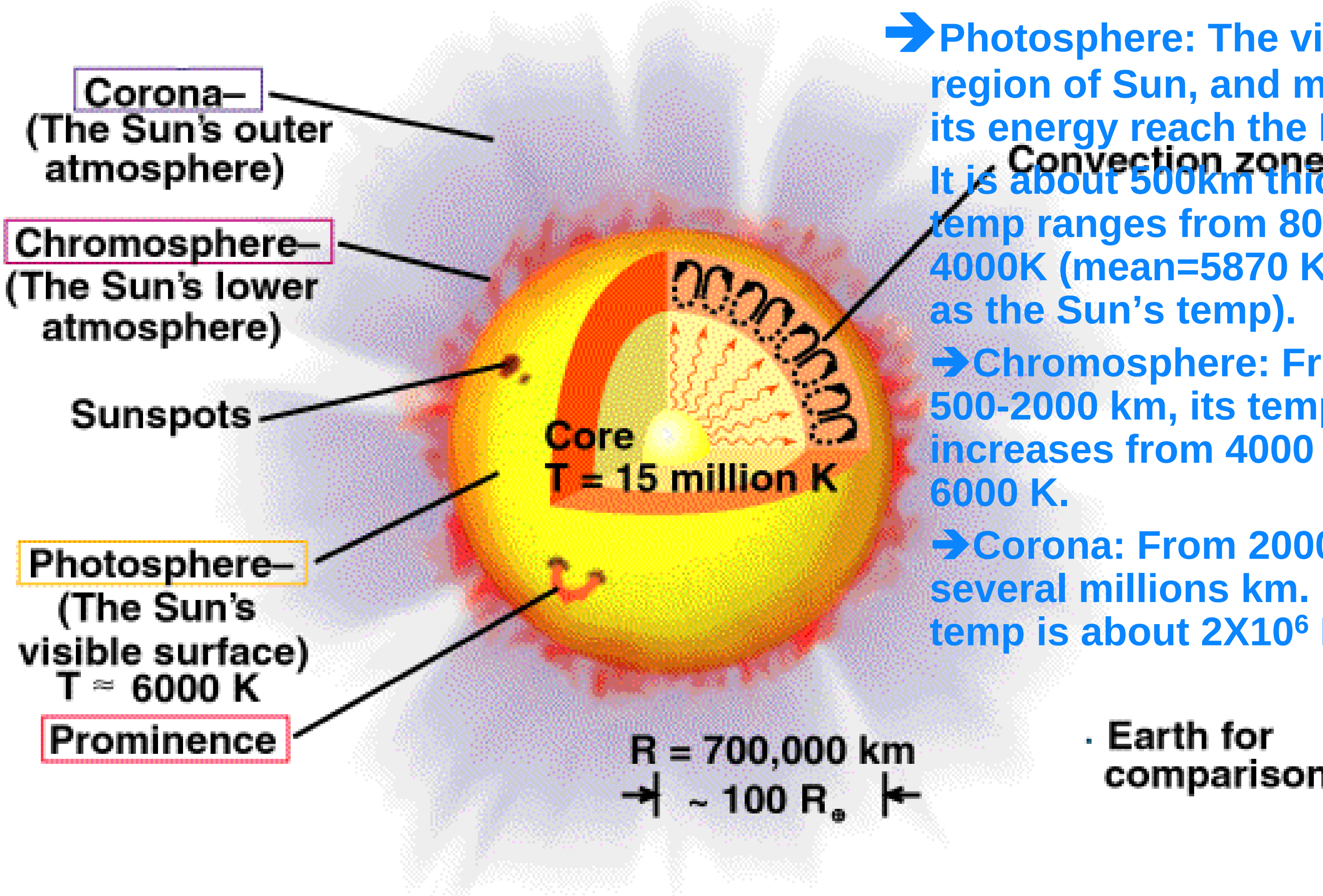
Lesson 2

Radiative Forcing, Earth Temperature, and Climate Sensitivity

Cut Away View of the Sun

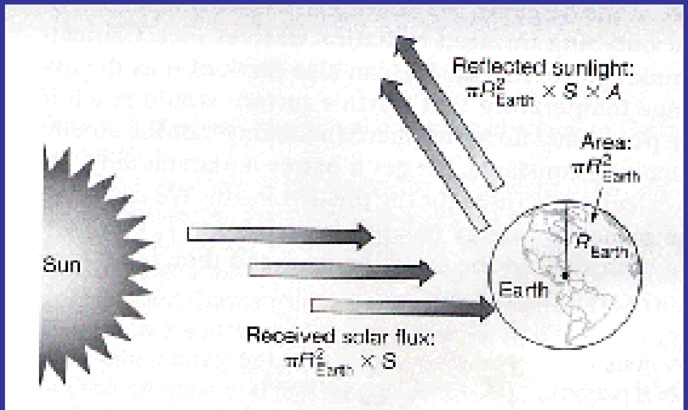


➔Photosphere: The visible region of Sun, and most of its energy reach the Earth. It is about 500km thick, its temp ranges from 8000K to 4000K (mean=5870 K, used as the Sun's temp).

➔Chromosphere: From 500-2000 km, its temp increases from 4000 to 6000 K.

➔Corona: From 2000 km to several millions km. Its temp is about 2X10^6 K.

Solar Energy Absorbed by Earth



BOX FIGURE 3-1
The amount of sunlight received by and reflected by Earth.

(from *The Earth System*)

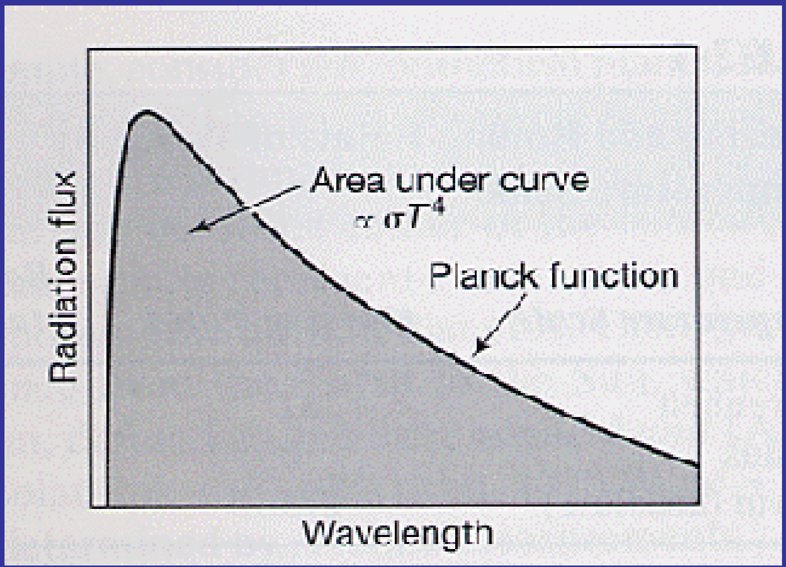
- **Solar Constant (S)**
  = solar flux density reaching the Earth
  = 1370 W/m^2

- **Solar energy incident on the Earth**
  = S x the "flat" area of the Earth
  = $S \times \pi R^2_{Earth}$

- **Solar energy absorbed by the Earth**
  = (received solar flux) – (reflected solar flux)
  = $S \pi R^2_{Earth} - S \pi R^2_{Earth} \times A$
  = $\mathbf{S \pi R^2_{Earth} \times (1-A)}$

A is the *planetary albedo* of the Earth, which is about 0.3.

Energy Emitted from Earth



(from *The Earth System*)

- **The Stefan-Boltzmann Law**

  The energy flux emitted by a blackbody is related to the fourth power of the body's absolute temperature

  $\mathbf{F = \sigma T^4}$ where σ is 5.67×10^{-8} W/m²/K

- **Energy emitted from the Earth**
  = (blackbody emission) x (total area of Earth)
  = $(\sigma T_e^4) \times (4\pi R^2_{Earth})$

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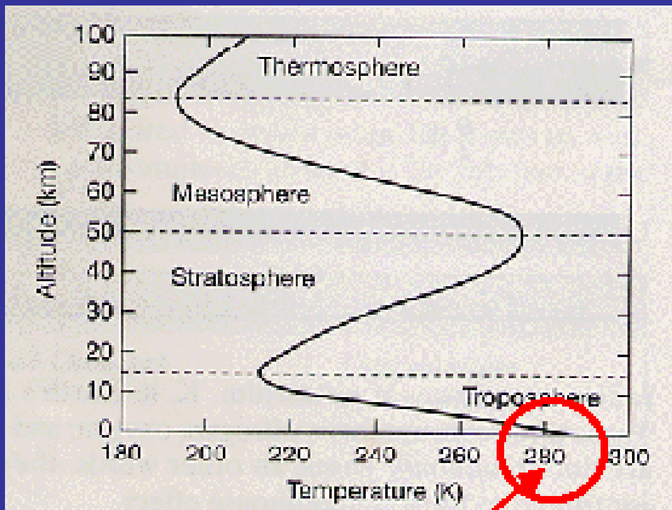
Planetary Energy Balance



(from *Global Physical Climatology*)

- **Energy emitted by Earth = Energy absorbed by Earth**

$$\sigma T_e^4 \times (4\pi R^2_{Earth}) = S \pi R^2_{Earth} \times (1\text{-}A)$$

$$\sigma T_e^4 = S/4 * (1\text{-}A)$$

$$= 1370/4 \ W/m^2 * (1\text{-}A)$$

$$= 342.5 \ W/m^2 * (1\text{-}A)$$

$$= 240 \ W/m^2$$

- **Earth's Effective temperature**

$T_e = 255$ K (-18C)

Earth's *surface* temperature

$T_S = 288$ K (15C)

greenhouse effect (33C) !!

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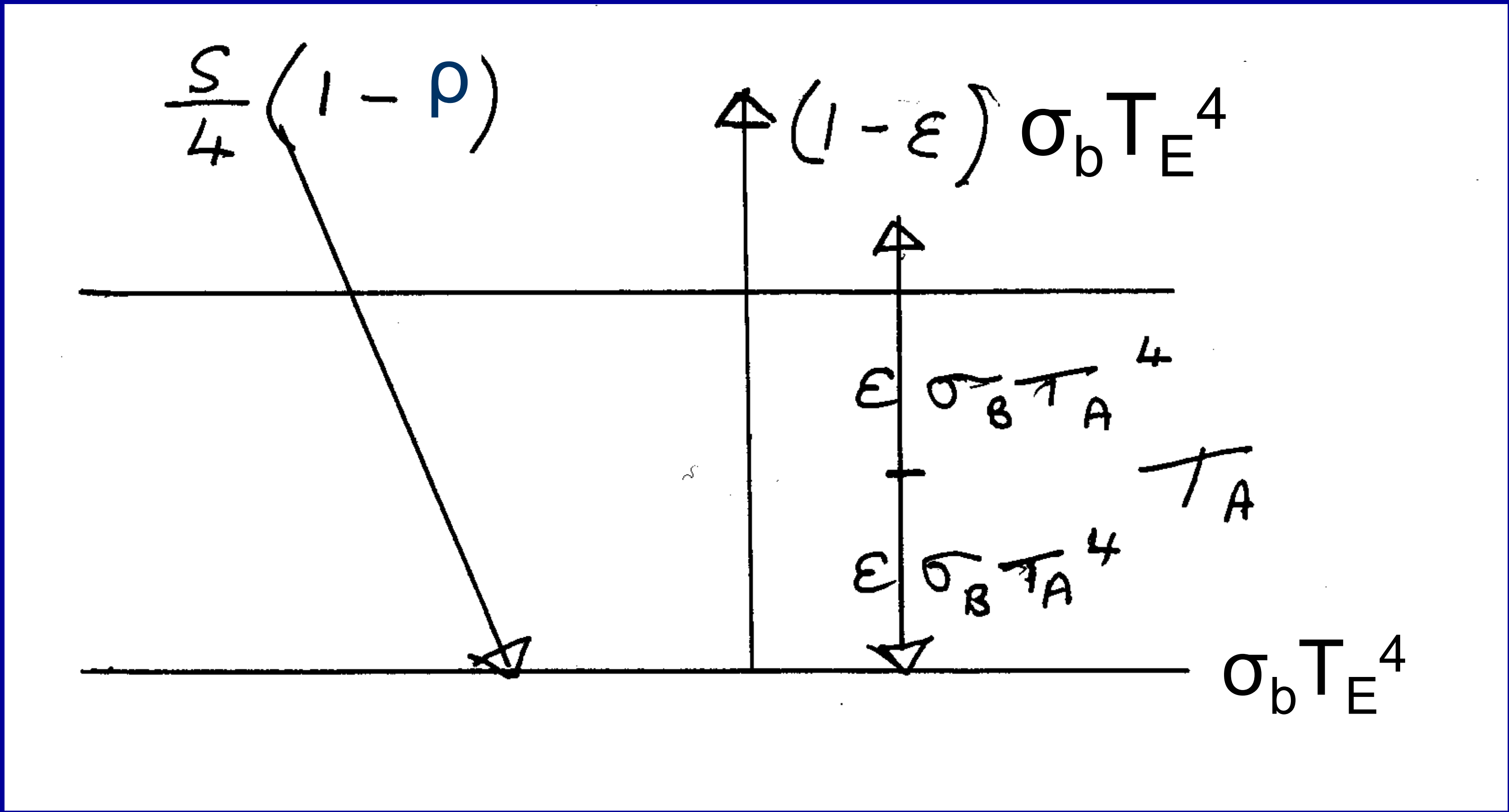
Greenhouse effect - one atmospheric layer model



- ε is the fraction of the IR radiation absorbed by the atmosphere

Greenhouse effect

Consider the radiative equlibrium in the atmosphere.

The amount of energy absorbed is $\varepsilon\sigma_b T_E^4$ and the amount emitted is $2\varepsilon\sigma_b T_A^4$. Hence in equilibrium:

$$T_A^4 = T_E^4 / 2$$

Now consider the energy balance at the surface:

$$\frac{(1-\rho)S}{4} + \varepsilon\sigma_b T_A^4 = \sigma_b T_E^4$$

substituting for T_A we get

$$\frac{(1-\rho)S}{4} + \frac{\varepsilon\sigma_b T_E^4}{2} = \sigma_b T_E^4$$

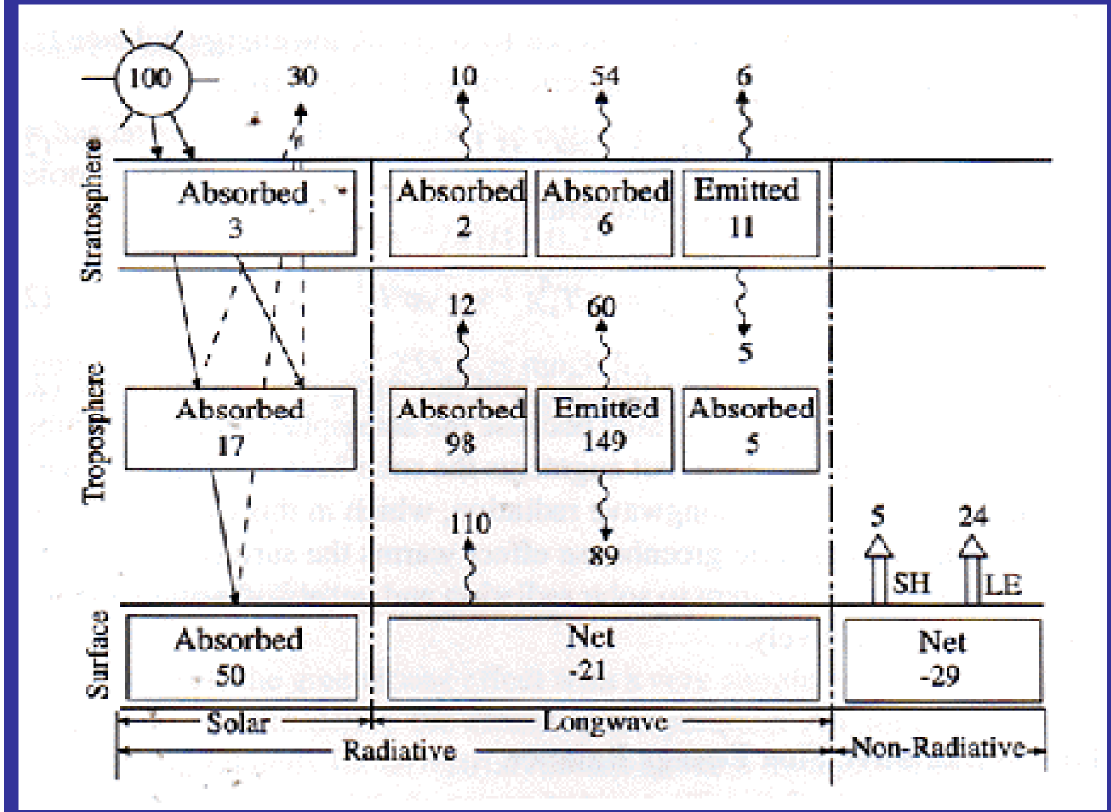
which gives

$$T_E = \left[\frac{(1-\rho)S}{4\sigma_b(1-\varepsilon/2)}\right]^{1/4}$$

Greenhouse effect

- An examination of the previous equation shows that as ε increases the ground temperature increases.
- This is what is referred to as greenhouse warming.
- As we shall show later, not all of the additional energy trapped by the additional absorption goes inot heating the surface. Some , for example goes into evaporation of water - which stores energy in the atmosphere as additional latent heat.
- So one should view the inference of the equation with some caution.
- This issue will be discussed later when climate feedback is addressed.

Vertical Distribution of Energy



(from *Global Physical Climatology*)

Incoming solar energy (100)

- 70% absorbed

  50% by Earth's surface

  20% by atmosphere

  3% in stratosphere (by ozone and O_2)

  17% in troposphere (water vapor & cloud)

- 30% reflected/scattered back

  20% by clouds

  6% by the atmosphere

  4% by surface

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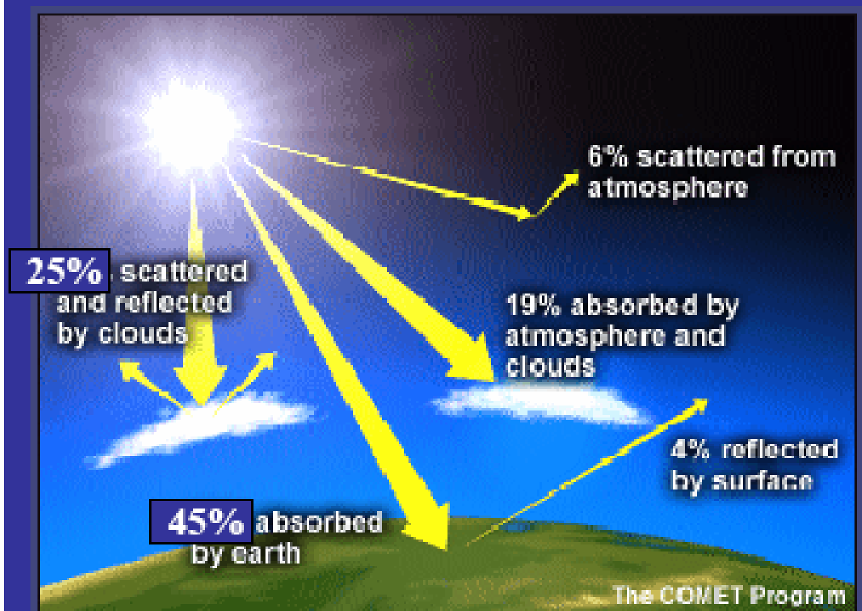
Where Does the Solar Energy Go?



(from NCAR/COMET website)

Incoming solar energy (100)

- 70% absorbed

  50% by Earth's surface (ocean + land)

  20% by the atmosphere and clouds

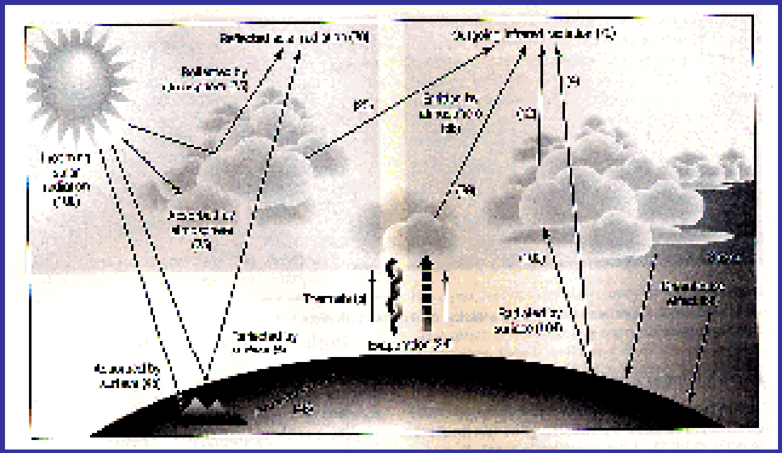
- 30% reflected and scattered back

  20% by clouds

  6% by the atmosphere

  4% by surface

Where Is Earth's Radiation Emitted From?



(from *The Earth System*)

Radiation back to Space (70 Units)

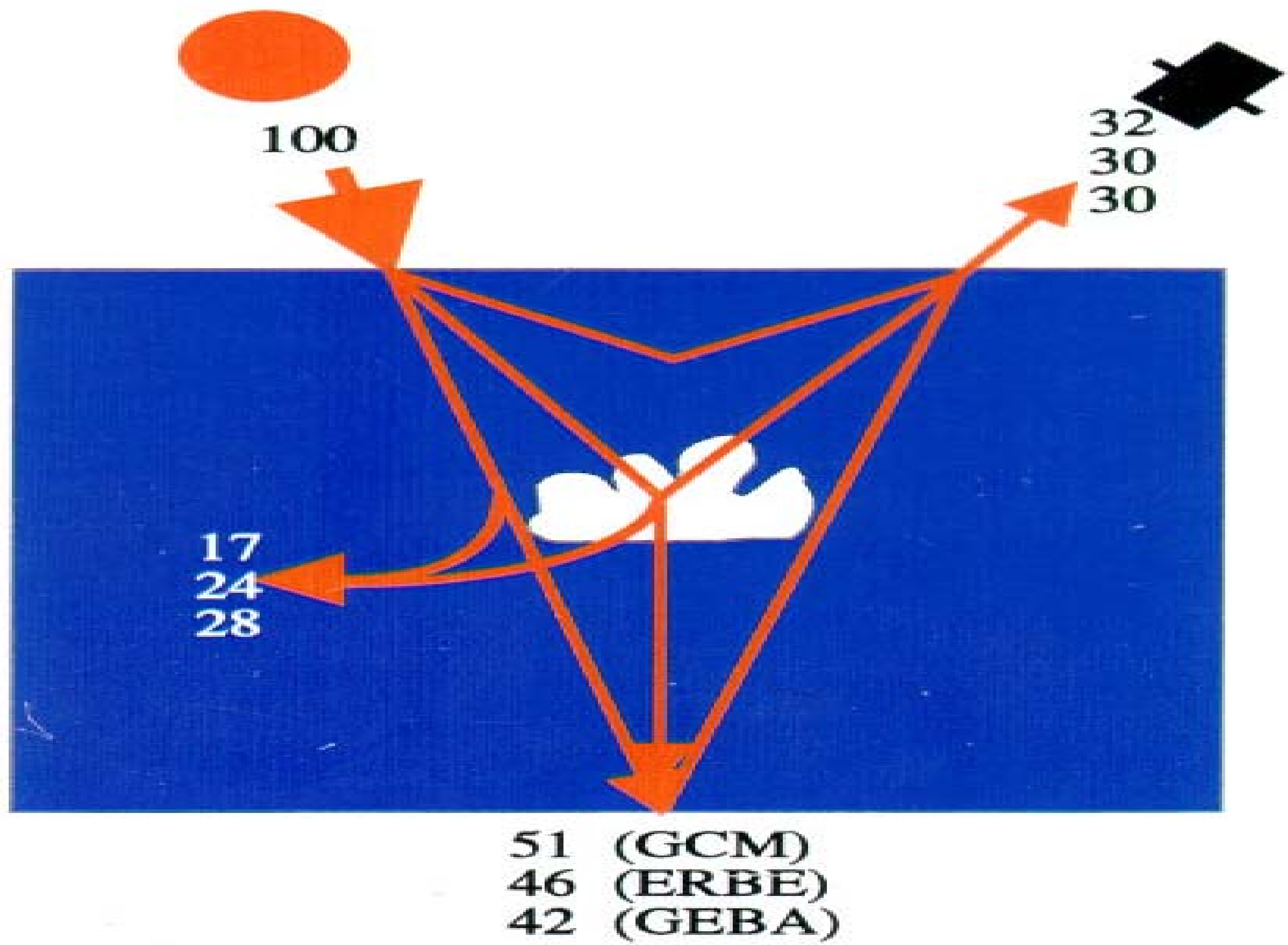
- 70 (units) radiation back to space

  60% by the atmosphere

  10% by surface (through clear sky)

- Greenhouse emission (back to surface)

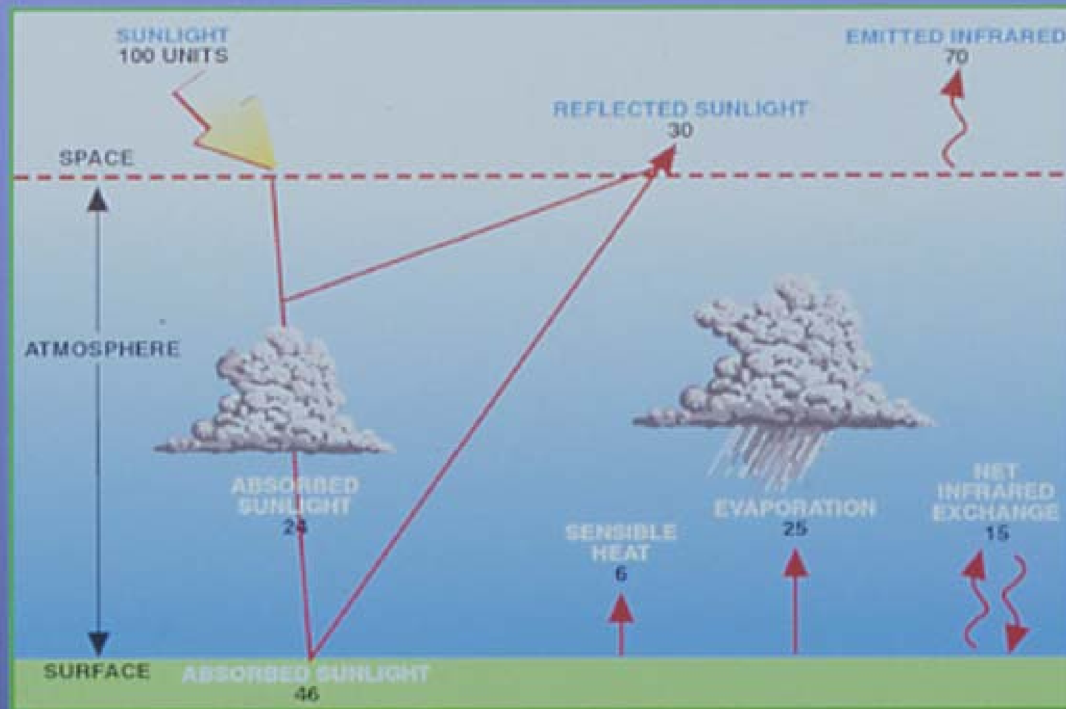
  89% (of solar radiation)


100
32
30
30
17
24
28
51 (GCM)
46 (ERBE)
42 (GEBA)

Cloud Radiative Effects

EARTH OBSERVING SYSTEM

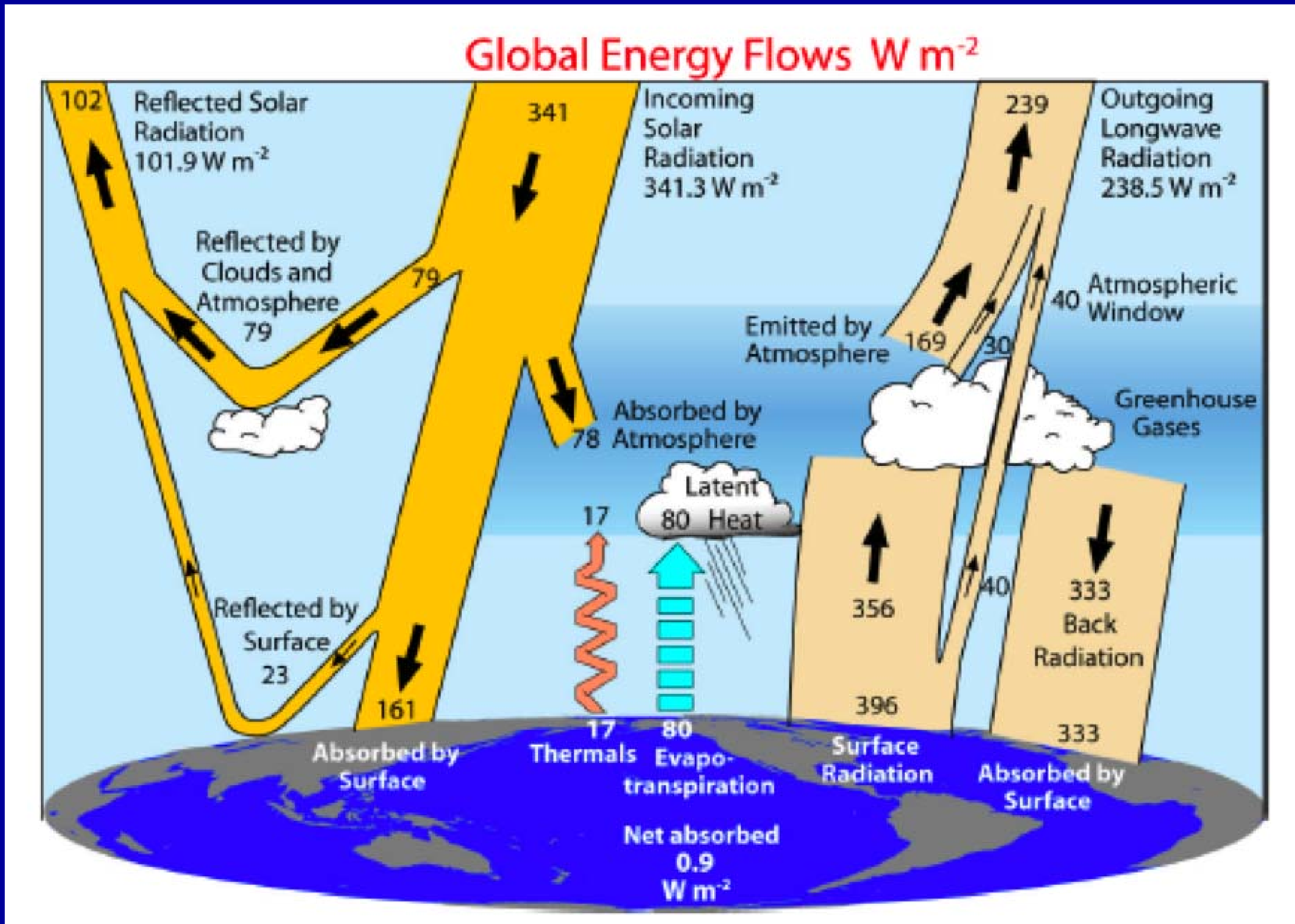
GLOBAL ENERGY BALANCE



GLOBAL ENERGY BALANCE FOR ANNUAL MEAN CONDITIONS.
100 units of incoming sunlight are balanced by 30 units of outgoing reflected sunlight and 70 units of outgoing emitted infrared radiation. Surface absorption of 46 units of sunlight is balanced by 6 units of sensible heat, 25 units of evaporation of water vapor (latent heat), and 15 units of net infrared radiative exchange, lost from the surface to the atmosphere. The 3 latter quantities plus the 24 units of sunlight absorbed by the atmosphere are balanced by 70 units of emitted infrared radiation lost to space.

National Aeronautics and Space Administration

EOS



Trenberth et al., 2009, BAMS

Greenhouse Effect and Diurnal Cycle

- The very strong downward emission of terrestrial radiation from the atmosphere is crucial to main the relatively small diurnal variation of surface temperature.

- If this large downward radiation is not larger than solar heating of the surface, the surface temperature would warm rapidly during the day and cool rapidly at the night.

  ➔ a large diurnal variation of surface temperature.

- The greenhouse effect not only keeps Earth’s surface warm but also limit the amplitude of the diurnal temperature variation at the surface.

Radiative equilibrium

- First Law of Thermodynamics - the time rate of change of the column energy is

$$\frac{\partial \overline{E}}{\partial t} = \overline{N} = (1-\rho)F_s - F_{TOA}$$

- Where N is called the radiative forcing

- and

$$F_{TOA} = \mathrm{T}_{eff}\,\sigma_B T_S^4$$

Where Teff is the effective transmission of the atmosphere to thermal radiation ((1- ε) in the simple model)

Perturbation to the radiative forcing

- What happens if *$N(T_S)$ is changed* by *$\Delta N(T_S)$*
- Assume that the atmosphere moves to a new equilibrium temperature, then we can write

$$\Delta N + \frac{\partial N}{\partial T_s} \Delta T_s = 0$$

We define the climate sensitivity α as

$$\Delta T_s^{\,d} = \alpha \Delta N$$

Climate sensitivity

$$\alpha = -(\partial N / \partial T_s)^{-1} = \left[\frac{\partial F_{TOA}}{\partial T_s} - \frac{\partial (1-\rho)\vec{F}^{s}}{\partial T_s} \right]$$

CO_2 doubling

- The calculated radiative forcing from doubling CO_2 is ~4 Wm^{-2}
- Assuming that the solar flux is constant we get

$$\alpha = \left\{ \frac{\partial(\sigma_B T_s^4 T_{eff})}{\partial T_s} \right\}^{-1} = \left\{ 4\sigma_B T_s^3 T_{eff} \right\}^{-1} = \frac{T_s}{4F_{TOA}}$$

- F_{TOA}= 240 Wm^{-2} and T_s = 288 K, hence α=0.3 $Wm^{-2}K^{-1}$
- Hence the increase in surface temperature is 1.2 K

Change in the solar constant

- Suppose the solar constant were to decrease by 1%
- Assume no feedbacks other than the reduced thermal emission. If there is no albedo change due to the decreased solar flux then the second term in the climate sensitivity is zero. Hence we get:

$$\alpha = \left\{ \partial F_{TOA} / \partial T_s \right\}$$

$$\Delta N = (1-\rho)\Delta F_S$$

$$\Delta T_S = \alpha(1-\rho)\Delta F_S$$

Change in the solar constant 2

- Substituting for F_{TOA}

$$\alpha = \left\{ \frac{\partial (T_{eff} \sigma_B T_s^4)}{\partial T_s} \right\}^{-1} = \left\{ \frac{4}{T_s} F_{TOA} \right\}^{-1}$$

$$\Delta T_s^d = \left\{ \frac{T_s}{4} \right\} \frac{\Delta F_S}{F_S}$$

- Change in temperature is -0.72 K

General expression for α

- Consider a parameter Q (such as albedo) that depends on the surface temperature
- The direct forcing Δ*N* is augmented by a term

$$\frac{\partial N}{\partial Q} \cdot \frac{\partial Q}{\partial T_s} . \Delta T_s$$

- Solving for the climate sensitivity we find

$$\alpha = \{4F_{TOA} / T_s - (\partial N / \partial Q)(\partial Q / \partial T_s)\}^{-1}$$

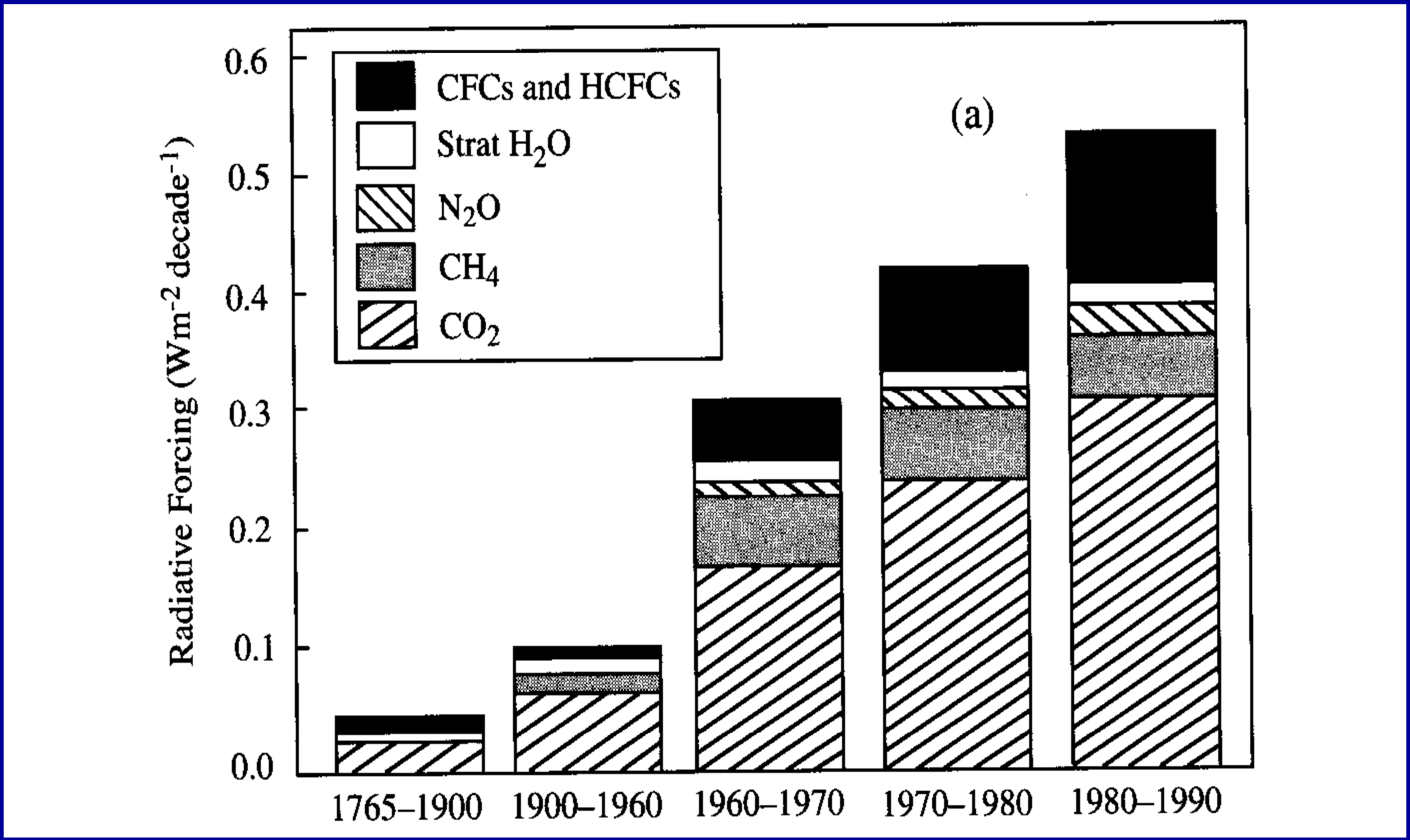
General expression for α

- If we have an arbitrary number of forcings Q then one can derive a general expression for the climate sensitivity

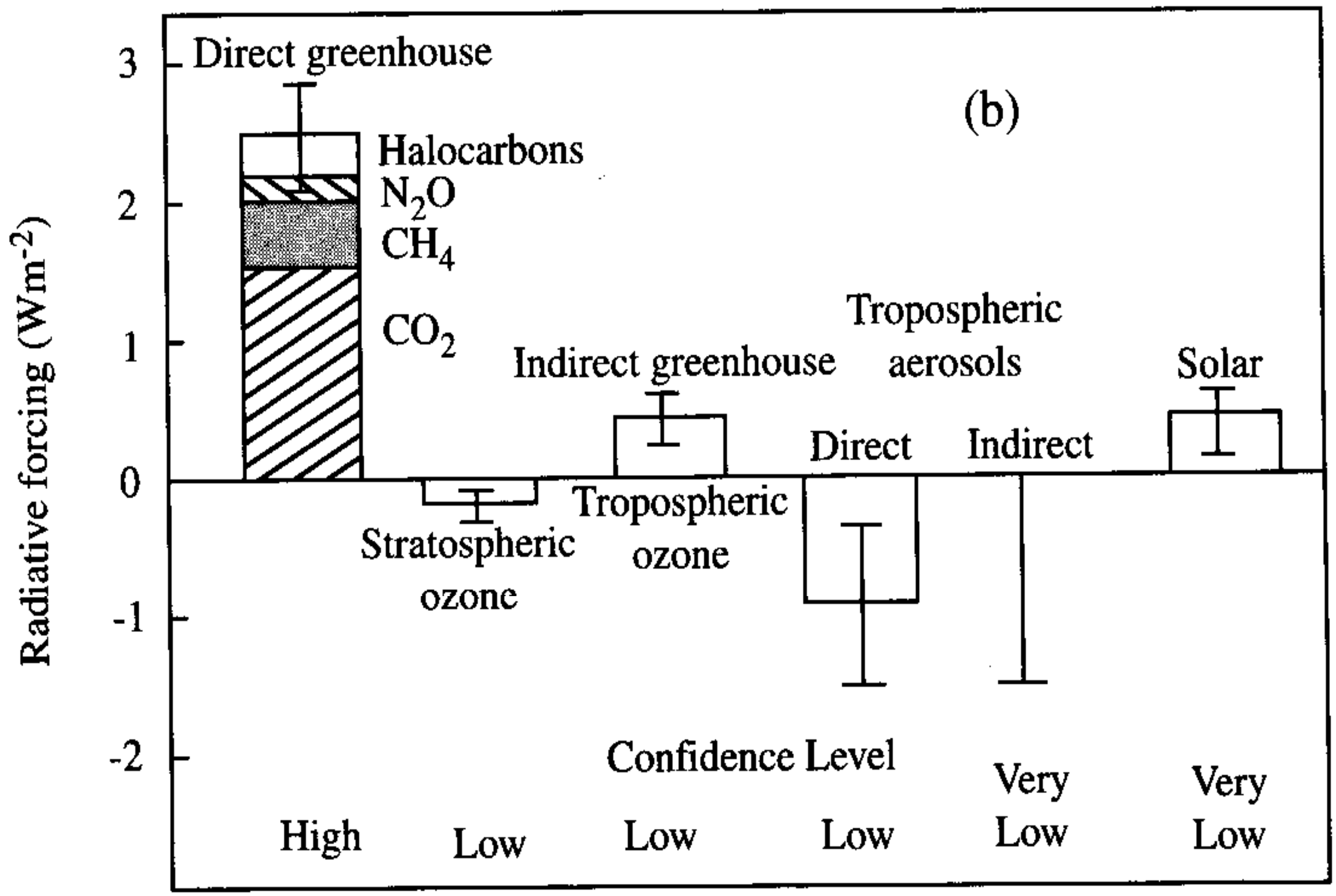
$$\alpha = \left[4F_{TAO} / T_s - \sum (\partial N / \partial Q) / (\partial Q / \partial T_s) \right]^{-1}$$

It should be noted that the above equation assumes that the individual forcings are independent of one another

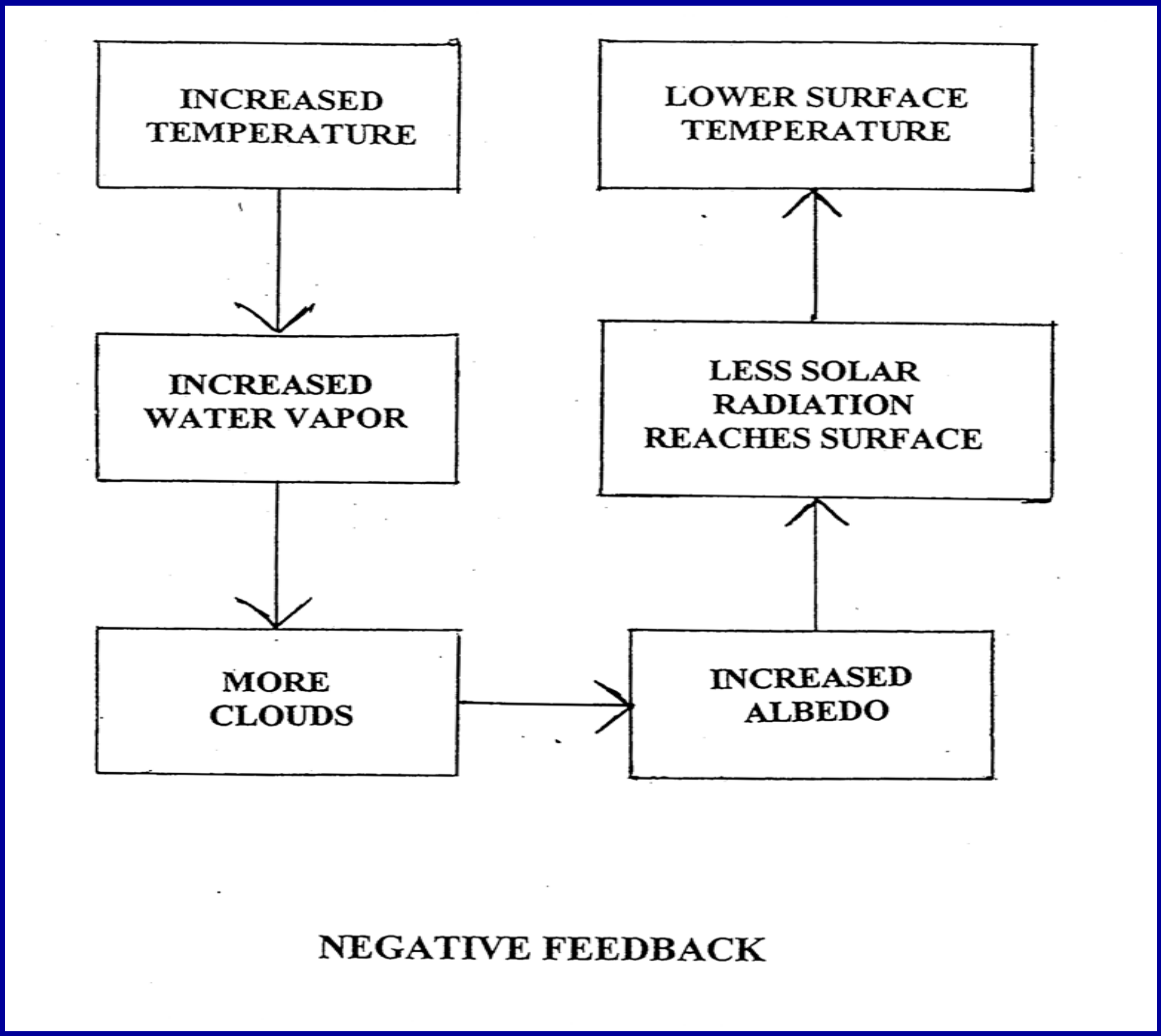
Radiative forcing of greenhouse gases



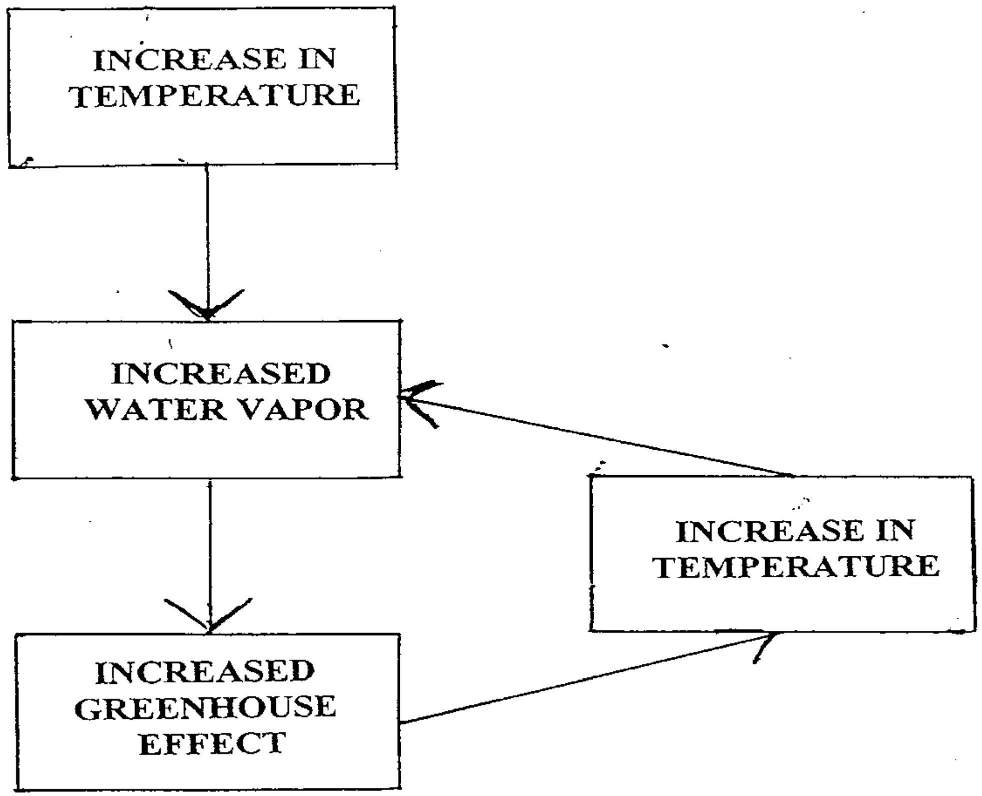
Radiative forcing



Negative feedback



Positive feedback



POSITIVE FEEDBACK

Polar ice coverage - positive feedback: Positive or negative ?

CLIMATE FEEDBACK MECHANISMS

- POSITIVE AND NEGATIVE FEEDBACKS
- WATER VAPOR - POSITIVE
- ICE COVER - POSITIVE
- CLOUDS - POSITIVE AND NEGATIVE - MAINLY NEGATIVE

Homework Due Feb 9

1. In addition to the planet earth, other planets in the solar system also have the greenhouse effects. Use the data in the following table for Mars, Venus and Earth to 1) determine the magnitude of the greenhouse effect, 2) elaborate its significance with respect to the solar effect, 3) place the earth in the positions of the Mars and Venus, what will be the earth's temperature, assuming earth's albedo remains the same.

THE EARTH SYSTEM

Terrestrial Planets

	Venus	Earth	Mars
radius, a	6.05×10^6 m	6.37×10^6 m	3.4×10^6 m
albedo, α	0.70	0.30	0.25
gravity, g	8.9 m s^{-2}	9.8 m s^{-2}	3.7 m s^{-2}
surface pressure, p_*	90×10^5 Nt m^{-2}	1×10^5 Nt m^{-2}	0.007×10^5 Ntm^{-2}
specific heat, C_p	0.9×10^3 J K^{-1} kg^{-1}	1.0×10^3 J K^{-1} kg^{-1}	0.9×10^3 J K^{-}kg^{-1}
gas constant, R	188 J K^{-1} kg^{-1} (M_{gas} = 44)	287 J K^{-1} kg^{-1} (M_{gas} = 29)	188 J K^{-1} kg^{-1} (M_{gas} = 44)
length of day	-1.0×10^7 s	8.6×10^4 s	8.9×10^4 s
length of year	1.94×10^7s	3.16×10^7s	5.94×10^7s
radius of orbit	1.08×10^{11}m	1.50×10^{11}m	2.28×10^{11}m
solar constant, S	2652 W m^{-2}	1369 W m^{-2}	595 W m^{-2}
effective temp, T_e	243K	255K	211K less greenhouse effect
surface temp, T_*	730K strong greenhouse effect	288K	218K
composition	CO_2, N_2	N_2, O_2	CO_2, N_2
scale height, H	15.4 km	8.4 km	11.1 km

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

2. Use the two-layer model as shown below,

1) Write the radiation budget equations at 1) TOA, Layer 1, 3) Layer 2, and 4) surface, assuming both layers are blackbody for LW and transparent for SW.
2) Derive the surface temperature (Ts) as a function of the planetary temperature (Te)
3) If the layer of the atmosphere is increased to n, what's the relationship between the two temperatures.