Chapter 5 大氣輻射與氣候

5-1 地球大氣系統的輻射能量收支

5-1-1 大氣層頂

$$F = (1 - r)Q - F_{IR} \tag{5.1}$$

where F 為淨輻射，Q 為太陽輻射，r 為地球的行星反照率，F_{IR} 則為地球長波輻射到外太空的通量(OLR, outgoing longwave radiation)

where <1> $F = 0$ ，地球系統處於熱力平衡狀態

<2> $F > 0$ ，地球系統加熱

<3> $F < 0$ ，地球系統冷卻

e.g.

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

其中，

λ ：氣候回饋參數，即地表每增一度所需之能量

G ：溫室效應作用力

ΔT_s ：地表溫度增加量

在氣候變遷的研究，如何計算出 λ 是非常重要的

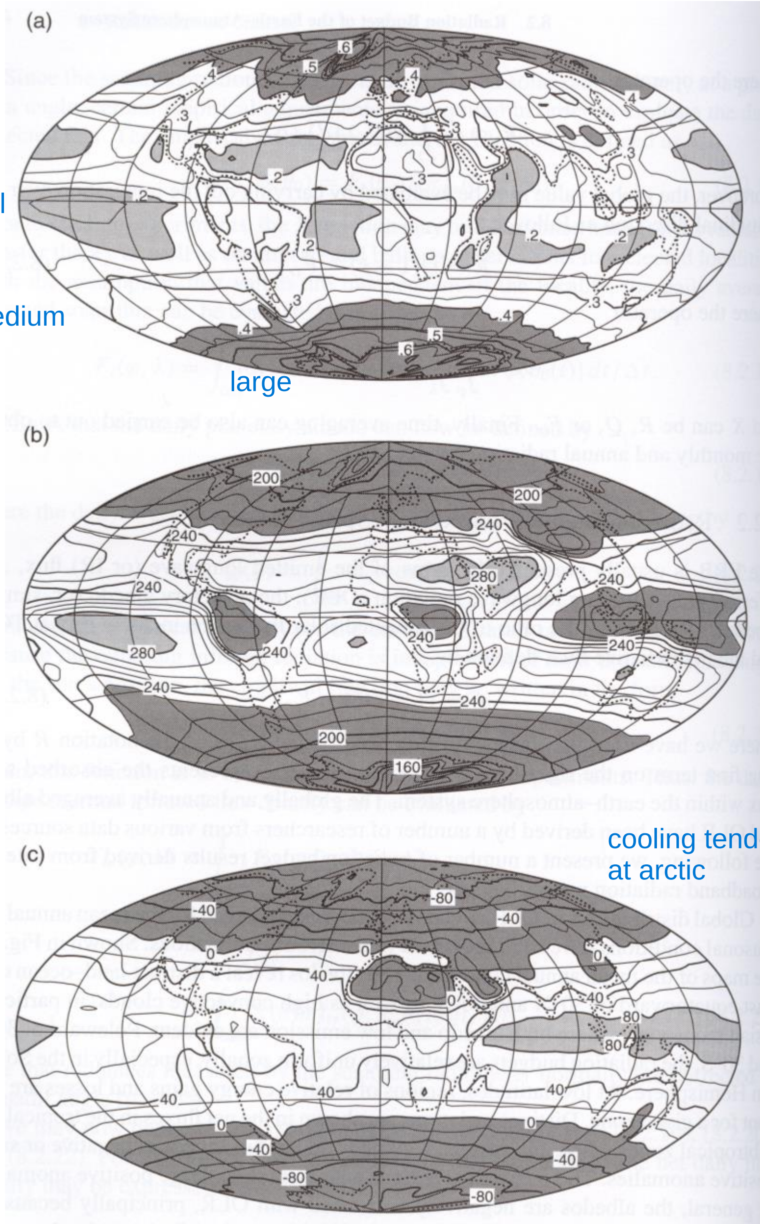

Fig 5.1: Global maps of (a) mean annual planetary albedo, (b) outgoing longwave radiation (Wm^{-2}), and (c) net radiative flux (Wm^{-2}) , in a Hammer equal-area projection (data taken from Hartmann, 1994). In these diagrams, heavier shaded areas denote albedos larger than 0.4, longwave fluxes smaller than $230Wm^{-2}$, and negative net radiative fluxes. [Liou02, Figure8.1]

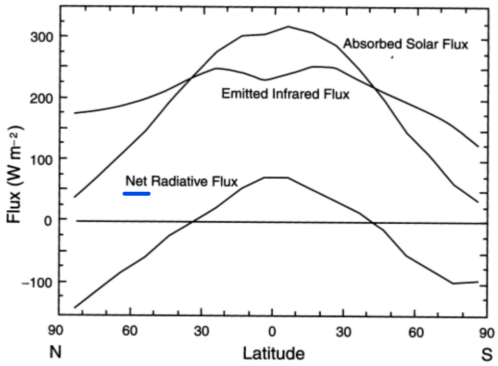

Fig 5.2: Zonally averaged components of the annual mean absorbed solar flux, emitted thermal infrared flux (or OLR), and net radiative flux at the top of the atmosphere, derived from satellite broadband radiation measurements. These patterns were originally presented by Vonder Haar and Suomi (1971), Stephens et al. (1981), and more recently by Hartmann (1994). [Liou02, Figure8.2]

5-1-2 雲對輻射的影響(cloud radiative forcing)

如果考慮雲量為η，則

$$F=(1-\eta)F^{cl}+\eta F^{ov} \tag{5.2}$$

where F^{cl} 為晴空(clear sky)的輻射通量

F^{ov} 為有雲時(cloudy sky)的輻射通量

➔雲對輻射的影響(CRF)

$$C=F^{cl}-F=\eta(F^{cl}-F^{ov}) \tag{5.3}$$

影響C的因素：

① η ：雲量如何在氣候變遷中改變

② F^{cl} ：包含大氣的組成和溫度　no cloud situation

③ F^{ov} ：雲在垂直方向的分佈和雲的特性

分別對於地球長波輻射和太陽短波輻射而言

$$C_{IR}=F_{IR}{}^{cl}-F_{IR} \tag{5.4a}$$

$$C_S=Q(r^{cl}-r) \tag{5.4b}$$

Q total solar radiation of a day

where $F_{IR}{}^{cl}$ 為晴空的 OLR，r^{cl} 為晴空的反照率

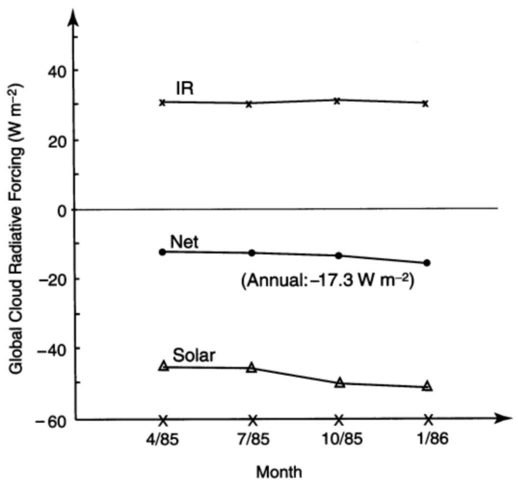

Fig 5.3: Global cloud radiative forcing in units of Wm^{-2} as a function of months estimated from Earth Radiation Budget Experiment (ERBE) data (data taken from Harrison *et al.*, 1990). [Liou02, Figure.3]

5-1-3 大氣中的輻射加熱與冷卻

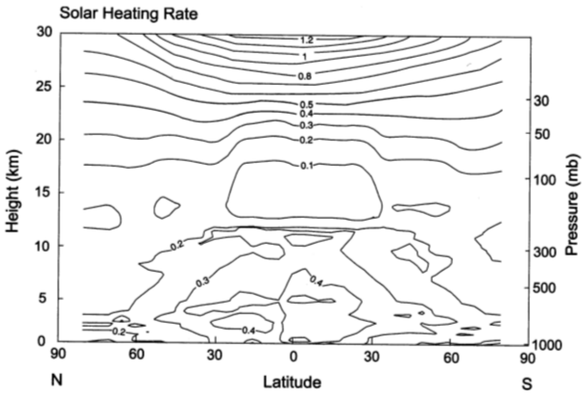

Fig 5.4: Annual meridional cross sections of the solar heating rate (K day^{-1}) of the atmosphere computed from a radiative transfer program using climatological temperature, cloud, gaseous, and surface albedo data. The input solar flux is 342 Wm^{-2}. The contour line is 0.1 K day^{-1}. [Liou02, Figure8.4]

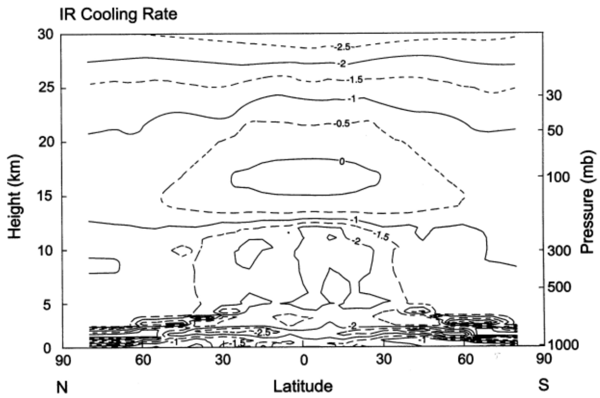

Fig 5.5: Annual meridional cross sections of the thermal infrared (IR) cooling rate (K day^{-1}) of the atmosphere computed from a radiative transfer program using climatological temperature, cloud, and gaseous data. The contour line is 0.5 K day^{-1}. [Liou 02, Figure8.5]

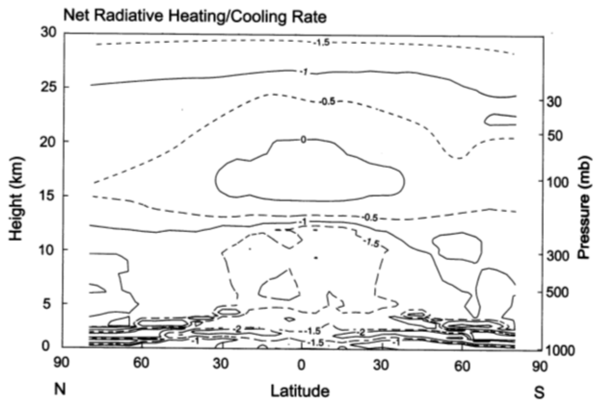

Fig 5.6: Annual meridional cross sections of the net radiative heating/cooling rate (K day^{-1}) of the atmosphere. The contour line is 0.5 K day^{-1}. [Liou02, Figure8.6]

5-1-4 地球表面

$$F(0) = F_S^{\downarrow}(0)(1 - r_S) - [\varepsilon_S \sigma T_S^{\,4} - \varepsilon_S F_{IR}^{\downarrow}(0)] \tag{5.5}$$

where $F(0)$ 為地球表面的淨輻射

$F_S^{\downarrow}(0)$ 為地球表面的太陽輻射

$F_{IR}^{\downarrow}(0)$ 為地球表面的大氣長波輻射

r_S 為地表反照率

ε_S 為地表放射率

T_S 為地表溫度

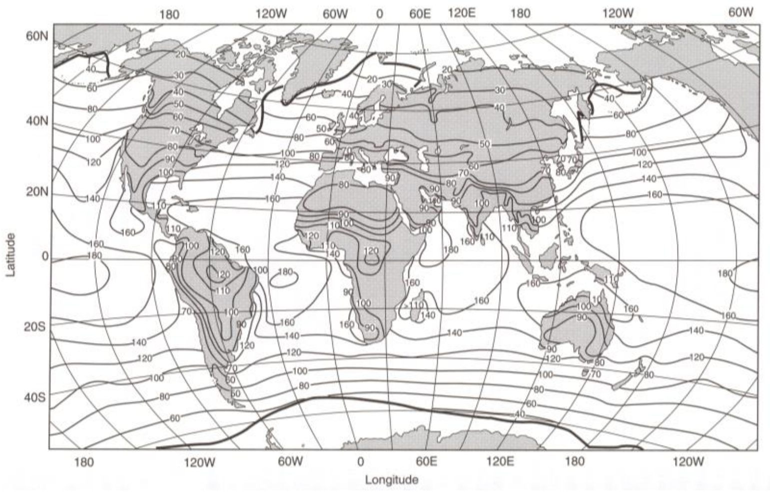

Fig 5.7: Global distribution of the mean radiation flux (Wm^{-2}) at the earth's surface based on a number of direct surface observations over land and the ocean. The mean annual ice boundary is also shown by heavy lines (data taken from Budyko, 1986). [Liou02, Figure8.7]

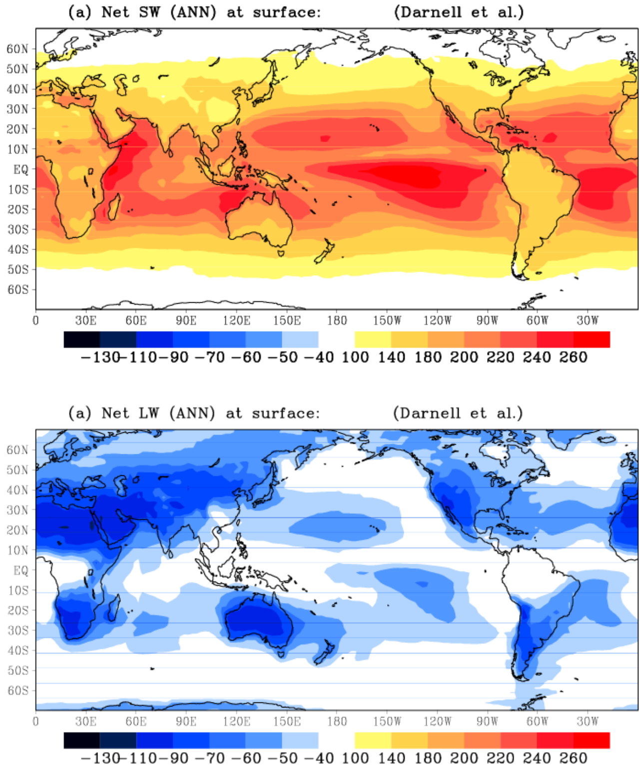

Fig 5.8

5-2 輻射和對流的大氣層

5-2-1 輻射平衡

<a>全球模式

no atmosphere $$\pi a_e^{\ 2}(1-\bar{r})S = 4\pi a_e^{\ 2}\sigma T_e^{\ 4} \tag{5.6}$$

where a_e 為地球半徑，$\bar{r}$ 為全球反照率，S 為太陽常數

T_e 為地球系統的平衡溫度

➔ $$T_e = \left[(1-\bar{r})S/4\sigma\right]^{1/4} \tag{5.7}$$

Note：溫度(T_e)的高低決定地表雪覆蓋的程度，進而影響到反照率($\bar{r}$)的大小。在(5.7)，地球表面溫度和大氣的輻射特性都無法包含。為了要模擬這些作用，一個二層模式是必要的。

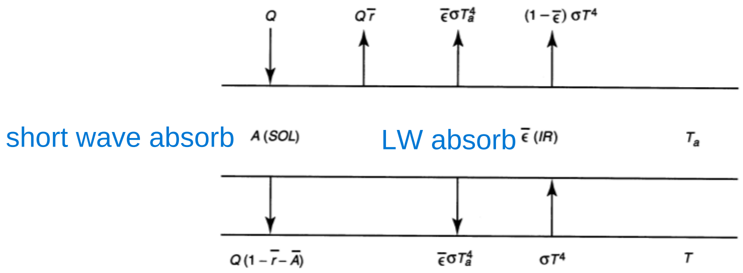

Fig 5.9: A two layer radiative equilibrium model involving the surface and the atmosphere with temperatures denoted by T and Ta, redpectively. The notations $\bar{A}$ and $\bar{\varepsilon}$ denote the absorptivity and thermal infrared emissivity, redpectively, and $\bar{r}$ is the reflectivity. The solar input is defined by Q. [Liou02, Figure8.8]

能量平衡在大氣層頂(TOA)和地球表面則為

for TOA
$$Q(1-\bar{r})-\bar{\varepsilon}\sigma T_a^{\ 4}-(1-\bar{\varepsilon})\sigma T^4=0 \tag{5.8}$$

for Surface
$$Q(1-\bar{r}-\bar{A})+\bar{\varepsilon}\sigma T_a^{\ 4}-\sigma T^4=0 \tag{5.9}$$

所以地表溫度和大氣溫度為

$$T^4=Q[2(1-\bar{r})-\bar{A}]/[\sigma(2-\bar{\varepsilon})] \tag{5.10}$$

$$T_a^{\ 4}=Q[\bar{A}+\bar{\varepsilon}(1-\bar{r}-\bar{A})]/[\sigma\bar{\varepsilon}(2-\bar{\varepsilon})] \tag{5.11}$$

where $\bar{A}$ 為大氣對太陽輻射的吸收率

$\bar{\varepsilon}$ 為大氣的長波輻射放射率

Discussions：

<1>假設 $\bar{r}$ 和 $\bar{A}$ 不變，當 CO_2 增加時 ➔ $\bar{\varepsilon}$ 變大 ➔

<i> T↗變大➔ 地表溫度增加

<ii> T_a 是否增加，則不明確，但假設大氣對太陽輻射的吸收很少(目前地球大氣的狀態)，即 $\bar{A}\to 0$ ➔ T_a 變大

<2>假設 $\bar{A}$ 和 $\bar{\varepsilon}$ 不變，當雲增加時，即 $\bar{r}$ 變大

➔ T 變小，T_a 變小

➔ 地表和大氣溫度都降低

<3>討論<1>和<2>的情況都可能再全球氣候變遷中同時發生，但<1>為正回饋，<2>為負回饋

<b>垂直模式

$$\rho C_p\left(\frac{\partial T}{\partial t}\right)_{RAD} = -\frac{\partial}{\partial z}(F_s - F_{IR}) \tag{5.12}$$

假設 steady state➔ $\dfrac{\partial}{\partial t} = 0$

且 $F_s(\infty) = F_{IR}(\infty)$

➔ $$F_s(z) = F_{IR}(z) \tag{5.13}$$

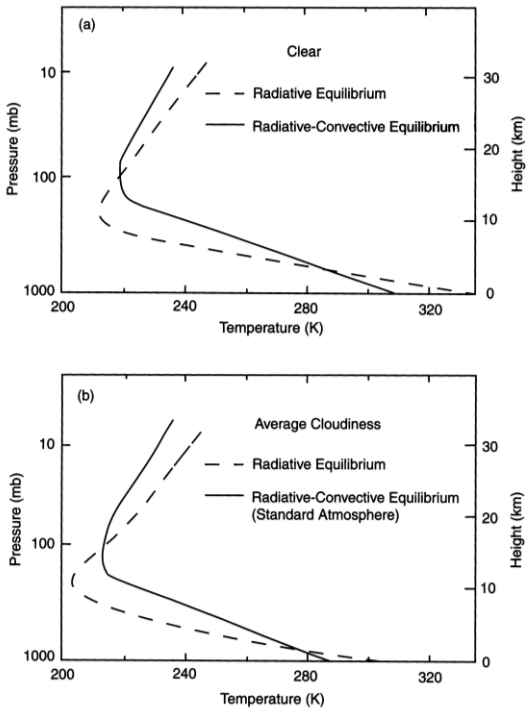

Fig 5.10: Vertical distributions of radiative and radiative-convective equilibrium temperatures in clear (a) and average cloud (b) conditions, simulated from a one-dimensional radiative-convective climate model. [Liou02, Figure8.9]

Discussions：

<1>地表溫度過高($\approx$340K)而對流層頂溫度過低($\approx$215K)

➔對流的產生，讓能量高的空氣(地表)向上移動，而能量低的空氣(高層)向下移動

➔輻射對流平衡

5-2-2 輻射對流平衡

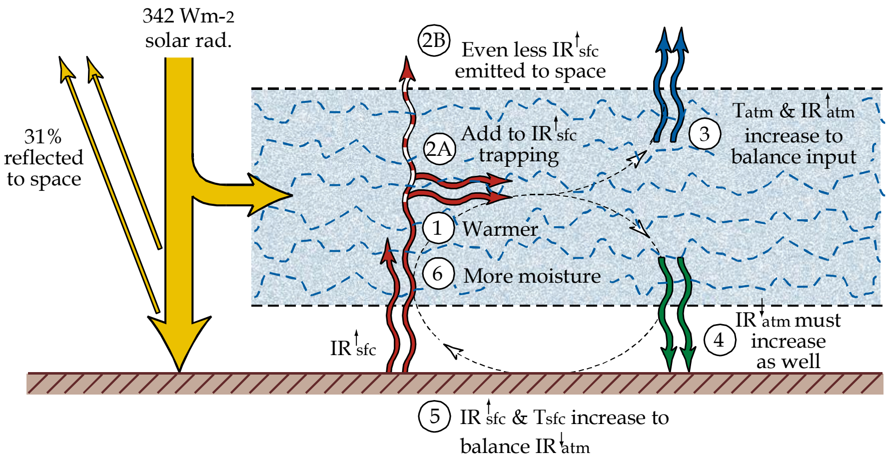

Fig 5.11: water vapor feedback

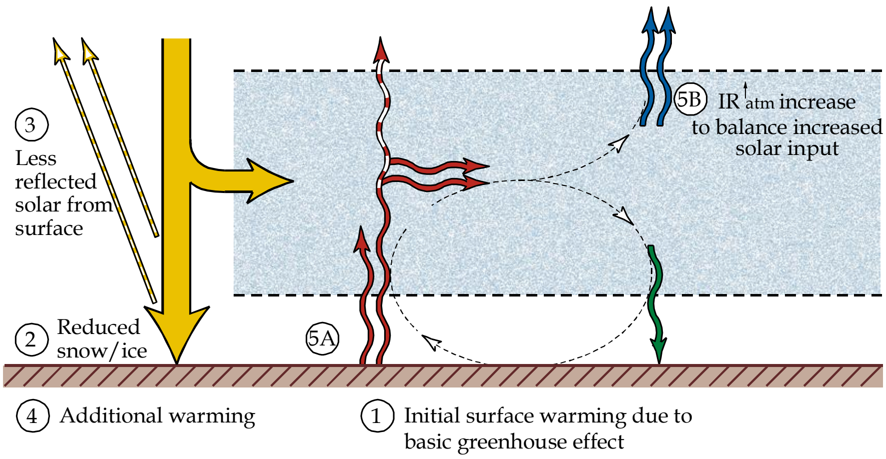

Fig 5.12: snow and ice feedback

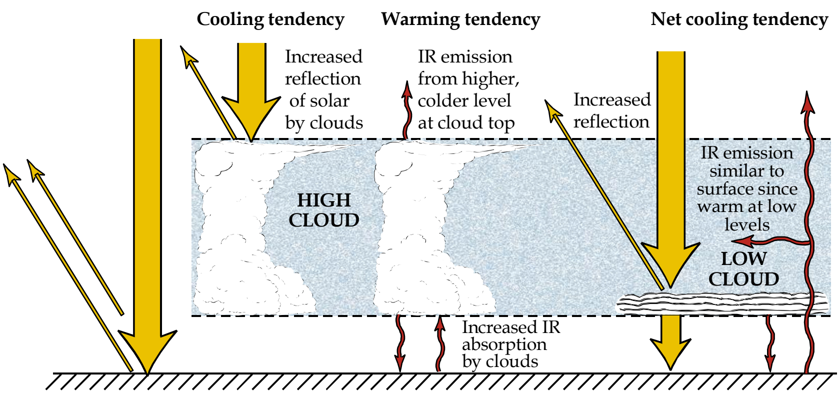

Fig 5.13: cloud effects

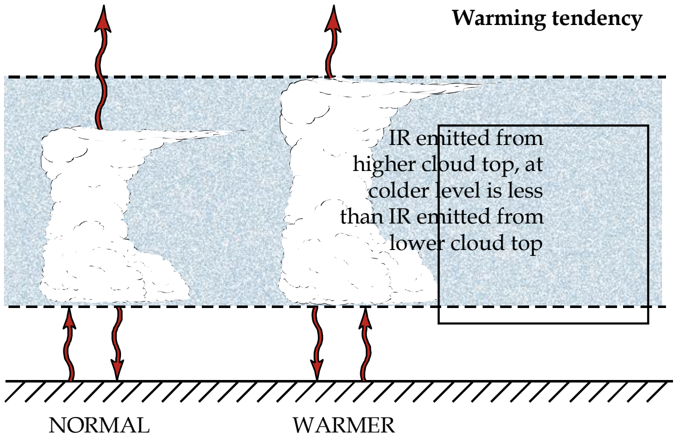

Fig 5.14: cloud top feedback

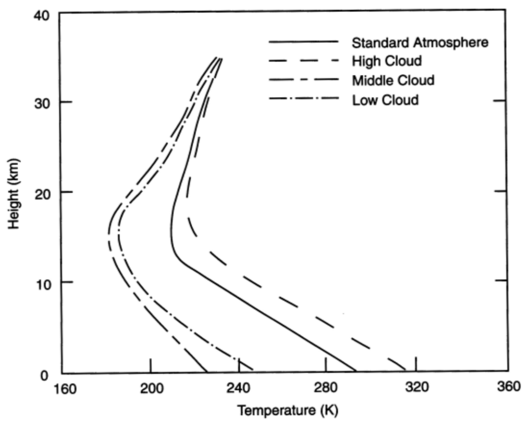

Fig 5.15: Effects of high, middle, and low clouds on atmospheric temperatures in a radiative convective model. The solid curve is the temperature profile of the standard atmosphere (data taken from Liou and Ou, 1983). [Liou02, Figure8.14]

5-3 全球氣候模式中的輻射

5-3-1 全球模式(general circulation model)

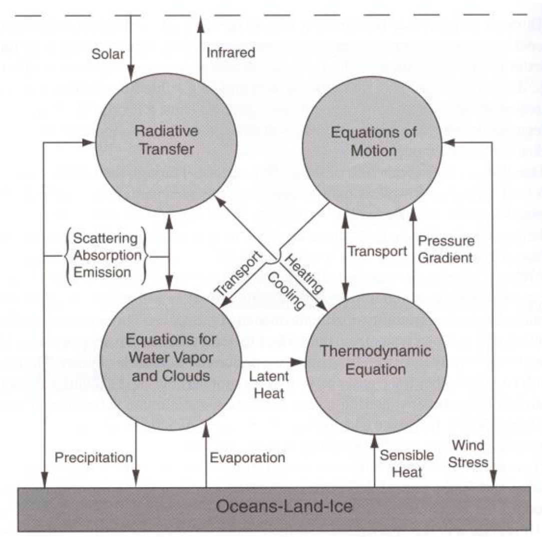

Fig 5.16: Principal components of the physical and mathematical definitions and interactions of a general circulation model (GCM) for climate simulations, particularly in reference to radiative transfer in the earth-atmosphere system. See also Fig. 8.17. [Liou02, Figure8.23]

5-3-2 雲對輻射的影響(CRF：cloud radiative forcing)

定義：(5.3)

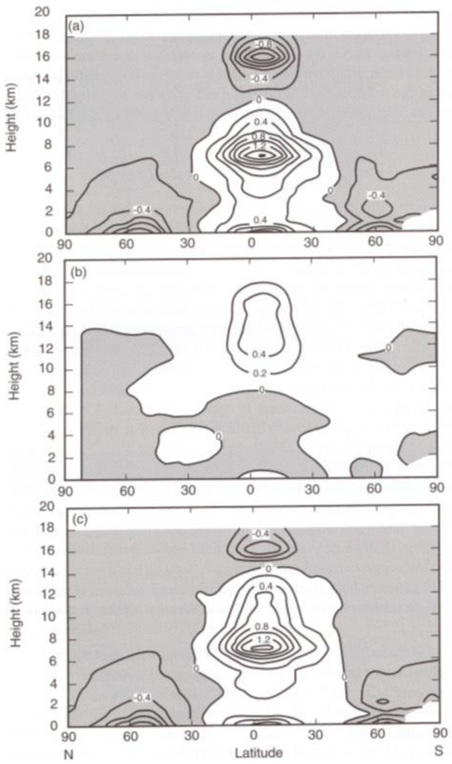

Fig 5.17: Latitudinal distribution of the zonal mean cross section for (a) cloud longwave (IR) radiative forcing; (b) cloud shortwave (solar) radiative forcing; (c) cloud net radiative forcing. The results are obtained from the perpetual January control simulation; the contour interval is 0.2 K day^{-1} (data taken from Randall *et al.*, 1989). [Liou02, Figure8.24]

<1>雲量和溫室效應

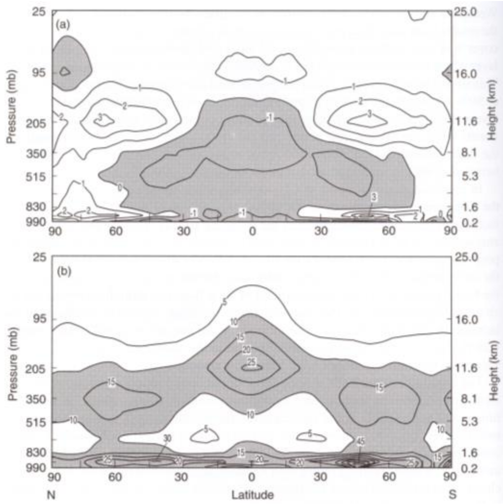

Fig 5.18: Height-latitude cross section for (a) CO_2-induced change of zonal mean cloud amount (%); and (b) zonal mean cloud amount (%) obtained from a GCM experiment (data taken from Wetherald and Manabe, 1988). [Liou02, Figrue8.25]

<2>雲中水和冰的含量

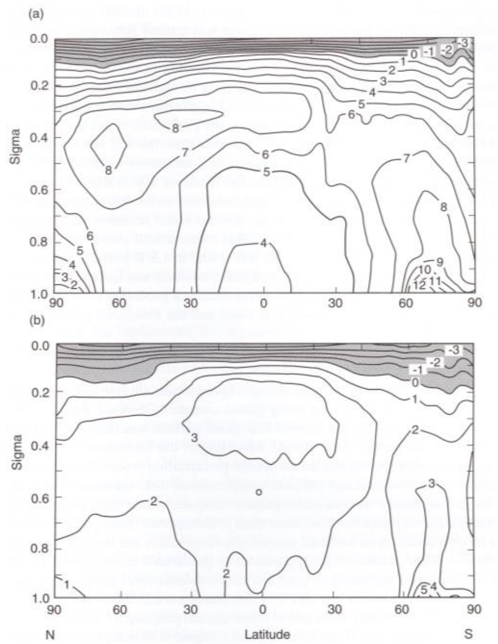

Fig 5.19: Height (σ-coordinate)-latitude cross section of equilibrium temperature changes in a 10-year summer simulation of doubling CO_2. Contours in every 1 K and reductions are shaded. (a) Cloud parametrization using an RH method; and (b) an interactive cloud water prognostic equation and radiative transfer feedback (data taken from Senior and Mitchell, 1993). [Liou02, Figure8.26]

<3>雲滴的大小

5-3-3 氣膠

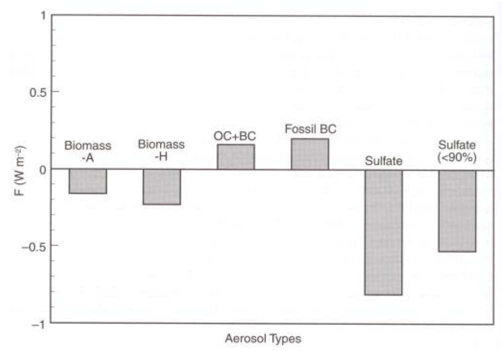

Fig 5.20: Global average radiative forcing at TOA for various aerosol types estimated from a GCM coupled with a chemical transport model. Biomass-A and －H denote the use of different assumed size distributions, OC denotes organic carbon, BC denotes black carbon, and sulfate(<90%) represents the case where the particle size and optical properties remain fixed at RH=90% if RH>90% (data taken from Penner *et al.*, 1998). [Liou02, Figure8.27]

5-3-4 聖嬰現象中的輻射

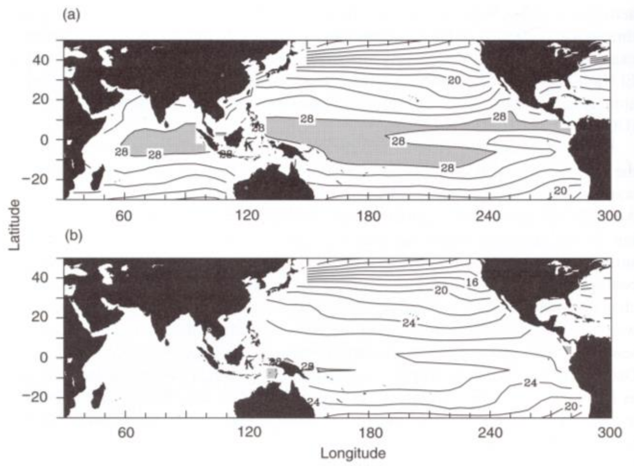

Fig 5.21: Climatological SST (℃) patterns simulated by the UCLA coupled atmosphere-ocean general circulation model: (a) a version with a suitable incorporation of high-cloud emissivity and the formation of low-level Peruvian stratus clouds, and (b) an earlier version without a specific inclusion of these two cloud effects. The shaded area in (a) shows the SST higher than 28℃ including the Indian ocean (data provided by Jin-Yi Yu of the University of California, Los Angeles). [Liou02, Figure8.29]

➔clouds affect SST