7. Earth's climate and radiation

Zero-dimensional planetary energy budget equation

- **Equivalent blackbody temperature: T_e**
- **Radius of Earth: a**
- **Distance between Earth and Sun in astronomical unit: R_{ps}**
- **Pseudo planetary emissivity for surface emission: ε**
- **Planetary albedo: α**
- **Solar constant: S**

Alchemy (albedo, Rubedo, Nigredo)

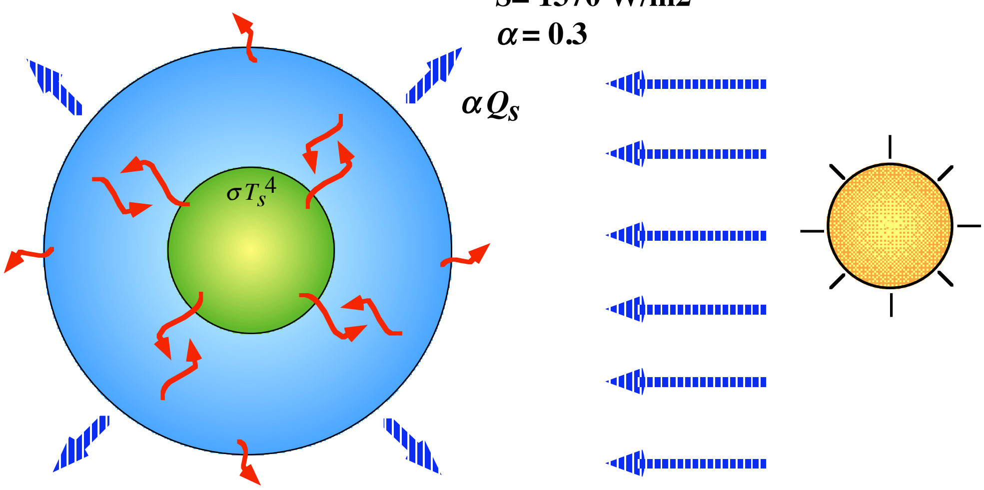
$$\pi a^2 (1-\alpha)\frac{S}{R_{ps}^2} = 4\pi a^2 \sigma T_e^4$$

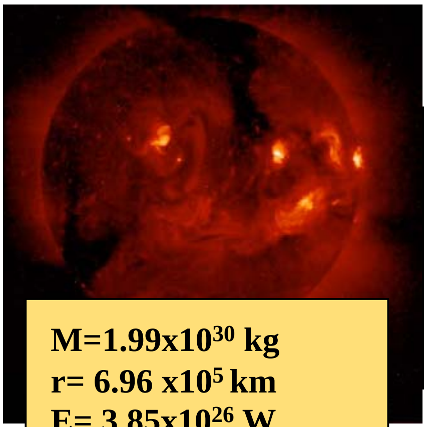
$T_e \approx 256\text{K}, T_s \approx 280\text{K}$ $\quad \sigma T_e^4 = \varepsilon\sigma T_s^4$

$\varepsilon \approx 0.69$

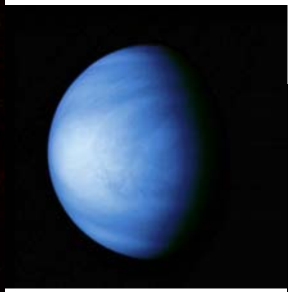
$S = 1370$ W/m2

$\alpha = 0.3$

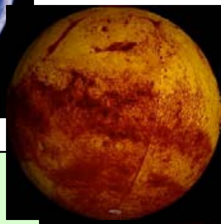




Planets and their climate



r= 6.37 x10^3 km



M=1.99x10^30 kg
r= 6.96 x10^5 km
E= 3.85x10^26 W
R_{pe}=1.50x10^8 km
S= 1370 W/m^2

	R_{ps}	α	T_e	$T_{e,m}$	T_s	$(1-g)\tau_{vs}$	τ_{IR}	ε
Venus	0.72	0.77	227	230	750	3.97	224	0.01
Earth	1.00	0.30	256	250	280	0.49	1.15	0.64
Mars	1.52	0.15	216	220	240	0.20	0.83	0.71
Jupiter	5.20	0.58	98	130	134	1.59	-	0.89

$$\pi a^2 (1-\alpha)\frac{S}{R_{ps}^2} = 4\pi a^2 \sigma T_e^4$$

Radiative energy budget change

$$\pi a^2 (1-A_p)\frac{S}{R_{ps}^2} = 4\pi a^2 \varepsilon\sigma T_s^4$$

???

$$\frac{\Delta S}{S} = 4\frac{\Delta T_s}{T_s}$$

if A_p and ε are constant

$$\Delta T_s = \lambda \Delta F$$

Cess et al. (1990)

$$\Delta F = \frac{\Delta S}{4}, \quad \lambda = \frac{T_s}{4(S/4)}$$

ΔF: Radiative forcing (放射強制力)
λ: Equilibrium Climate Sensitivity (平衡気候感度)

T_s=280K, S=1366 W/m^2 (Q=S/4= 341.5):
λ= 0.20 K/(W/m^2) cf. GCMs: λ = 1

ΔS= 2 W/m^2: ΔT_s= 0.1K (GCMs: 0.5K)

質問

- 大気のeが変化しないと仮定した。
この仮定のどこが間違っているのか?

International Satellite Cloud Climatology Project (ISCCP)

- Rossow et al. (1993)
- 4 geostational satellites and 2 polar orbiters
- Cloud reflectance and clear sky reflectance

$$n(\tau_c, T_c)$$

$$t_c = \frac{1}{1 + b\gamma\tau_c}, \quad r_c = 1 - t_c, \quad b(=\gamma^-) = \frac{1-g}{2}$$

$$r_p = nr_c + (1-n)r_g$$

$$n = 0.6, \quad r_g = 0.1, \quad r_p = 0.3$$

$$\rightarrow r_c = \frac{r_p - (1-n)r_g}{n} = 0.43$$

$$g = 0.85, \quad b = 0.075, \quad \gamma = 1.73$$

$$\tau_c = \frac{1}{b\gamma}(\frac{1}{1-r_c} - 1) = 5.8$$

$$W = \frac{2r_e\tau_c}{3} = 38\ g/m^2 \quad (r_e = 10\mu m)$$

Region	ISCCP	SOBS	METEOR	Nimbus-7
Global	62.6	61.5	60.9	52.9
NH	59.7	59.0	55.7	51.7
SH	65.4	64.0	66.0	54.1
Polar	52.3	68.6	50.4	58.0
Midlatitude	72.2	67.3	68.5	56.9
Tropics	58.4	55.4	58.2	48.5
Land	47.1	53.3	46.5	45.5
Ocean	70.2	65.5	67.9	56.5

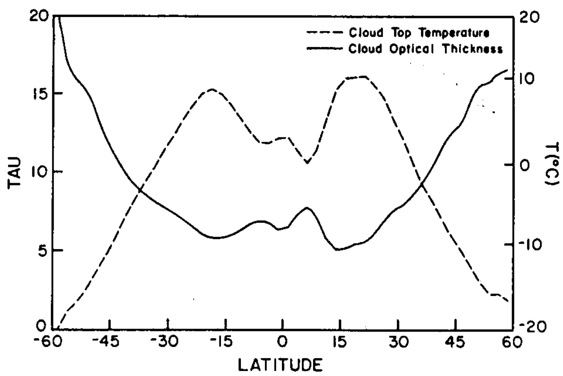


FIG. 2. Annual zonal-mean distributions of optical thickness and top temperature for all clouds in 1984.

Two layer emissivity approximation

- No absorption of the shortwave radiation in the atmosphere & no dynamical effect
- Radiative equilibruim

$$F^{-}(0)=\varepsilon\sigma T^{4}+(1-\varepsilon)\sigma T_{g}^{4},\quad F^{-}(\tau_{1})=\sigma T_{g}^{4},\quad F^{+}(\tau_{1})=\varepsilon\sigma T^{4}$$

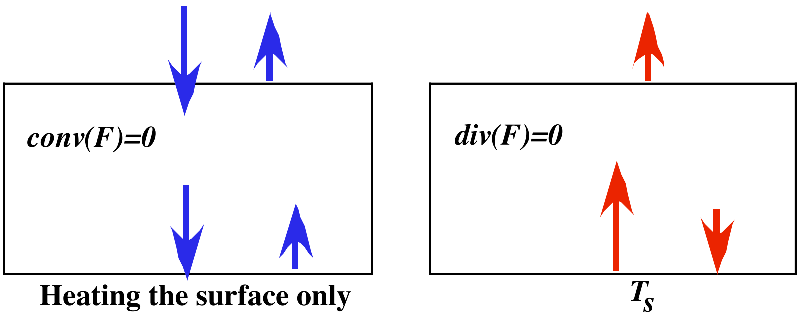
$$\Phi=\varepsilon\sigma T^{4}+(1-\varepsilon)\sigma T_{g}^{4}=\sigma T_{g}^{4}-\varepsilon\sigma T^{4}$$

$$\sigma T_{g}^{4}=\frac{2}{2-\varepsilon}\Phi,\quad \sigma T^{4}=\frac{1}{2-\varepsilon}\Phi$$

$$T<T_{e}<T_{g}$$

$$\sigma T^{4}=\frac{1}{2}\sigma T_{g}^{4},\quad F^{-}(0)=\sigma T_{e}^{4}=(1-\frac{\varepsilon}{2})\sigma T_{g}^{4}$$

$$T=235K$$
$$T_{e}=256K$$
$$T_{g}=280K$$
$$\varepsilon=0.6$$

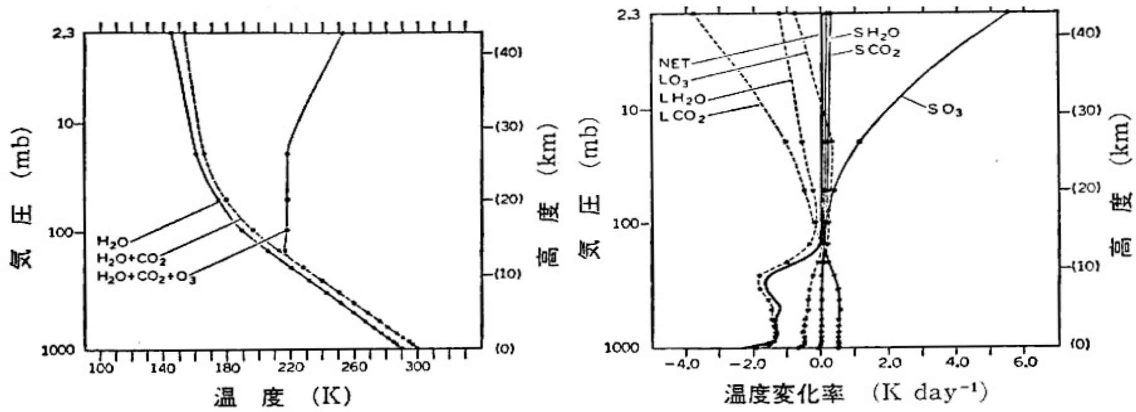


Heating the surface only

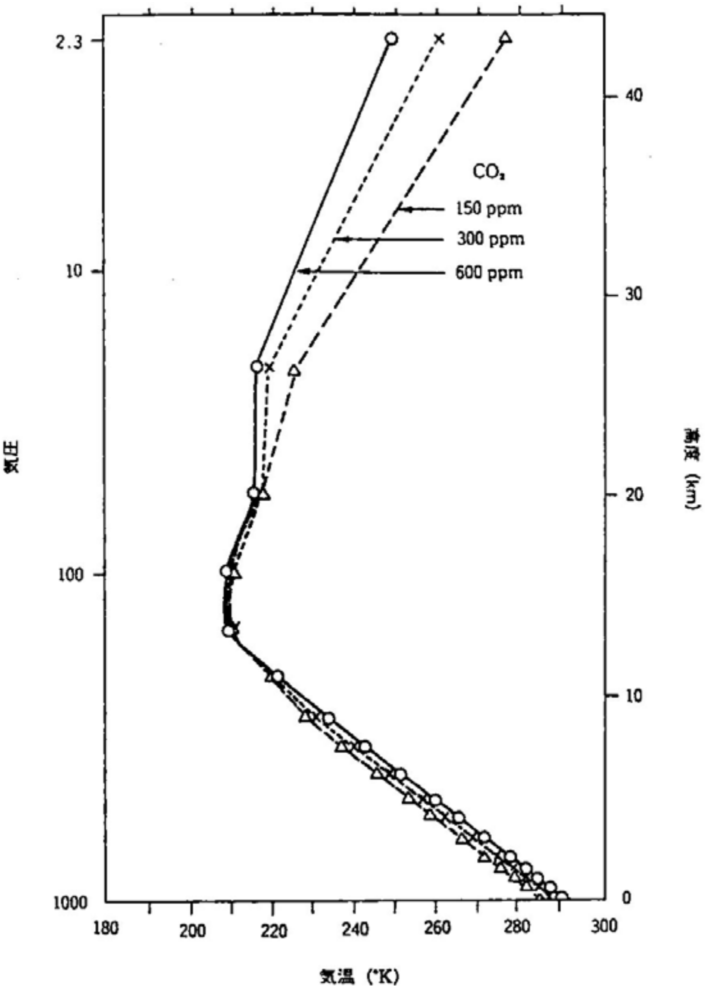
Solar Radiation

Terrestrial Radiation

Radiative equilibrium; Radiative-convective equilibrium



(Manabe and Strickler, 1964)



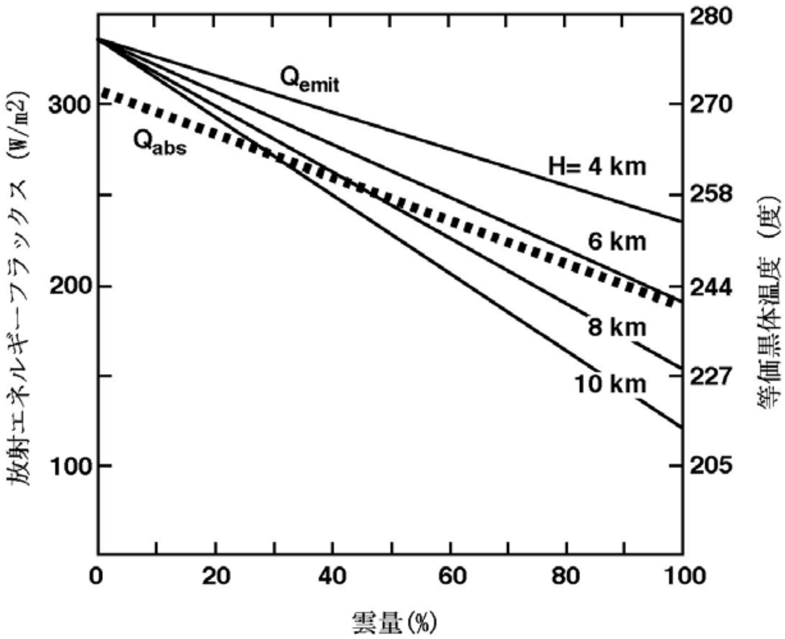
Thermal stratification of the atmosphere

Cooling and warming by absorbing gases

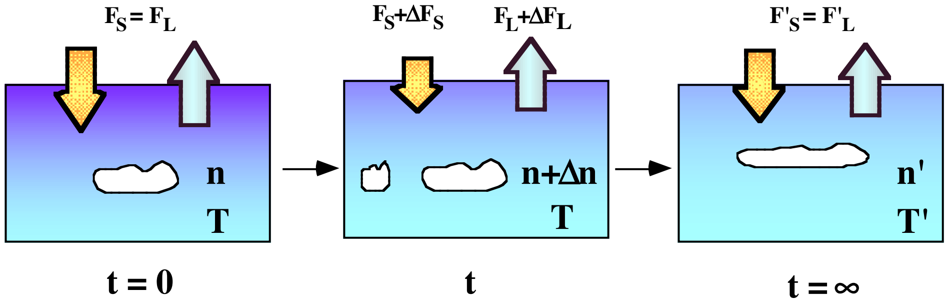
Manabe and Wetherald (1967)

- **Cloud liquid water path and cloud top temperature are important parameters to control the earth's energy budget.**

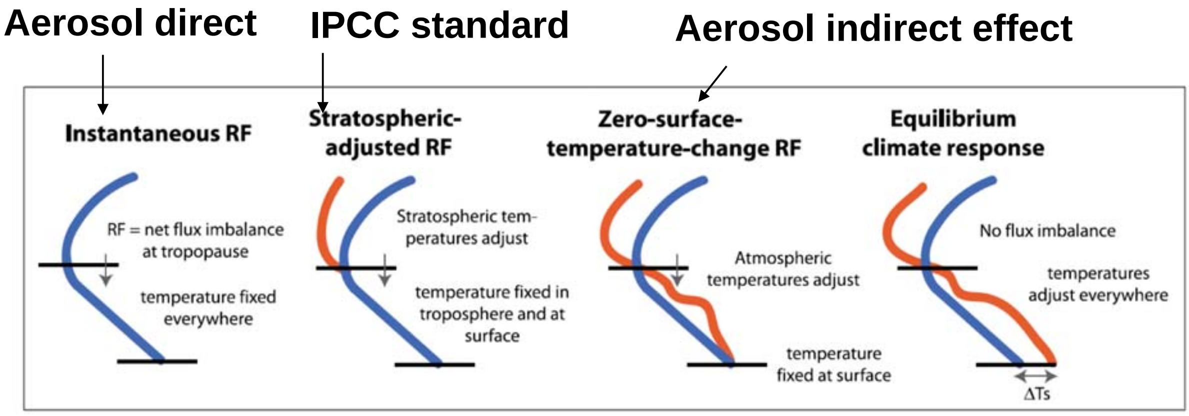
$$[n(1-r_c)+(1-n)(1-r_s)]Q = n\sigma T_c^4 + (1-n)\sigma T_g^4$$



Radiative forcing $\Delta F = \Delta F_S + \Delta F_L$



Cloud radiative forcing: $CRF = F - F_{clear}$
$= n F_{cloud} + (1-n) F_{clear} - F_{clear} = n (F_{cloud} + F_{clear})$



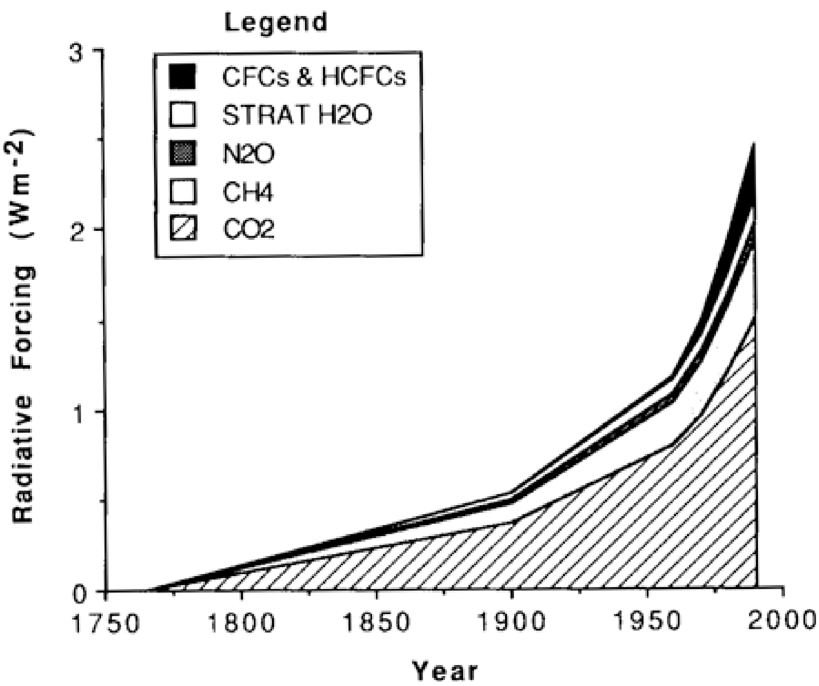
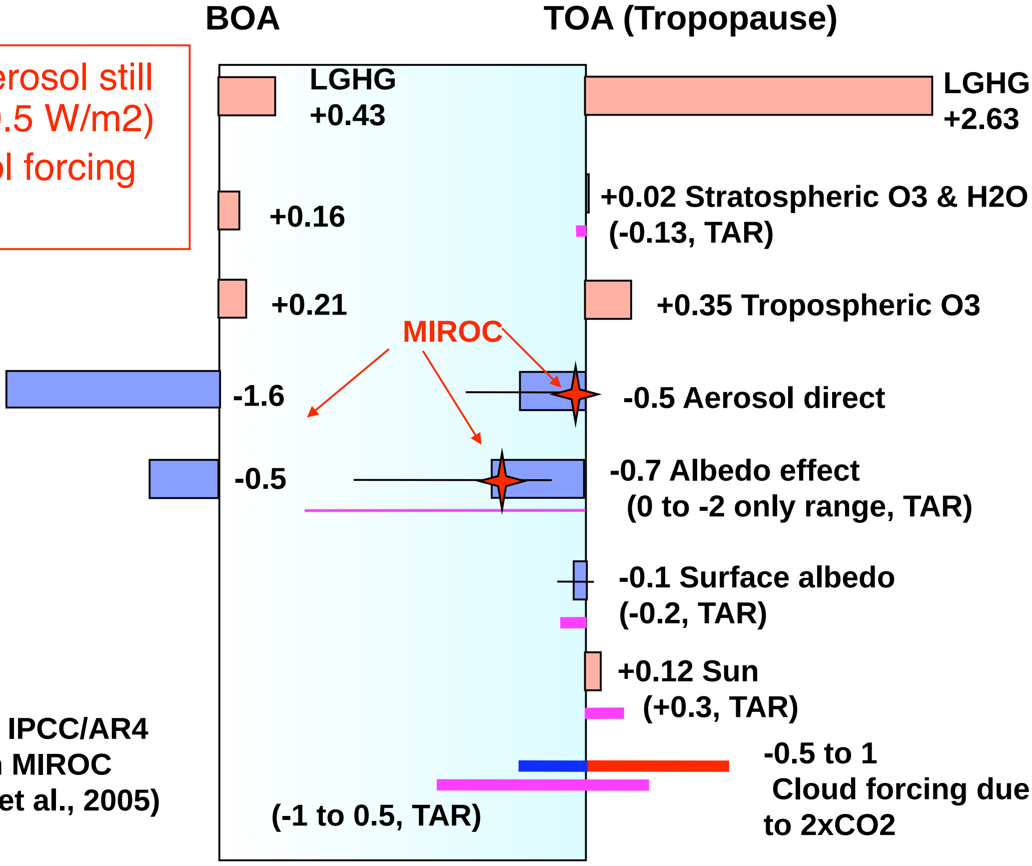


Figure 2.2: Changes in radiative forcing (Wm^{-2}) due to increases in greenhouse gas concentrations between 1765 and

(IPCC, 1990)

Radiative forcings since 1750

- Cloud and aerosol still uncertain (±0.5 W/m2)
- Large aerosol forcing at surface

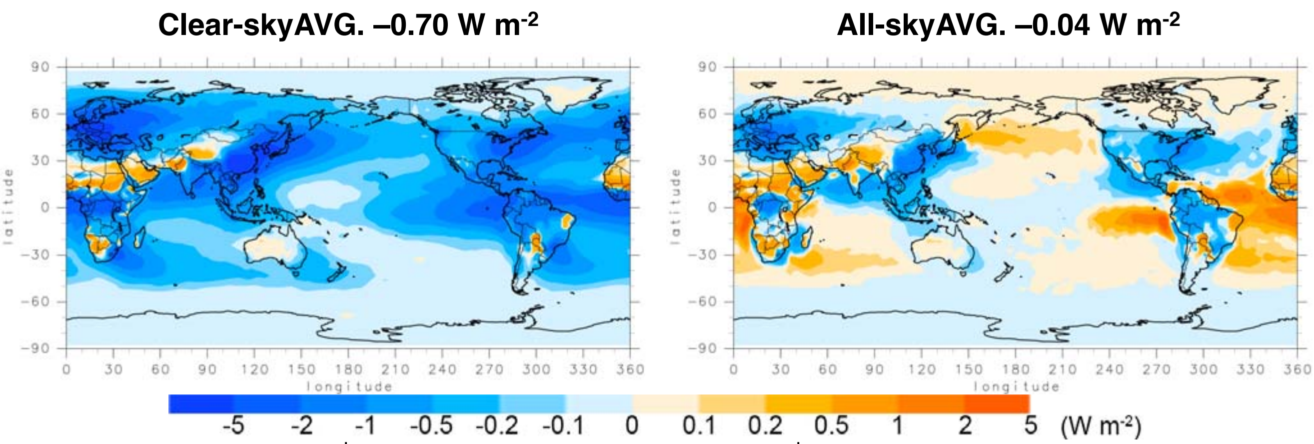


TOA: Values from IPCC/AR4
BOA: Values from MIROC
(Takemura et al., 2005)

Report of Science Council of Japan on global warming problem (2008)

Aerosol direct forcing by MIROC/AGCM+SPRINTARS

- **Uncertainty of about 0.5 W/m2 due to stratification**
- **Boundary layer modeling and hygroscopic growth modeling**



TOA Radiative Forcing	Tropopause ($W m^{-2}$)		Surface ($W m^{-2}$)	
	All-sky	Clear-sky	All-sky	Clear-sky
BC	+0.42	+0.22	–0.75	–0.95
OC	–0.26	–0.48	–0.35	–0.55
Sulfate	–0.20	–0.44	–0.16	–0.36
Total	–0.04	–0.70	–1.26	–1.86

Takemura et al. (JGR2005)

References

- Hansen, J., M. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G.A. Schmidt, G. Russell, I. Aleinov, M. Bauer, S. Bauer, N. Bell, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, M. Kelley, N. Kiang, D. Koch, J. Lean, J. Lerner, K. Lo, S. Menon, R. Miller, P. Minnis, T. Novakov, V. Oinas, J. Perlwitz, J. Perlwitz, D. Rind, A. Romanou, D. Shindell, P. Stone, S. Sun, N. Tausnev, D. Thresher, B. Wielicki, T. Wong, M. Yao, and S. Zhang, 2005: Efficacy of climate forcings. *J. Geophys. Res.*, **110**, D18104, doi:10.1029/2005JD005776.
- IPCC, 1990: Climate Change, The IPCC Scientific Assessment. Eds. J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, *Cambridge Univeristy Press*, 364 pp.
- IPCC, 2001: J. T. Houghton, Ed., *Cambridge Univ. Press*, " Climate Change 2001-The Scientific Basis".
- Manabe, S. and R. F. Strickler, 1964: Thermal equilibrium of the atmosphere with a convective adjustment. *J. Atmos. Sci.*, **21**, 57-81.
- Manabe, S, and R.T. Wetheraldm, 1967: Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci.*, **24**, 241-59.
- Rossow, W. B., A. W. Walker, and L. C. Garder, 1993: Comparison of ISCCP and other cloud amounts. *J. Climate*, **6**, 2394-2418.

Climate sensitivity 1

- **Radiation budget imbalance due to a change (Radiative forcing):** ΔF (W/m^2)
- **Radiative forcing causes a surface air temperature chage after a time** t**:** ΔT_s (K)

$$\Delta T_g = \gamma(t)\lambda\Delta F$$

- **Equilibrium climate sensitivity:** λ **(**W/m^2K**)**
  - **Current GCMs** $\lambda \sim 1$
- **Thermal inertia efficiency:** γ
  - γ **= 1 for perpetual forcing**
  - $\gamma \sim$ **0.4 for CO2 increase**
  - $\gamma \sim$ **0.1 for volcanic erruption aerosols**

Climate sensitivity 2

- **Perturbation of the system**

$$\Delta F = \frac{\partial F}{\partial e}\Delta e + \{\frac{\partial F}{\partial T_S} + \sum_i \frac{\partial F}{\partial q_i}\frac{dq_i}{dT_S}\}\Delta T_S \to 0$$

- **Radiative forcing** $RF = \frac{\partial F}{\partial e}\Delta e$

- **Equiliburium climate sensitivity** $\Delta T_S = \lambda \times RF$

- **Feedback gain factors**

$$1/\lambda = \frac{\partial(-F)}{\partial T_S} + \sum_i \frac{\partial(-F)}{\partial q_i}\frac{dq_i}{dT_S} = \beta_0 + \sum_i \beta_i$$

Radiation damping

- **Radiative energy budget of the planet**

$$F = (1-\alpha)Q_s - \varepsilon\sigma T_s^4$$

- **Total gain factor is the sum of three effects: radiative dampling, planetary albedo change, and emissivity change:**

$$\beta = 4\varepsilon\sigma T_s^3 + Q_s\frac{d\alpha}{dT_s} + \sigma T_s^4\frac{d\varepsilon}{dT_s} = \beta_0 + \beta_\alpha + \beta_\varepsilon$$

- **The radiation damping factor causes a strong stablization of the system**

$$\lambda_0 = \frac{1}{4\varepsilon\sigma T_s^3} = 0.31, \quad \varepsilon = 0.64, T_s = 280K$$

- **If there is no atmosphere, the system is very stable**

$$\lambda_{0,blck} = 0.20, \quad \varepsilon = 1, T_s = 279K$$

Feedback of water vapor

- **Suppose no-radiation energy convergence atmosphere similar to the cloud case in visible region.**

$$\varepsilon = \frac{1}{1+\gamma\tau_g/2} \qquad \tau_{wv} = \exp(8.3 - 2563/T_s) + 0.2$$

$$F = (1-\alpha)Q_s - \frac{\sigma T_s^4}{1+0.83\tau_{wv}} \qquad F = 0 \rightarrow T_s = 288K,\ \tau_{wv} = 0.75$$

- **Water vapor can cause a strong instability to the atmosphere**

$$\beta_0 = \frac{\partial(-F)}{\partial T_s} = \frac{4\sigma T_s^3}{1+0.83\tau_{wv}} = 3.3 \qquad \beta_{wv} = \frac{\partial(-F)}{\partial \tau_{wv}}\frac{d\tau_{wv}}{dT_s} = -\frac{2127(\tau_{wv}-0.2)\sigma T_s^2}{(1+0.83\tau_{wv})^2} = -2.1$$

$$\lambda = \frac{1}{\beta_0 + \beta_{wv}} = 0.81$$

- **α=0.1 has no solution: Runaway greenhouse effect**

Climate sensitivity of the GCM

- **Total sensitivity is relatively similar among models. But, partitioning among the various climate change factors is very uncertain, for example, between GFDL and GISS GCMs.**

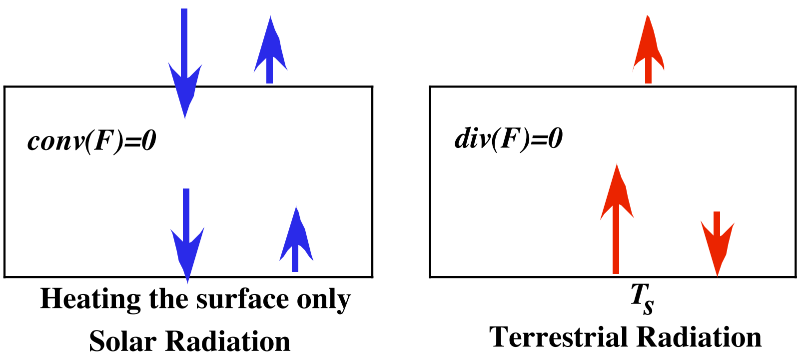
IPCC90	λ	λ
Feedbacks	GFDL	GISS
Cloud, albedo fixed	0.43	0.50
Cloud feedback	0.50	0.80
Albedo feedback	1.00	1.05

Constants

Acceraration of gravity	9.80665 m/sec2
Speed of light	2.9979e8 m/sec
Boltzman constant	1.3807e-23 J/K
Plank constant	6.6261e-34 Jsec
Avogadro number	6.0221e23 /mol
Volume of ideal gas at 0。C and 1 atom	2.241e4 cm3/mol
Absolute temperature	273.15 K (0C)
Gas constant	8.314 J /deg/mole
Stephan-Boltzman constant	5.670e-8 W /m2 K4
Molecular weight of dry air	28.964 g/mol
Latent heat of vaporization at 273K	2.500E6 J/Kg
1 bar 10^6 dyne/cm2 = 10^5 N/m2 = 10^5 Pa	
Earth's radius	6370 km
Mean solar angular diameter	31.99 minutes of arc
Air= 0.78083 (N2)+0.20947 (O2)+ 0.00934 (Ar)+0.00033 (CO2) by volume ratio	
Globe= 0.708 (Ocean)+ 0.292 (Land) by area ratio	
Molecular weight of air	29 g/mole

Radiative energy balance 1

- **Equation for broad band thermal radiation**



$$+\frac{dF^+}{dx} = -F^+ + \sigma T^4, \quad -\frac{dF^-}{dx} = -F^- + \sigma T^4$$

$$\frac{d\Phi(x)}{dx} = -\Psi(x) + 2\sigma T^4, \quad \frac{d\Psi(x)}{dx} = -\Phi(x)$$

Radiative energy balance 2

$$div(F)=0 \rightarrow \Phi = C \rightarrow \Psi = 2\sigma T^4, \quad \Psi(x) = A - \Phi x$$

$$F^+(x) = \frac{1}{2}[A + (1-x)\Phi]$$

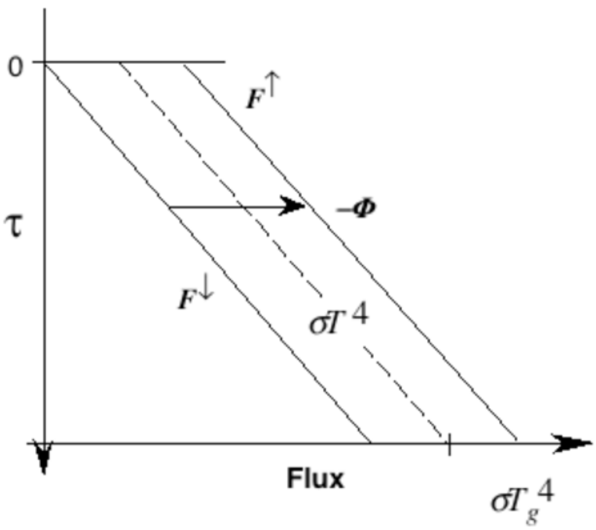
$$F^-(x) = \frac{1}{2}[A - (1+x)\Phi]$$

- **Boudary condition**

$$F^+(0)=0, \quad F^-(x_g) = \sigma T_g^4$$

$$A = -\Phi$$

$$2\sigma T_g^4 = -(2 + x_g)\Phi$$



Houghton (1972)

Radiative energy balance 3

$$\Psi = 2\sigma T^4 = -(1+x)\Phi = \frac{1+x}{2+x_g} 2\sigma T_g^4$$

$$-\Phi = \frac{2\sigma T_g^4}{2+x_g} \qquad F^+(x) = \frac{x}{2+x_g}\sigma T_g^4$$

$$T^4 = \frac{1+x}{2+x_g} T_g^4 \qquad F^-(x) = \frac{2+x}{2+x_g}\sigma T_g^4$$

- **Equivalent black body temperature of the planet**

$$F^-(0) = \sigma T_e^4 = \frac{2}{2+x_g}\sigma T_g^4$$

- **There is a temperature discontinuity at surface.**
- **Greenhouse effect**

Q10.

- **Calculate the optical thickness of the atmosphere in the infrared spectrum region with Ts and Te given in Table 1.**

Radiative energy balance 4

- **More realistic value of the optical thickness of the earth's atmosphere**
  - **From the planetary albedo condition,**

$$A = 0.3 \rightarrow A_{g,s} = 0.1, n = 0.6, \tau_{c,Vis} = 5$$

$$\tau_{c,IR} \approx 0.5\tau_{c,Vis}$$

$$t_{sky,normal} \approx 0.2 \quad or \quad \tau_{gas,IR} = -\ln(t_{sky,normal}) = 1.6$$

$$\tau_g \approx n(\tau_{c,IR} + \tau_{gas,IR} / 2) + (1-n)\tau_{gas,IR} = 2.6$$

$$T_s = (\frac{2 + x_g}{2})^{1/4} T_e = 342K, \quad T_e = 255K$$

- **This value is similar to Manabe et al. for radiative-equilibrium model. Upward energy transfer by convection is important to cool the surface.**

イタリアの古い絵画から

マイアミ大学のProspero先生によると・・・

ヴァランシェンヌ, イタリア, 1790

それなら、1873年のパリのそらは?

モネ, パリ, 1873

Dust vail index and paiting color

- Lamb (1970): (1) the depletion of radiation, (2) temperature variations following the eruption, and (3) the amount of solid material dispersed as dust after an eruption.
- Zerefos et al. (2007): R/G col

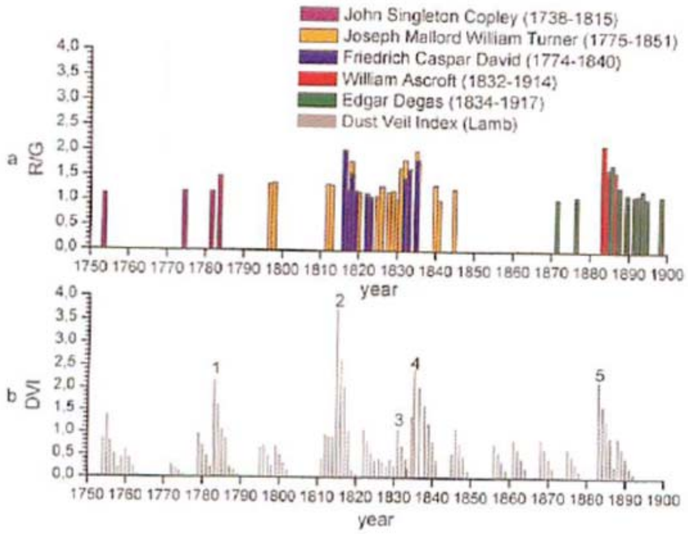


Fig. 1. (a) The variation of the chromatic ratio R/G that correspond to paintings of Copley, Turner, David, Ascroft and Degas. **(b)** The Dust Veil Index. The numbered peaks are 1. Laki, 2. Tambora, 3. Babuyan, 4. Coseguina and 5. Krakatau.