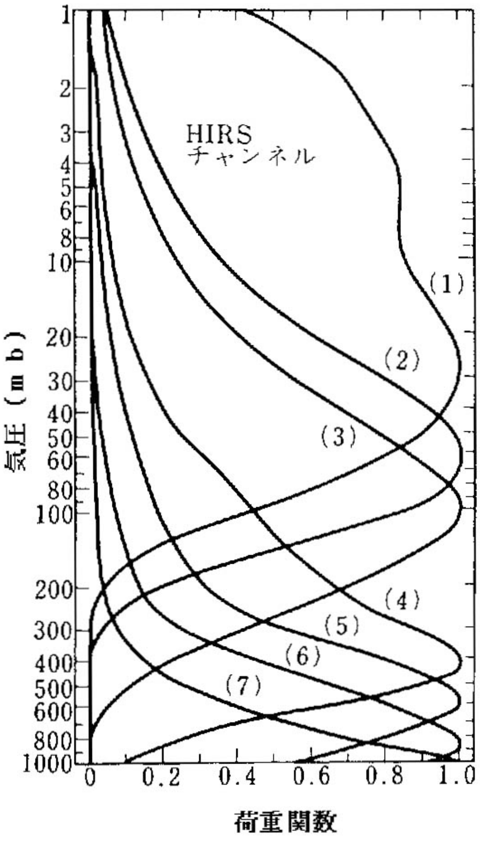
	HIRSチャンネル番号	中心波数 (cm^{-1})	中心波長 (μm)	主要な吸収気体	荷重関数のピーク位置	各チャンネルの主な目的と特性
HIRS	1	663	15.00	CO_2	30(mb)	鉛直温度分布
	2	679	14.70		60	
	3	691	14.50		100	
	4	704	14.20		400	
	5	716	14.00		600	
	6	732	13.70	CO_2/H_2O	800	
	7	748	13.40		900	
	8	898	11.10	H_2O	地表	表面温度、雲の検出
	9	1028	9.70	O_2/H_2O	25	オゾン量
	10	1217	8.30	H_2O	900	水蒸気量鉛直分布
	11	1364	7.30		700	
	12	1484	6.70		500	
	13	2190	4.57	N_2O	1000	比較的高温大気の鉛直温度分布
	14	2213	4.52		950	
	15	2240	4.46	CO_2/N_2O	700	
	16	2276	4.40		400	
	17	2361	4.24	CO_2	5	
	18	2512	4.00	$N_2/CO_2/N_2O$	地表	表面温度、雲の検出(8)より雲の透過度良、太陽光反射が含まれる
	19	2671	3.70	N_2O/H_2O	地表	
	20	14367	0.70	H_2O	地表	日中の雲の検出
SSU	1	668	15.0	CO_2	15.0	成層圏鉛直温度分布
	2				14.0	
	3				1.5	
MSU	1	50.31 (GHz)		O_2/H_2O	地表	地表の射出率、雲の透過度
	2	53.73		O_2	700	雲の影響をあまり受けないので悪天域の温度分布に使う
	3	54.96			300	
	4	57.95			90	

Remote sensing of temperature profile

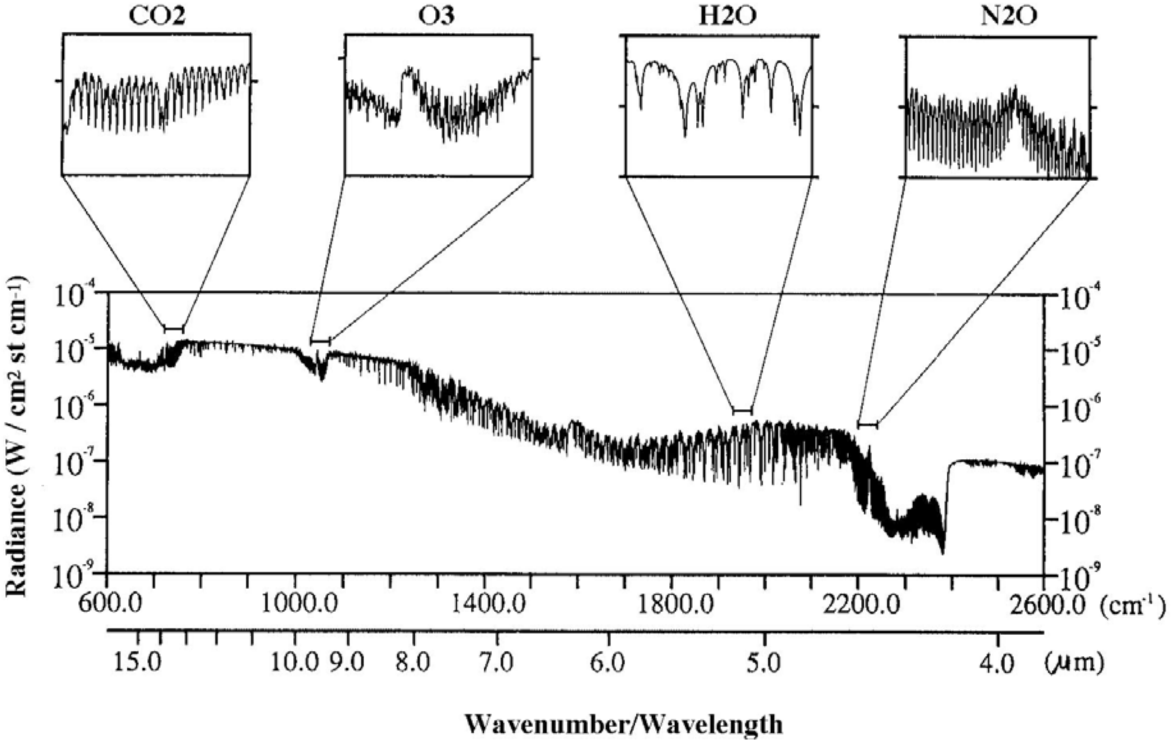
- **Use of infrared radiance spctrum**







High resolution spctrum

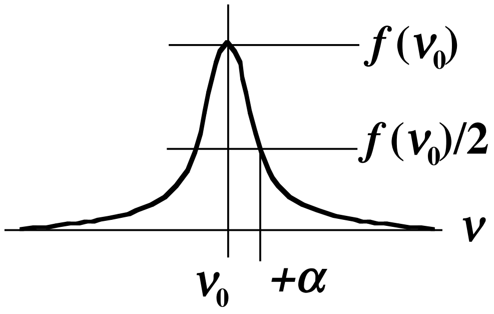


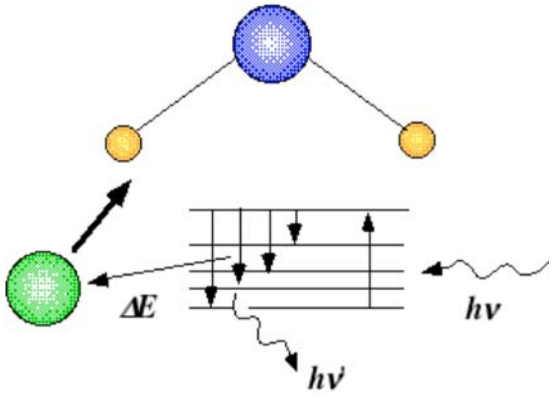
Gas absorption line and band

$$E = E_e + E_v + E_r + E_t$$

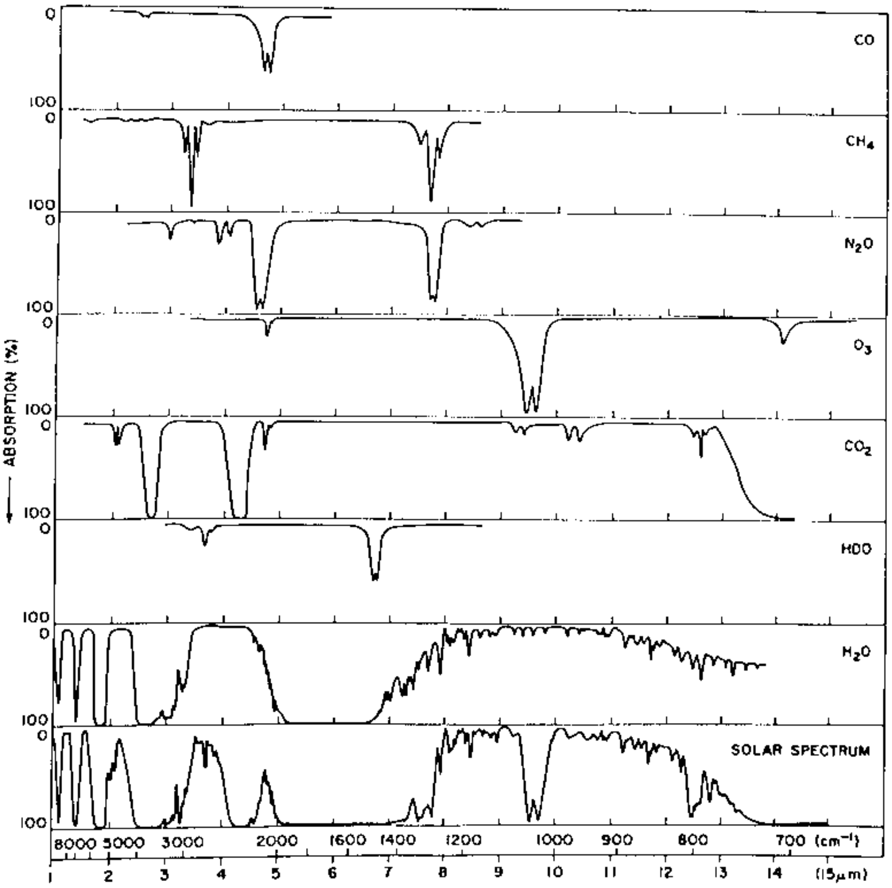
- **Water vapor: 0.7, 0.8, 0.9, 1.1, 1.4, 1.9, 2.7, 6.3, rotation**
- **CO2 ：2.0, 2.7, 4.3, 15**
- **O3 ：UV, 0.76, 9.6, 14**

$$\alpha_L(p, T) = \alpha_L(p_0, T_0)\frac{p}{p_0}\left(\frac{T_0}{T}\right)^n$$



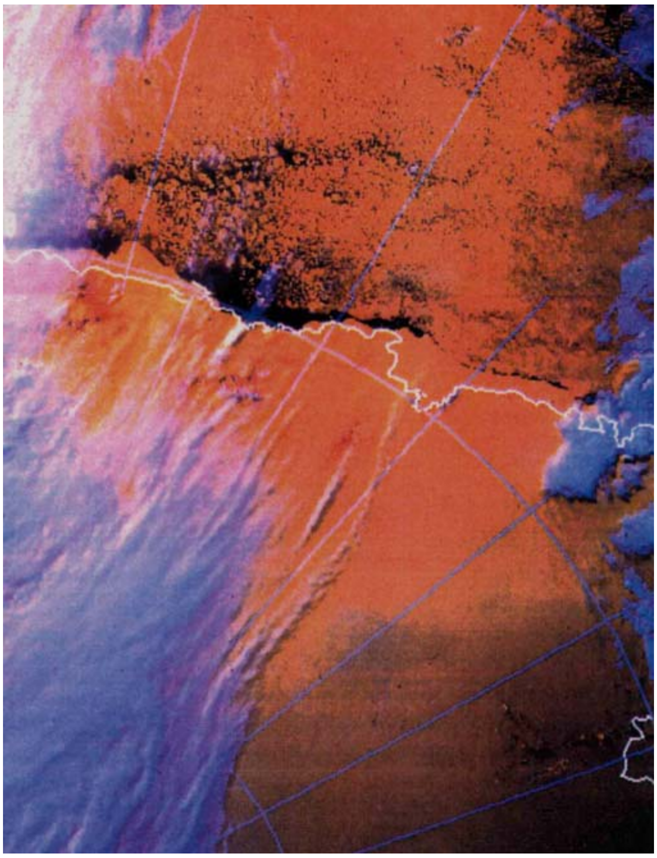


Light absorption bands of molecules



Polar clouds over snow

- ε(3.7μm)- ε(10μm)
- Cirrus
  - ε(10μm)- ε(11μm)



Yamanouchi et al. (JMSJ1987)

5. Radiative Transfer in Optically Thin Atmospheres
光学的に薄い大気における放射伝達

Solar radiation transfer (B=0) in the Clear sky atmosphere (Optically thin atmosphere)- Direct radiation（直達放射）

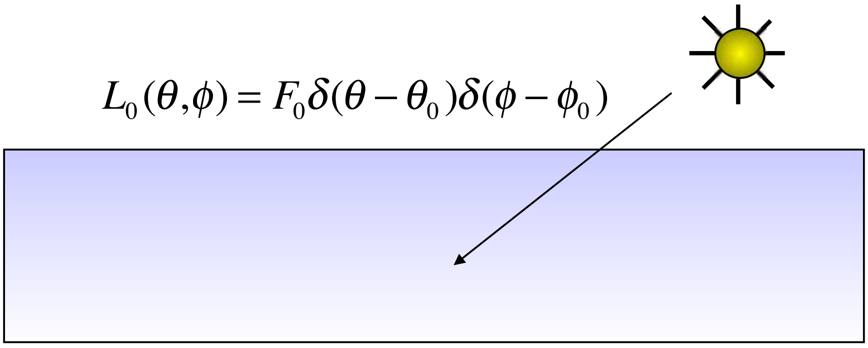
$$\mu\frac{dL(\tau,\mu,\phi)}{d\tau} = -L(\tau,\mu,\phi)+\omega\int_{-1}^{1}d\mu'\int_{0}^{2\pi}d\phi' P(\mu,\mu',\phi-\phi')L(\tau,\mu',\phi')$$

$$L = L^{(0)}(\omega^0)+L^{(1)}(\omega^1)+L^{(2)}(\omega^2)+\ldots$$

Non scattering, single scattering, multiple scattering

$$\mu\frac{dL^{(0)}(\tau,\mu,\phi)}{d\tau} = -L^{(0)}(\tau,\mu,\phi)$$

$$L^{(0)}(\theta,\phi) = F_0 e^{-\tau/\mu_0}\delta(\theta-\theta_0)\delta(\phi-\phi_0)$$



$$L_0(\theta,\phi) = F_0\delta(\theta-\theta_0)\delta(\phi-\phi_0)$$

直達放射
一次散乱放射
多重散乱放射

Solar radiation transfer in the Clear sky atmosphere (Optically thin atmosphere)- Single scattering radiation（一次散乱放射）

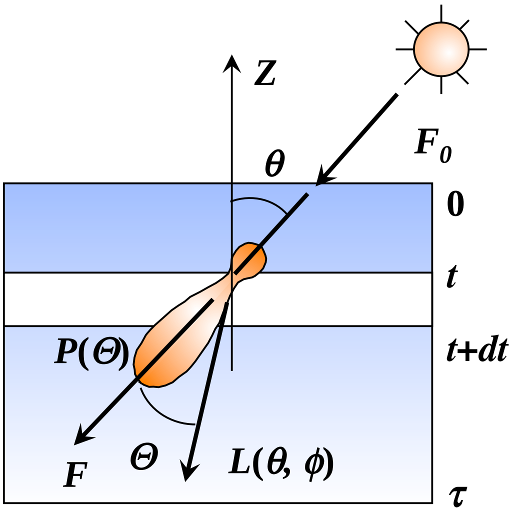
$$L^{(0)}(\tau,\theta,\phi) = \mathrm{e}^{-\tau/\mu} F_0 \delta(\theta-\theta_0)\delta(\phi-\phi_0)$$

$$\mu \frac{dL^{(1)}(\tau,\theta,\phi)}{d\tau} = -L^{(1)}(\tau,\theta,\phi) + \omega \int_{-1}^{1} d\mu' \int_{-1}^{1} d\phi' P(\mu,\mu',\phi-\phi') L^{(0)}(\tau,\theta,\phi)$$

$$= -L^{(1)}(\tau,\theta,\phi) + \omega P(\mu,\mu_0,\phi-\phi_0)\mathrm{e}^{-\tau/\mu_0} F_0$$

$$\mu \frac{dL(\tau,\mu,\phi)}{d\tau} = -L(\tau,\mu,\phi) + J(\tau,\mu,\phi)$$

$$L(\tau,\mu,\phi) = L(\tau_0,\mu,\phi)e^{-(\tau-\tau_0)/\mu} + \frac{1}{\mu}\int_{\tau_0}^{\tau} J(t,\mu,\phi)e^{-(\tau-t)/\mu}dt$$



Solar radiation transfer in the Clear sky atmosphere (Optically thin atmosphere)- Single scattering radiation（一次散乱放射）

$$L(\tau,\mu,\phi) = L(\tau_0,\mu,\phi)e^{-(\tau-\tau_0)/\mu} + \frac{1}{\mu}\int_{\tau_0}^{\tau} J(t,\mu,\phi)e^{-(\tau-t)/\mu}dt$$

$$J(\tau,\mu,\phi) = \omega P(\mu,\mu_0,\phi-\phi_0)\mathrm{e}^{-\tau/\mu_0} F_0$$

$$L_1(\tau,+\mu,\phi) = \omega F_0 P(+\mu,\mu_0,\phi-\phi_0)\frac{e^{-\tau/\mu_0} - e^{-\tau/\mu}}{1-\mu/\mu_0}$$

$$L_1(0,-\mu,\phi) = L(\tau_0,\mu,\phi)e^{-(\tau-\tau_0)/\mu} + \omega F_0 P(-\mu,\mu_0,\phi-\phi_0)\frac{1-\mathrm{e}^{-\tau(1/\mu+1/\mu_0)}}{1+\mu/\mu_0}$$

$$\tau << 1$$

$$\text{2nd term} \approx \frac{1}{\mu}\omega\tau F_0 P(\pm\mu,\mu_0,\phi-\phi_0)$$

Thin atmospheres

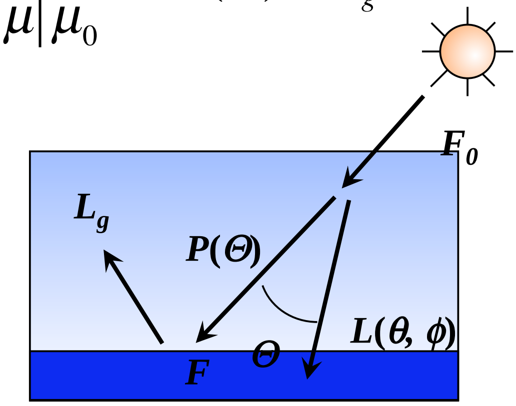
- Molecules and aerosols in the shortwave region
- 2 wavelength problem (color ratio)

$$\mu > 0, \quad L \approx \frac{\omega\tau}{|\mu|} P(\Theta) F_0$$

$$\mu < 0, \quad L \approx \frac{\omega\tau}{|\mu|} P(\Theta) F_0 + L_g, \quad \rho = \frac{\pi}{|\mu|\mu_0} \omega\tau P(\Theta) + A_g$$

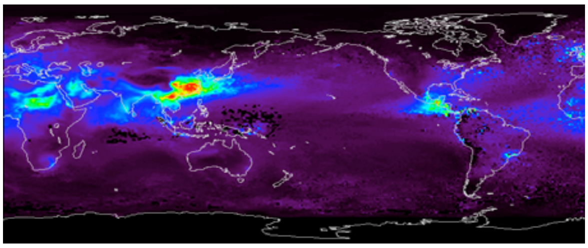
$$\frac{\rho_2}{\rho_1} \approx \frac{\omega_2\tau_2 P_2(\Theta)}{\omega_1\tau_1 P_1(\Theta)} \approx \frac{\tau_2}{\tau_1} = \left(\frac{\lambda_2}{\lambda_1}\right)^{-\alpha}$$

Reciprocity principle

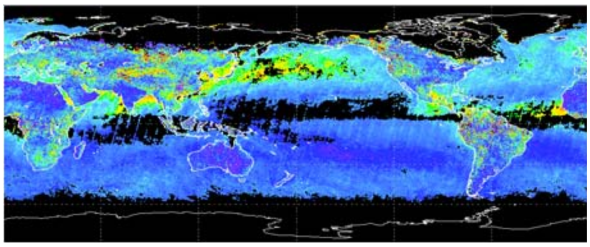


Comparison of Aerosol optical thickness (*AOT*) from MIROC-GCM and two satellites (GLI and MODIS) (Nakajima and Schulz, 2009).

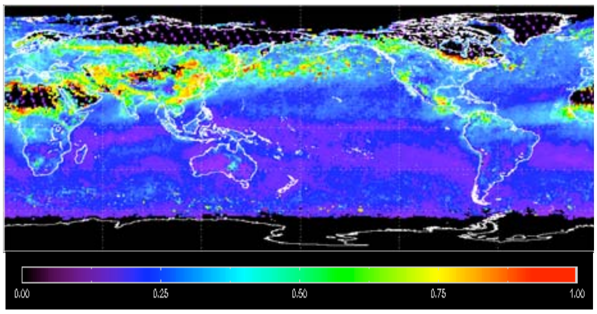
April 2003 MIROC+SPRINTARS



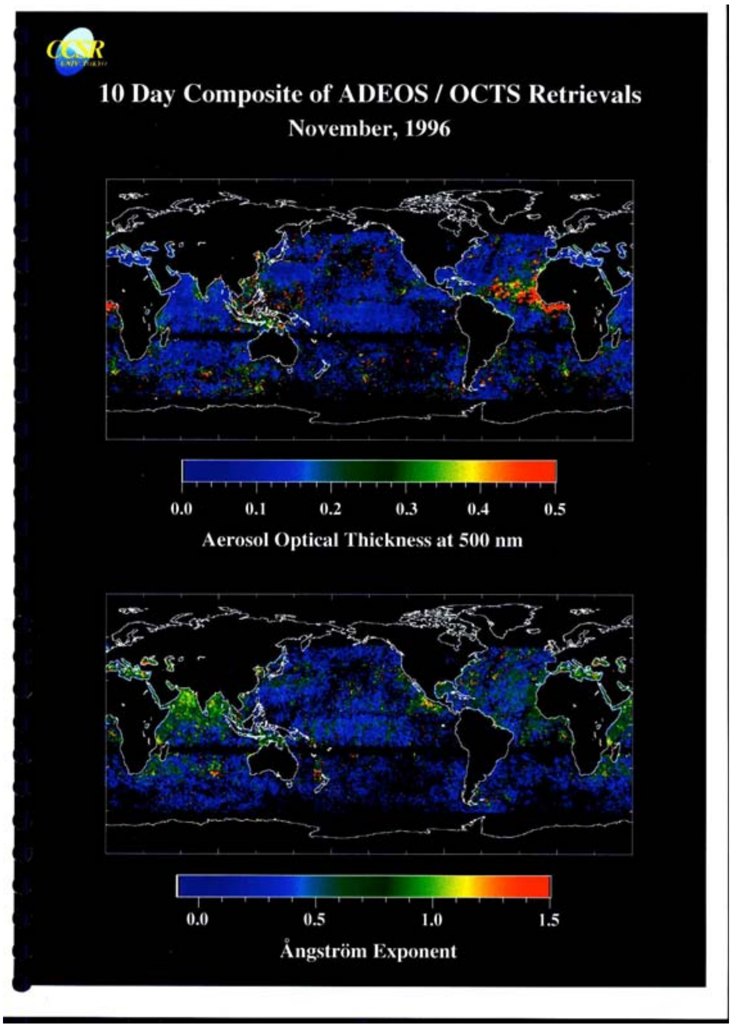
ADEOS-II/GLI (Fukuda)



TERRA/MODIS (NASA/GSFC)



AOT



10 Day Composite of ADEOS / OCTS Retrievals

November, 1996

Aerosol Optical Thickness at 500 nm

Ångström Exponent

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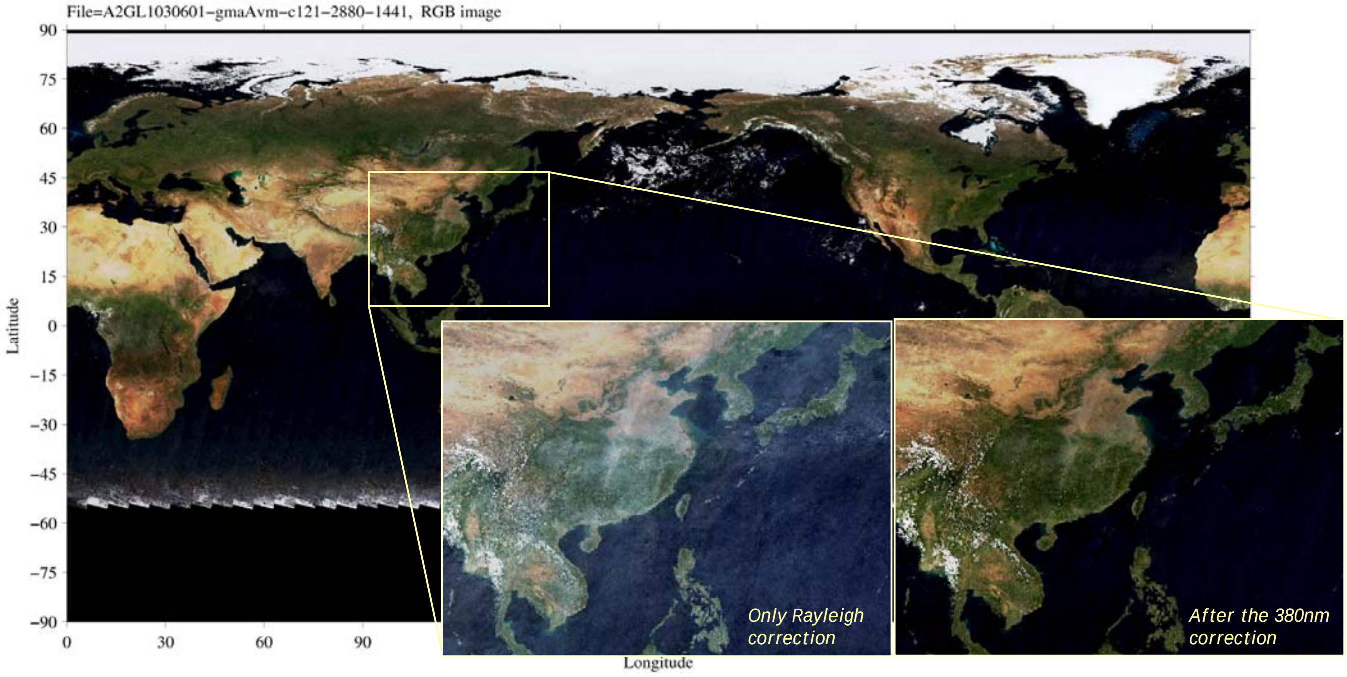
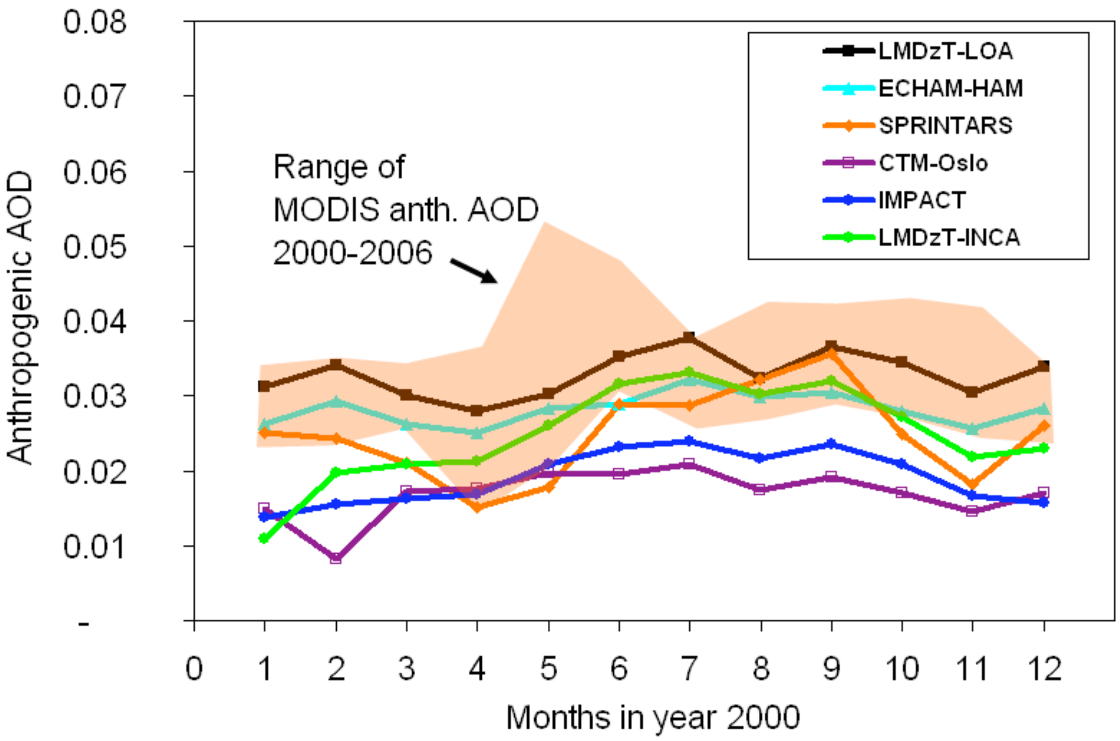
9) Atmospheric correction and Land PAR



- By using GLI 380nm channel, we can estimate aerosol scattering.

Courtesy: H.Murakami (JAXA)

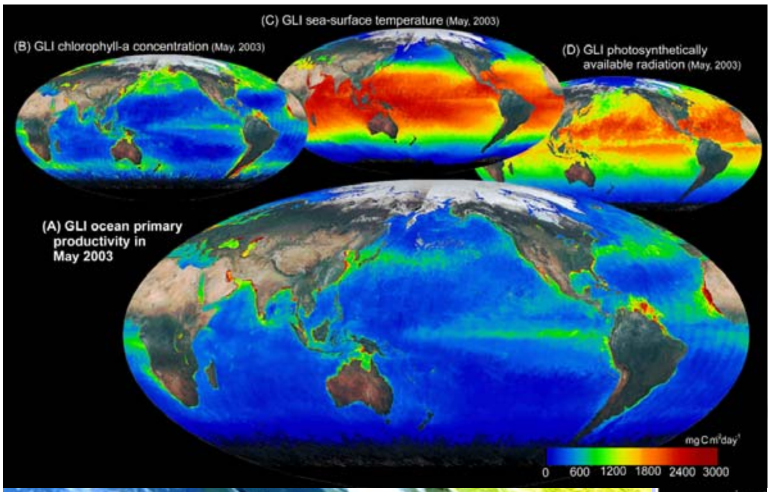
Global monitoring and simulation of aerosols

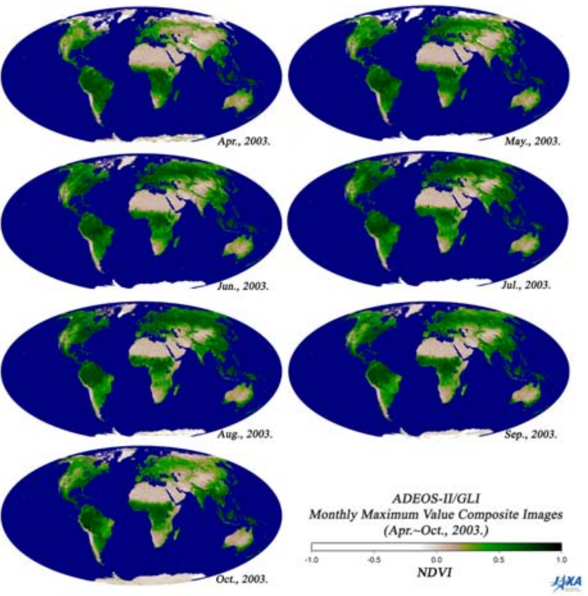


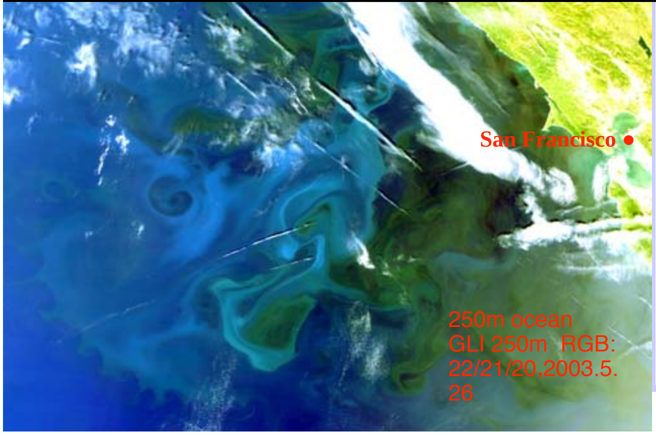
- Model underestimation of AOT

Nakajima and Schulz (FIAS2008)

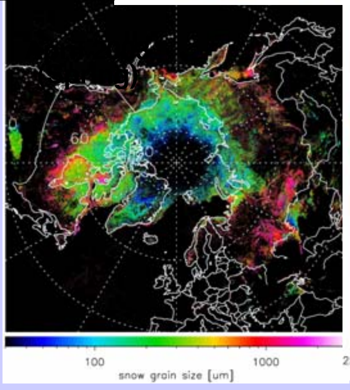
ADEOS-II/GLI products

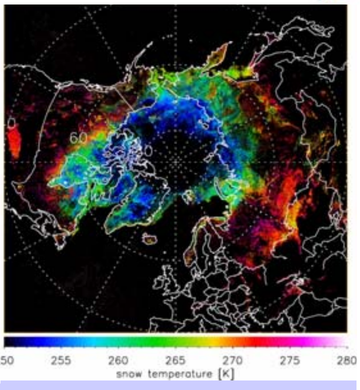






250m ocean
GLI 250m RGB:
22/21/20,2003.5.26





Snow grain size

Snow surface tempearture

Angular scattering cross section

- Sky brightness distribution（天空輝度分布）: $L(\mu, \mu_0, \phi\text{-}\phi_0)$
- Direct solar irradiance（太陽直達照度）: F_0
- Scattering phase function（散乱位相関数）: $P(\Theta)$

$$L \approx \frac{\omega\tau}{\mu} P(\Theta_+) F_0$$

$$\omega\tau P(\Theta_+) = sdzP(\Theta_+) = C_{sca} N dz P(\Theta_+)$$

$$\omega\tau P(\Theta_+) = \int_0^\infty dr n(r) \pi r^2 Q_{sca}(\alpha, \Theta, \tilde{m}), \quad \alpha = \frac{2\pi r}{\lambda}$$

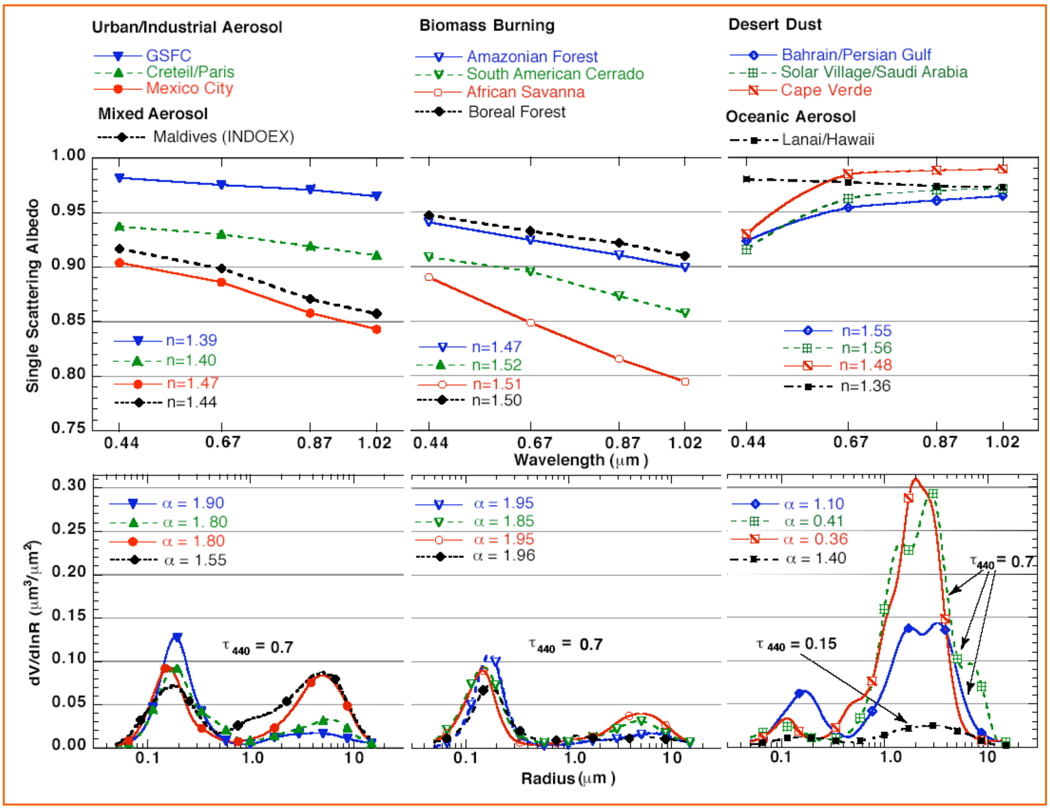
$$\omega\tau P(\Theta_+), \quad Q_{sca}(\alpha, \tilde{m}) \rightarrow n(r)$$

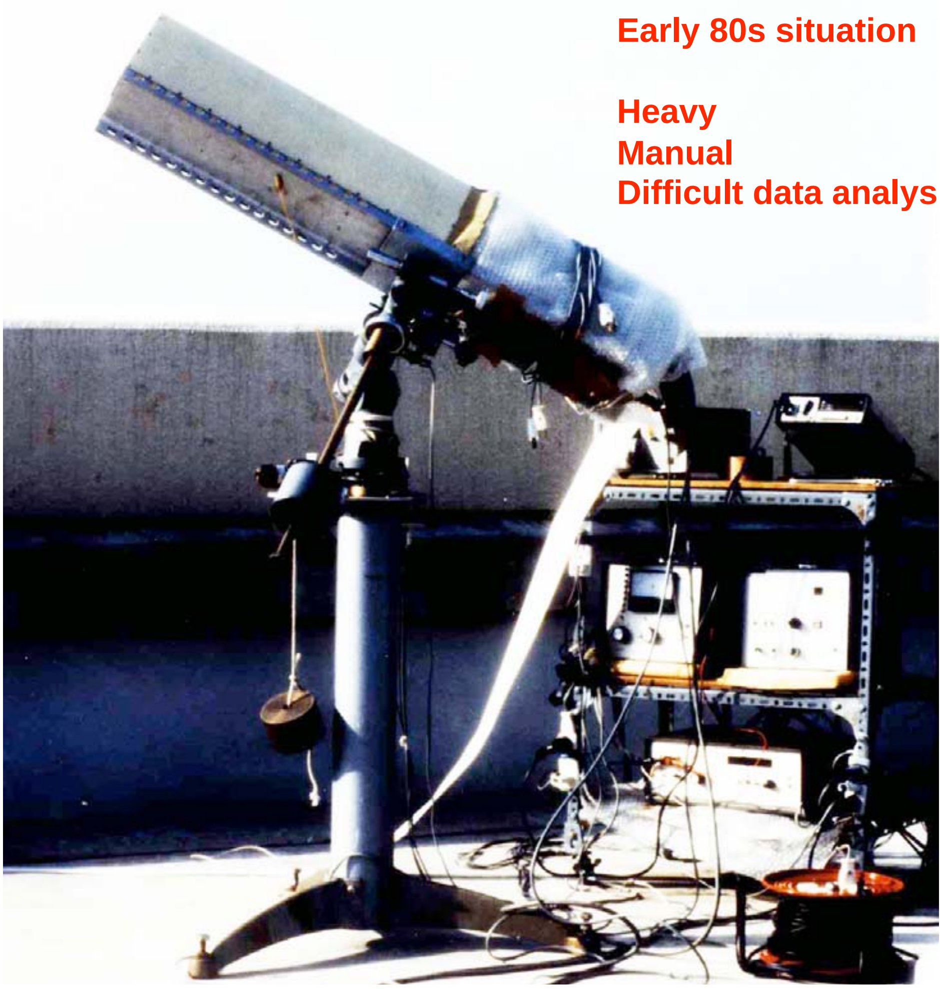
Inversion problem of size distribution
粒径分布を求める逆（反転）問題

$$v(\ln r) \equiv \frac{dV}{d \ln r} = \frac{4\pi r^4}{3} n(r)$$

The averaged optical properties of various aerosol types

Dubovik et al. (2002)





Early 80s situation

Heavy
Manual
Difficult data analysis

SKYNET
Sky radiometers

Angular integrations of the phase function

- **Legendre polynomial expansion**
- **Asymmetry factor**
    - **g: 0 (isotropic), 0.6-0.7 (aerosols), and 0.8-0.85 (clouds)**
- **Forward and backward scattering fractions**
- **Up and down scatter fractions**

$$P(\cos\Theta) = \frac{1}{4\pi}\sum_{n=0}^{\infty}(2n+1)g_n P_n(\cos\Theta) \approx \frac{1}{4\pi}(1+3g\cos\Theta)$$

$$\cos\Theta_{\pm} = \pm\mu\mu_0 + \sqrt{(1-\mu^2)(1-\mu_0^2)}\cos(\phi-\phi_0)$$

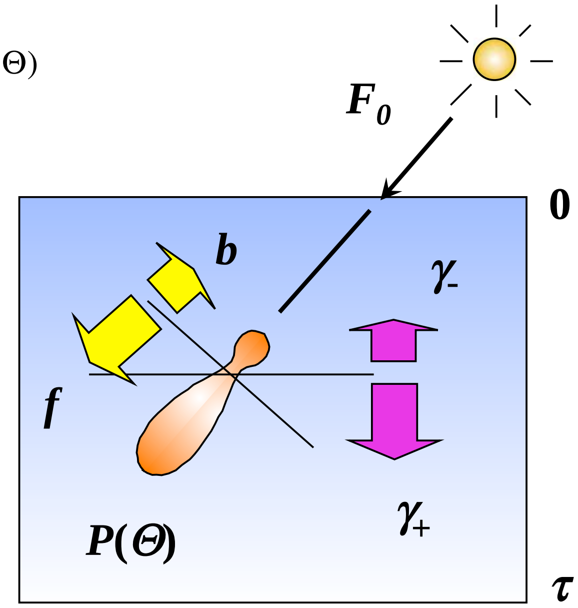
$$\int_{-1}^{1} d\cos\Theta \int_{0}^{2\pi} d\Phi P(\cos\Theta) = 1$$

$$\int_{-1}^{1} d\cos\Theta \int_{0}^{2\pi} d\Phi \cos\Theta P(\cos\Theta) = g$$

$$\gamma_{\pm}(\mu_0) = \int_{0}^{1} d\mu \int_{0}^{2\pi} d\phi P(\cos\Theta_{\pm}) = \frac{1}{2}(1 \pm \frac{3}{2} g\mu_0)$$

$$f = \int_{0}^{1} d\cos\Theta \int_{0}^{2\pi} d\Phi P(\cos\Theta) = \frac{1}{2}(1+\frac{3}{2}g)$$

$$b = 1 - f \qquad g > 0.7 \rightarrow f > 1, \quad b < 0!$$



Flux transmissivity and reflectivity

- Unidirectional flux transmissivity: $t(\mu_0)$
- Unidirectional flux reflectance: $r(\mu_0)$
- Spherical reflectance: <r>

$$\mu = \cos\theta, \quad \mu_0 = \cos\theta_0$$

$$m = 1/\mu, \quad m_0 = 1/\mu_0$$

$$(m+m_0)\tau << 1$$

$$L \approx e^{-m_0\tau}\delta(\mu-\mu_0)\delta(\phi-\phi_0)F_0 + \omega\tau m P(+\mu,\mu_0,\phi-\phi_0)F_0$$

$$t(\mu_0) = \frac{1}{\mu_0 F_0}\int_{0}^{2\pi} d\phi \int_{0}^{1} d\mu\mu L(\mu,\mu_0,\phi-\phi_0)$$

$$= e^{-m_0\tau} + \omega\tau m_0 \int_{0}^{2\pi} d\phi \int_{0}^{1} d\mu P(\Theta) = e^{-m_0\tau} + \omega\tau m_0\gamma_+(\mu_0) = 1 - m_0\tau[1-\omega\gamma_+(\mu_0)]$$

$$r(\mu_0) = \omega\tau m_0\gamma_-(\mu_0)$$

$$\gamma_{\pm}(\mu_0) = \int_{0}^{1} d\mu \int_{0}^{2\pi} d\phi P(\cos\Theta_{\pm}) = \frac{1}{2}(1 \pm \frac{3}{2} g\mu_0)$$

Radiative energy budget（放射収支）

$$t(\mu_0) = 1 - m_0\tau[1 - \omega\frac{1}{2}(1 + \frac{3}{2}g\mu_0)]$$

$$r(\mu_0) = \omega\tau m_0\frac{1}{2}(1 - \frac{3}{2}g\mu_0)$$

$$t + r = 1 - m_0\tau[1 - \omega\frac{1}{2}(1 + \frac{3}{2}g\mu_0)] + \omega\tau m_0\frac{1}{2}(1 - \frac{3}{2}g\mu_0)$$

$$= 1 - m_0\tau(1 - \omega)$$

$$t + r + a = 1$$

		w	1		w	0.9		w	1	
		g	0.5		g	0.5		g	0.6	
tau	mu0	t	r	a	t	r	a	t	r	a
0.00	1	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000
0.05	1	0.994	0.006	0.000	0.989	0.006	0.005	0.998	0.003	0.000
0.10	1	0.988	0.013	0.000	0.979	0.011	0.010	0.995	0.005	0.000
0.50	1	0.938	0.063	0.000	0.894	0.056	0.050	0.975	0.025	0.000
0.00	0.5	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000	0.000
0.05	0.5	0.969	0.031	0.000	0.962	0.028	0.010	0.973	0.028	0.000
0.10	0.5	0.938	0.063	0.000	0.924	0.056	0.020	0.945	0.055	0.000
0.50	0.5	0.688	0.313	0.000	0.619	0.281	0.100	0.725	0.275	0.000

Spherical albedo (Planetary albedo)

- 球面反射率（惑星反射率）

$$\bar{r} = \int_0^1 d\mu_0 \int_0^{2\pi} d\phi_0 r(\mu_0)\mu_0 F_0 \Big/ \int_0^1 d\mu_0 \int_0^{2\pi} d\phi_0 \mu_0 F_0 = \int_0^1 d\mu_0 \int_0^{2\pi} d\phi_0 \omega\tau\gamma_-(\mu_0)/\pi$$

$$= \omega\tau\int_0^1 d\mu_0(1 - \frac{3}{2}g\mu_0) = 2\omega\tau\frac{1}{2}(1 - \frac{3}{4}g) = r(\frac{1}{2})$$

Atmosphere-Earth’s surface problem

- **Principle of reciprocity（双対原理）**

$$L = \omega\tau m P(-\mu,\mu_0,\phi-\phi_0)F_0 + \frac{1}{\pi} t^-(\mu)A(1-\bar{r}A)^{-1} t^+(\mu_0)\mu_0 F_0$$

$$\rho = \frac{\pi L}{\mu_0 F_0} = \pi m m_0 \omega\tau P(\Theta\_) + t(\mu)A(1+\bar{r}A)t(\mu_0)$$

$$t(\mu_0) = 1-\hat{t}(\mu_0)\tau, \quad \bar{r} = \hat{r}(\frac{1}{2})\tau$$

$$\hat{t}(\mu_0) \equiv m_0[1-\omega\frac{1}{2}(1+\frac{3}{2}g\mu_0)], \quad \hat{r}(\mu_0) \equiv m_0\omega\frac{1}{2}(1-\frac{3}{2}g\mu_0)$$

$$\rho \approx \pi m m_0 \omega\tau P(\Theta\_) + A - [\hat{t}(\mu)+\hat{t}(\mu_0)-\hat{r}(\frac{1}{2})A]A\tau$$

Reflected radiation from a thin atmospheres (Detailed)

- **Neutral reflectance: deriving ω**

$$\frac{d\rho}{d\tau} = \pi m m_0 \omega P(\Theta\_) - [\hat{t}(\mu)+\hat{t}(\mu_0)-\hat{r}A]A = 0$$

$$A << 1$$

$$A_n = \frac{\pi m m_0 \omega P(\cos\Theta\_)}{\widehat{t}(\mu)+\widehat{t}(\mu_0)}$$

tau	0.1	0.1	0.1
w	1	0.9	0.8
g	0.7	0.7	0.7
m0	2	2	2
m	1	1	1
gam(mu0)	0.763	0.763	0.763
gam(mu)	1.025	1.025	1.025
t^(mu0)	0.475	0.628	0.780
t^(mu)	−0.025	0.078	0.180
P	0.02	0.02	0.02
rho, path	0.013	0.011	0.010
An	0.279	0.160	0.105

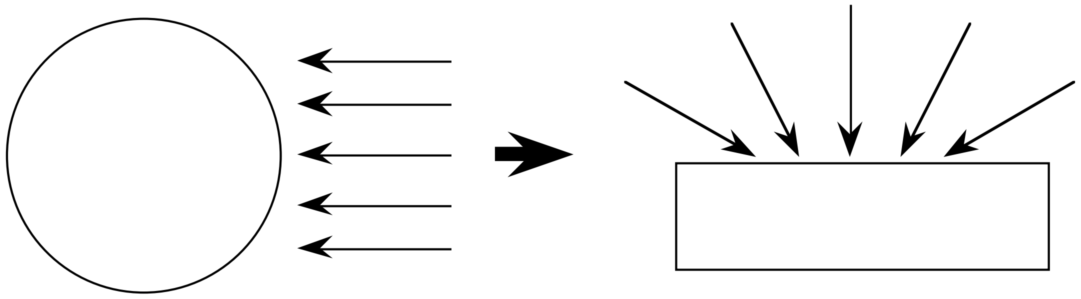
Equation for the planetary albedo

- **Averaged radiation field for the planet**

$$Q_{SW} = \frac{S}{4}(global\ average)$$

$$= \frac{S}{2}(daytime\ average)$$

$$\pi a^2 S$$



Earth’s reflectance in the clear sky condition

- Flux reflectance
- Planetary albedo

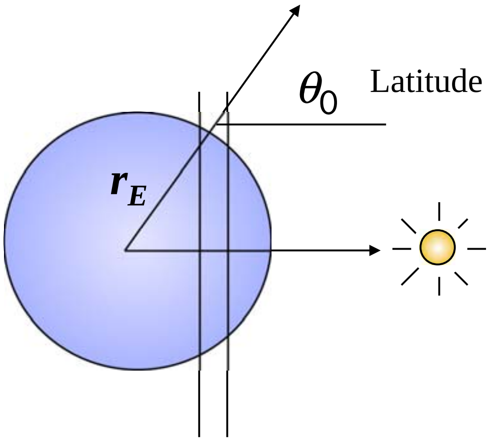
$$\rho \approx \pi m m_0 \omega \tau P(\Theta_-) + t(\mu)t(\mu_0)A_g$$

$$r_{AL}(\mu_0) \equiv \frac{F_{ref}}{\mu_0 F_0} = \int_0^1 d\mu\mu \int_0^{2\pi} d\phi[mm_0\omega\tau P(\Theta_-) + \frac{1}{\pi}t(\mu)t(\mu_0)A_g]$$

$$r_{AL}(\mu_0) = r(\mu_0) + t(\frac{1}{2})t(\mu_0)A_g$$

$$dS = 2\pi r_E \sin\theta_0 r_E d\theta_0 = 2\pi r_E^2 d\mu_0$$

$$r_P = \frac{\int_{2\pi} dS r_{AL}(\mu_0)\mu_0 F_0}{\pi r_E^2 F_0} = 2\int_0^1 d\mu_0 r(\mu_0)\mu_0 = r_{AL}(\frac{1}{2})$$



Shortwave radiative forcing of aerosols

$$t(\mu_0)=1-\hat{t}(\mu_0)\tau, \quad \overline{r}=\hat{r}(\frac{1}{2})\tau$$

$$\hat{t}(\mu_0)\equiv m_0[1-\omega\frac{1}{2}(1+\frac{3}{2}g\mu_0)], \quad \hat{r}(\mu_0)\equiv m_0\omega\frac{1}{2}(1-\frac{3}{2}g\mu_0)$$

$$\rho\approx\pi m m_0\omega\tau P(\Theta\_)+A-[\hat{t}(\mu)+\hat{t}(\mu_0)-\hat{r}(\frac{1}{2})A]A\tau$$

$$A\approx 0.07\rightarrow r_P=\hat{r}(\mu_0)\tau+A-2\hat{t}(\mu_0)A\tau, \quad \mu_0=\frac{1}{2}$$

$$\Delta r_P\approx\{\hat{r}(\mu_0)-2\hat{t}(\mu_0)A\}\Delta\tau$$

$$\omega=1\rightarrow\hat{t}(\mu_0)=\hat{r}(\mu_0)$$

$$\Delta r_P\approx\hat{r}(\mu_0)(1-2A)\Delta\tau$$

Charlson et al. (1992)

$$\Delta F_S=-(1-n)\Delta r_p\pi r_E^2/4\pi r_E^2$$

$$=-2(1-n)t_u{}^2(1-A)^2\gamma\_(\mu_0)\Delta\tau Q$$

$$Q=\frac{F_0}{4},\Delta\tau=0.04, \quad \Delta F_S=-1.3W/m^2$$

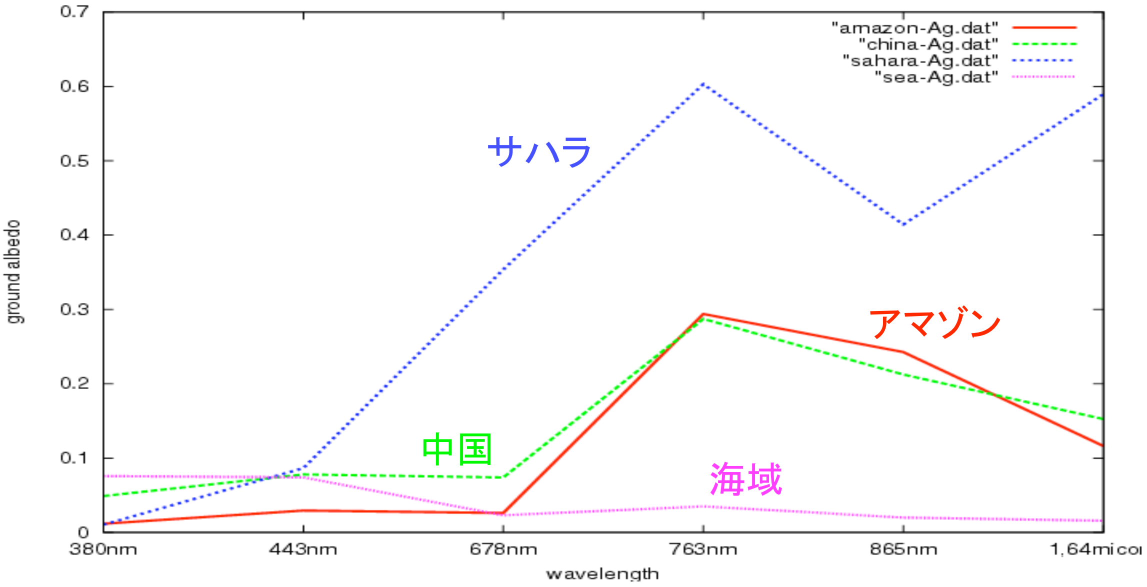
人間起源対流圏エアロゾルに関するパラメーター（Charlson et al., 1992）

g	0.60
gam-	0.28
tau	0.04
n	0.60
Tu	0.76
A	0.15
ARF	-1.26

S. Fukuda (2006)

レーリー補正後地表面反射率

2003年4月



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