ATMOSPHERIC PHYSICS II
(MET 358)

LECTURER: DR. LEONARD K. AMEKUDZI

T.A: MARIAN OSEI

Course outline (Atmospheric radiation and Boundary layer physics)

- Atmospheric Radiation
- Single Scattering Properties
- Radiative Properties of Clouds
- Cloud and Aerosol Response to Climate Change
- Properties of Atmospheric Boundary Layer (ABL)
- Benard Convection
- Turbulent characteristics of the ABL and impacts on resolvable-scale flow
- Reynolds decomposition of N-S equations
- Surface layer characteristics and Bulk transfer formulations
- Ekman layer, Turbulent Kinetic Energy equation and Flow Stability
- Nocturnal low-level jet
- One-dimensional mixed layer models
- Effects of moist convective processes on boundary-layer properties.

ATMOSPHERIC RADIATION

GOALS

- Model of earth’s radiation system
- Amount of solar energy absorbed by the earth
- Amount of energy radiated by the earth
- One-layered radiation model of the atmosphere.
- Characteristics of radiation
- Radiation laws

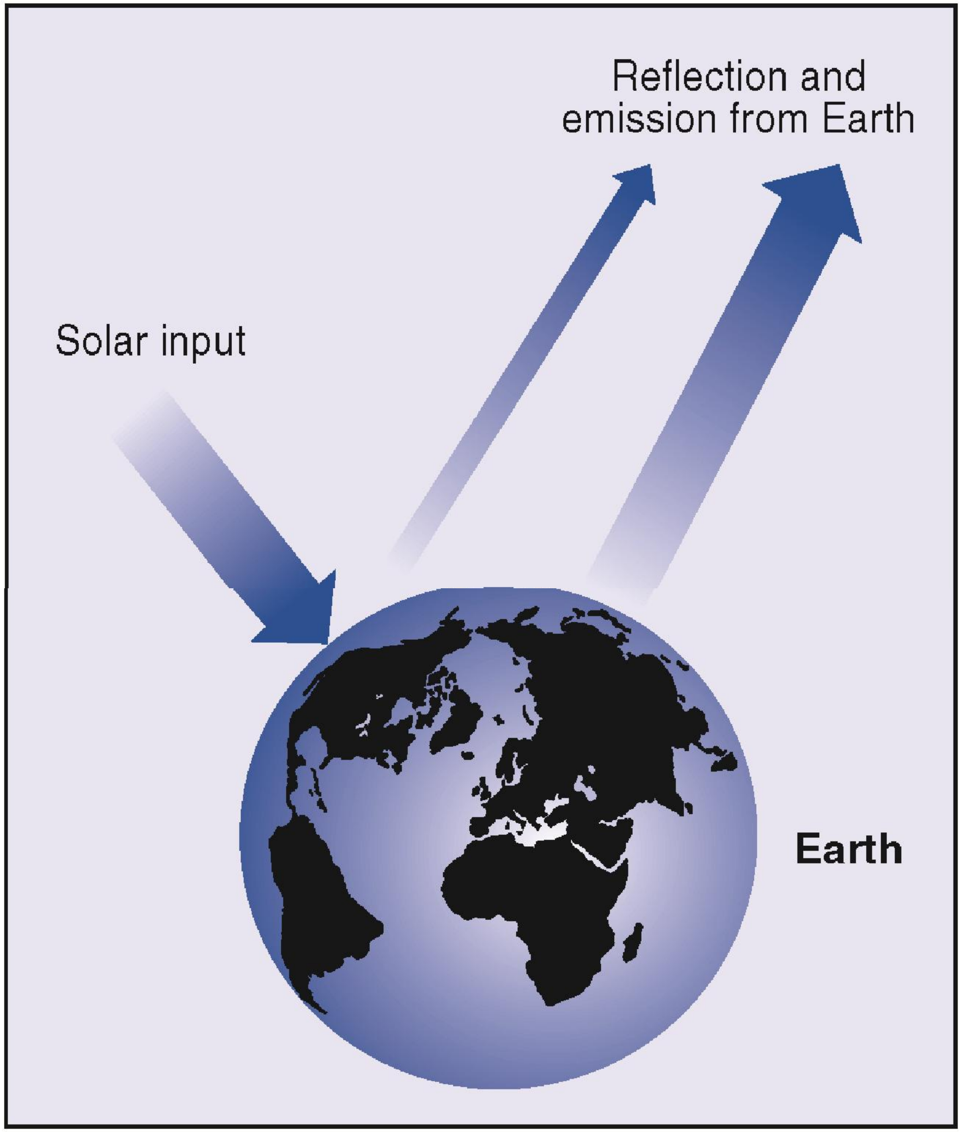
A "BLACK BOX" MODEL OF EARTH'S SYSTEM

– The simplest view of the system, we only see what enters and leaves the globe

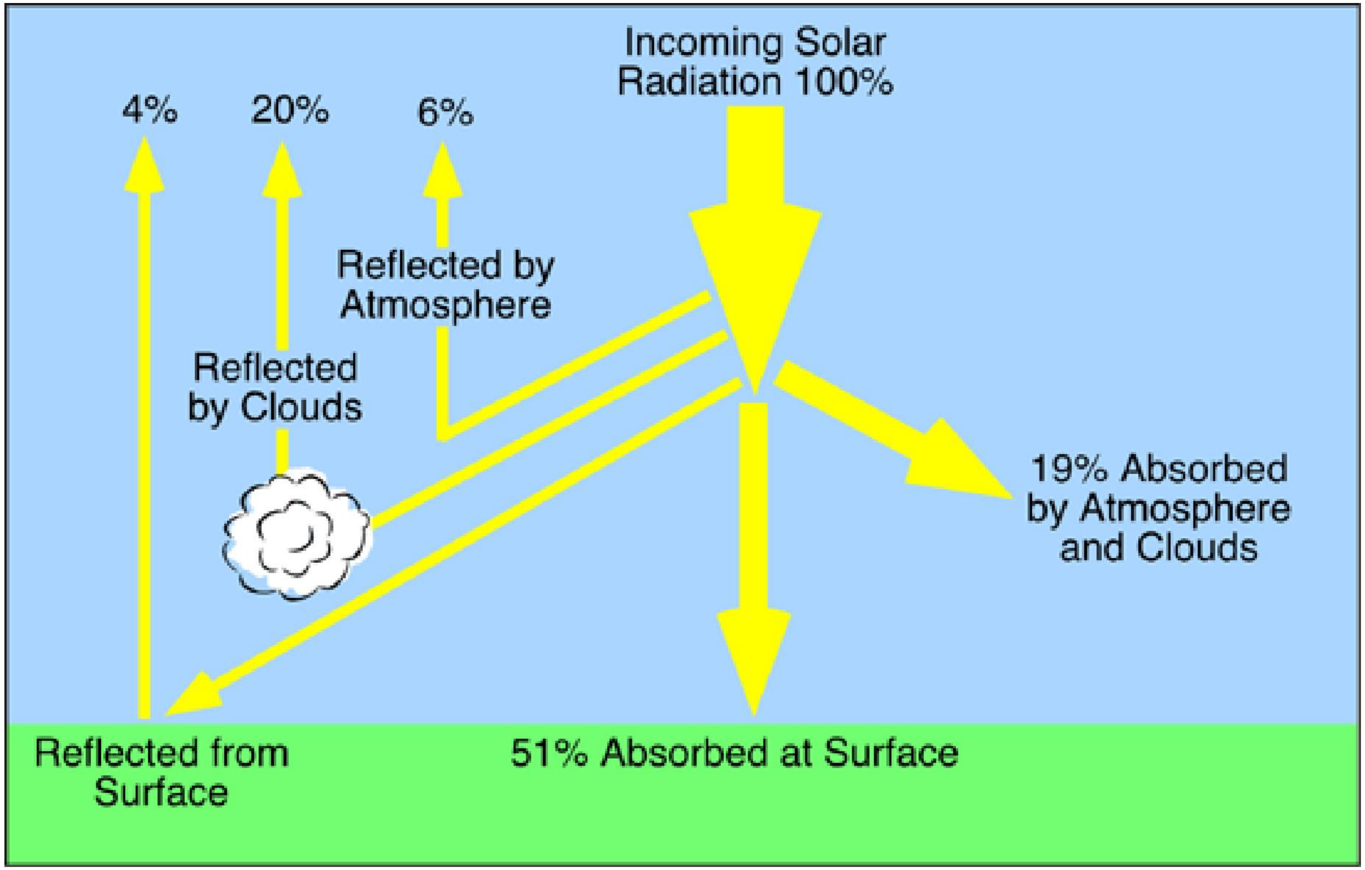
– Main input is from Sun, all other inputs are negligible

– Output is dominated by radiant energy

– Input Energy equals output Energy, because overall energy level of Earth is not changing



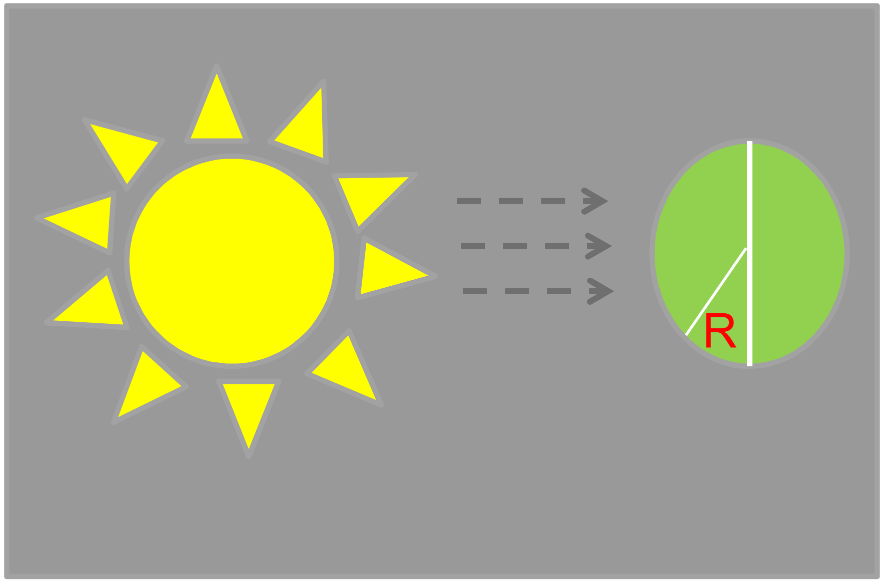
SIMPLE RADIATION MODEL OF THE EARTH



- All significant exchange of energy between the Earth and the rest of the universe is by way of radiation.
- The energy received from the sun is by far the dominant energy source driving all processes on the Earth surface.

HOW MUCH SOLAR ENERGY DOES EARTH ABSORB?

The planet is a disk of area πR^2



- If S is the intensity of Solar Energy reaching the Earth
- Then, energy incident on the earth

$$= \pi R^2 S$$

- The energy reflected due to the earth's albedo (α)

$$= \alpha \pi R^2 S$$

- Therefore, Solar Energy absorbed by the Earth

$$= \pi R^2 S - \alpha \pi R^2 S$$

$$= (1- \alpha) \pi R^2 S$$

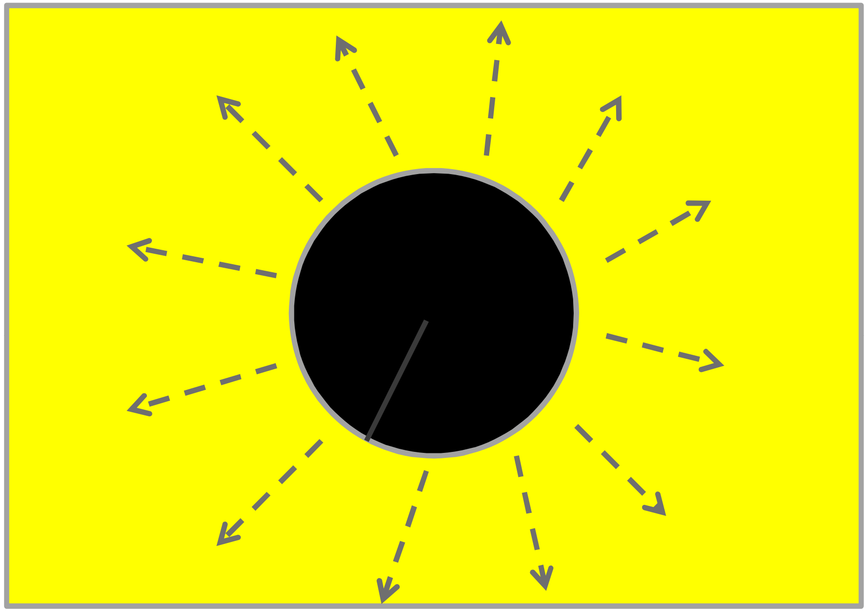
HOW MUCH ENERGY DOES EARTH RADIATE?

- The entire area of the surface of the Earth radiates.

- Area of the Earth's surface
  $= 4\pi R^2$

- If E is the intensity of Energy Radiated by the Earth

- Then Energy Radiated by Earth $= 4\pi R^2 E$
  $= 4\pi R^2 \sigma T^4$



ONE-LAYERED RADIATIONAL MODEL OF THE ATMOSPHERE

From the Atmospheric Law (1) Conservation of energy:

Energy absorbed by Earth = Energy radiated by Earth

$$(1-\alpha)\,\pi R^2 S = 4\,\pi R^2 \sigma T^4$$

$$\boxed{T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma}}}$$

S (Solar constant= 1372 W m^{-2}

$\alpha = 0.3$

$\sigma = 5.67 \times 10^{-8}$

$$T = -18^{\circ}C \neq \text{Observed } T_S = +15^{\circ}C\ ?$$

Including the Greenhouse effect

$$T = \sqrt[4]{\frac{S(1-\alpha)}{4\varepsilon\sigma}}$$

CHARACTERISTICS OF RADIATION

- Radiation is characterized by:

1. Wavelength, λ, in metres
2. Frequency, v , in Hertz

- The quantities are related by;

$$\boxed{v = c / \lambda}$$

Where c =2.9979250 x 10^8, the speed of light

Planck's law:

$$L_\lambda = \frac{2hc^2}{\lambda^5 \left[e^{\left(\mathrm{hc}/_{k\lambda T}\right)} - 1\right]}$$

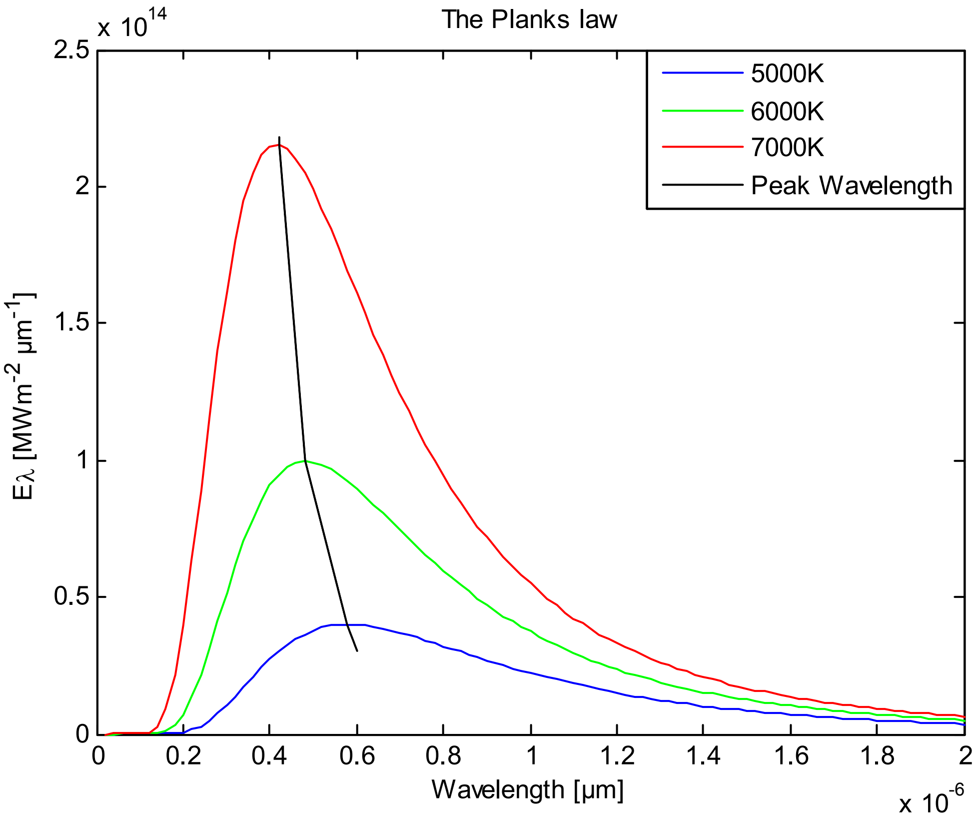
Stefan-Boltzmann's law:

$$E^* = \sigma T^4$$

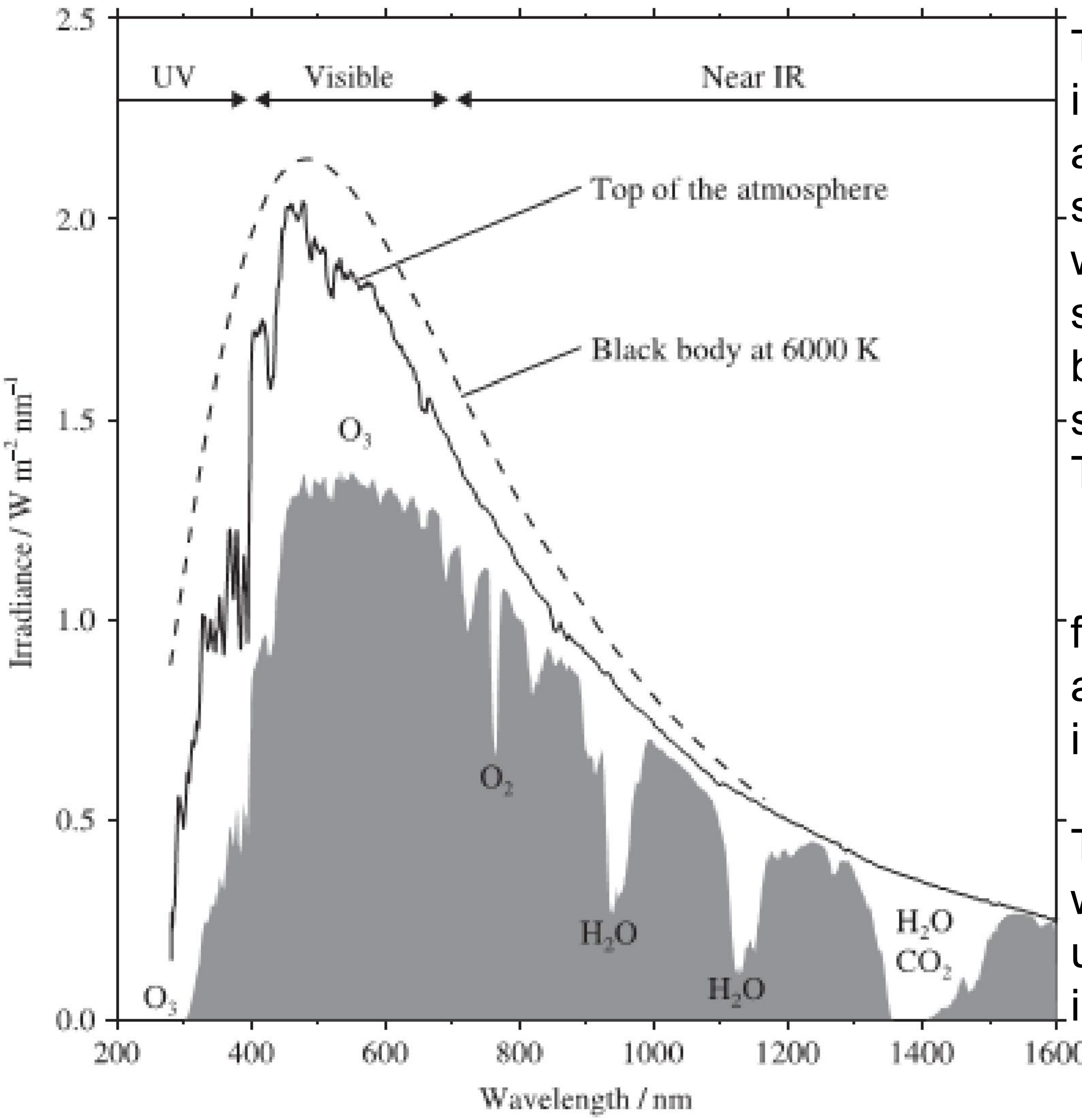
Wien's displacement law:

$$\lambda_m = 2897/T$$

EMISSION SPECTRA FOR BLACKBODIES



- At room temperature blackbodies emit mostly infra red light (λ>4μm)
- As the temperature increases past a few hundred degrees Celsius, black bodies start to emit visible wavelengths. (from red, through orange, yellow, and white before ending up at blue, beyond which the emission includes increasing amounts of ultraviolet)



The irradiance spectrum of insolation at the top of the atmosphere (solid line) and at sea-level (shaded), compared with the black-body irradiance spectrum (dashed line), given by Bλ(T) times the solid angle subtended by the Sun, for T=6000 K.

Gases responsible for the most prominent absorption features are indicated.

The approximate wavelength regions of ultra-violet, visible and near infra-red radiation are also shown.

Courtesy: D.G. Andrews (2010), page 71

RADIATION LAWS

- All objects emit radiation as a function of their temperature.

$$E = \sigma T^4$$

where σ (sigma) = 5.67×10^{-8} Wm^{-2} K^{-4}

and T is the temperature in Kelvin

- Stephan-Boltzmann Law:
  – A perfect emitter (black body) emits radiation proportional to the 4th power of its temperature

$$\lambda_{max} = C/T$$

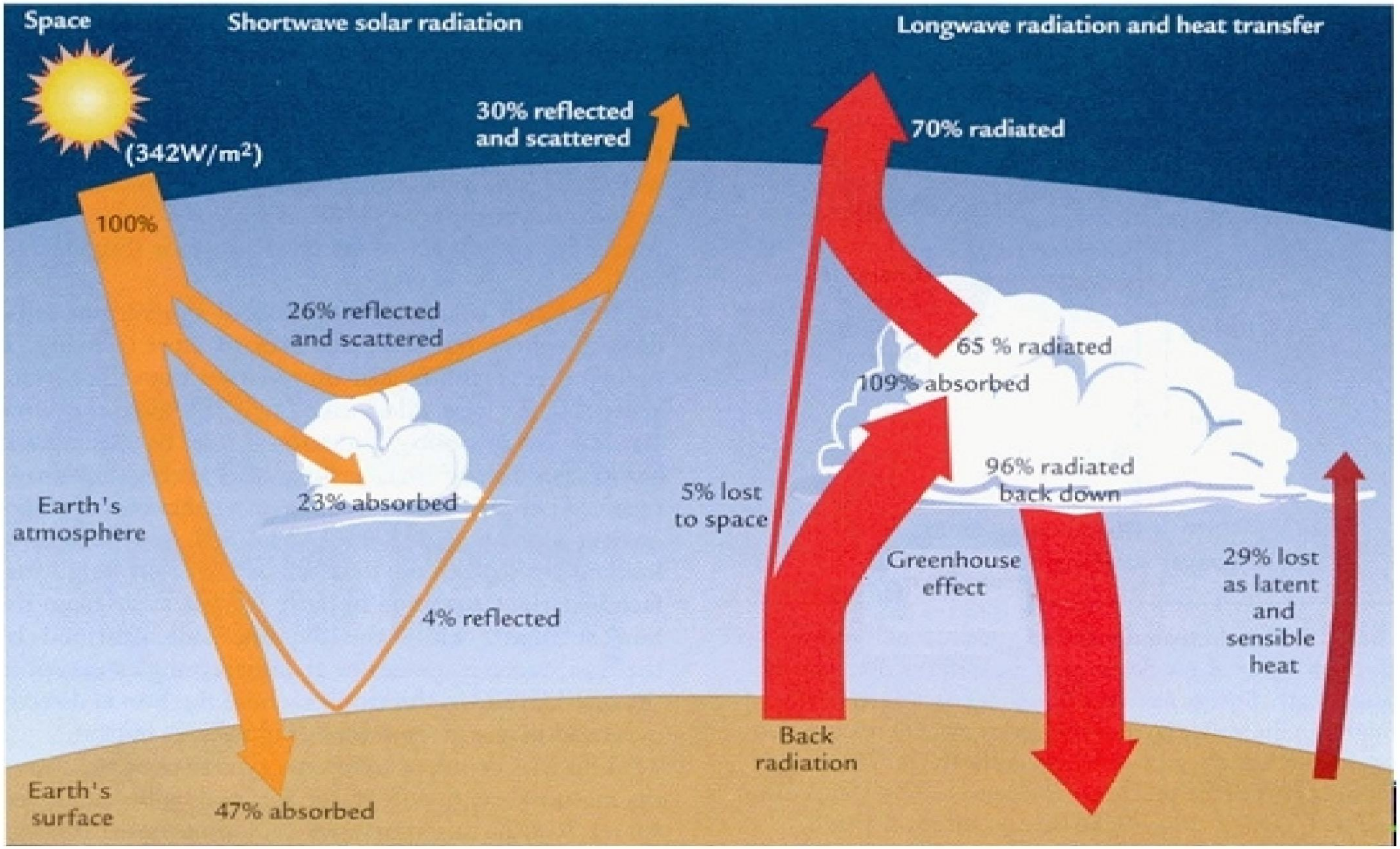
where C is a constant equal to 2897

and T is the temperature in Kelvin

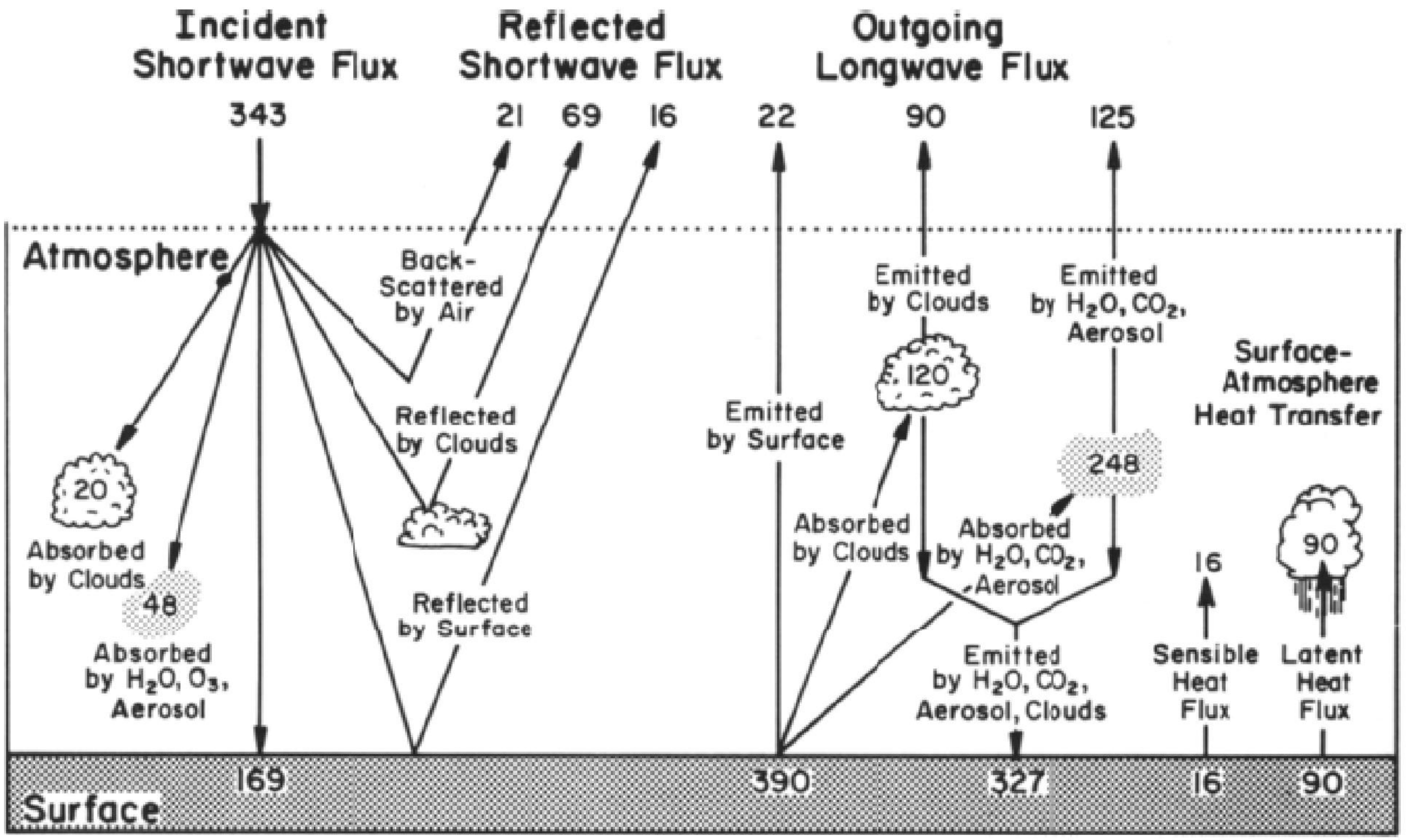
- Wien's Law:
  – As body becomes hotter the wavelength of the radiation it emits becomes shorter

The Earth's energy balance

=> *Solar radiation in = Terrestrial radiation out*



: GLOBAL-MEAN ENERGY BUDGET (WM^{-2}). UPDATED FROM M. L. SALBY 1996)



SUMMARY

- All significant exchange of energy between the Earth and the rest of the universe is by way of radiation.
- All objects emit radiation as a function of their temperatures following the Planck, Stephan-Boltzmann and Wien's displacement laws.
- The one-layered radiation model implements the first atmospheric law analogous to the conservation of energy that, energy absorbed by the earth is equal to the energy radiated by the earth.
- The greenhouse effect accounts for observed warmer temperature of the earth (288 K) as opposed to 255 K

SINGLE SCATTERING PRINCIPLE

GOALS

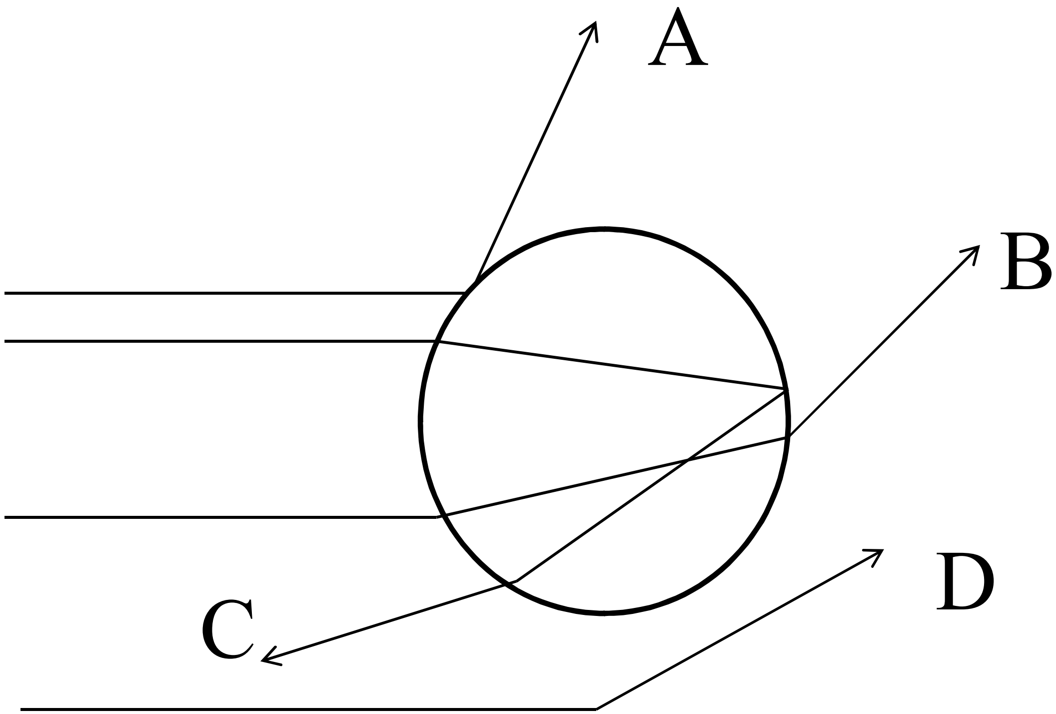
- Interaction of radiation with matter
- The scattering principle
- Types of scattering
- Scattering and visibility
- Scattering and perturbation to climate

WAYS BY WHICH RADIATION INTERACT WITH MATTER

- There are three different ways by which radiation interact with matter:

1. Absorption: Energy is removed from radiation and converted to thermal energy (sink)
2. Emission : Matter is emitting radiation (source)
3. Scattering: The path of radiation is changed or deflected (source or sink)

SCATTERING



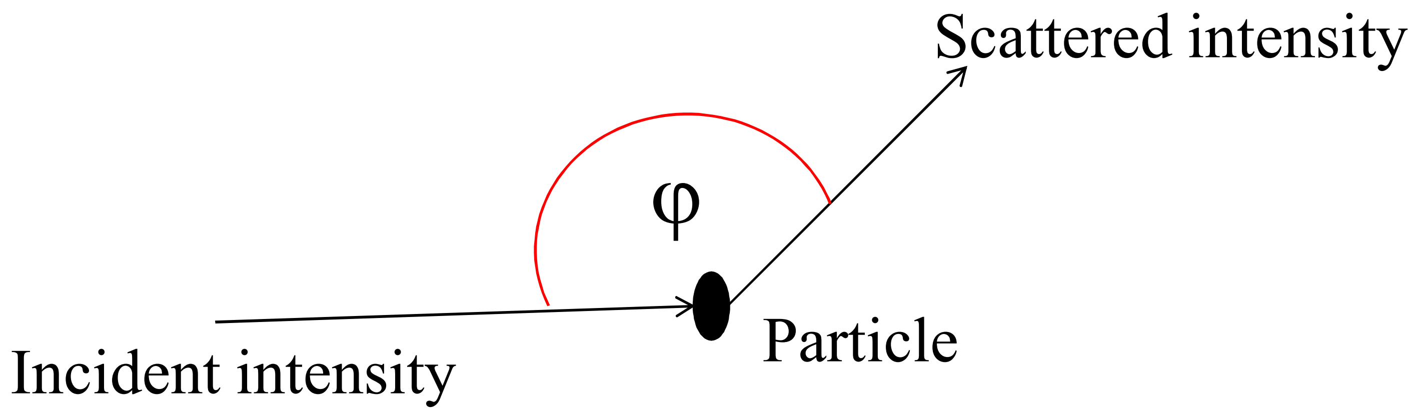
- Scattering occurs when the <u>direction of propagation</u> of radiation beam is <u>altered</u> by a particle in its path <u>without absorption taking place</u> .

- Scattering may take place by:

A. reflection
B. refraction
C. internal reflection
D. diffraction

SCATTERING EFFICIENCY AND PHASE FUNCTION

- Scattering efficiency of a particle is the probability that a photon incident on the particle would be scattered.
- Scattering phase function, φ ,is the angular distribution of light intensity scattered by a particle at a given wavelength.



- Scattering efficiency and the scattering phase function depend strongly on the ratio between particle size and wave length;

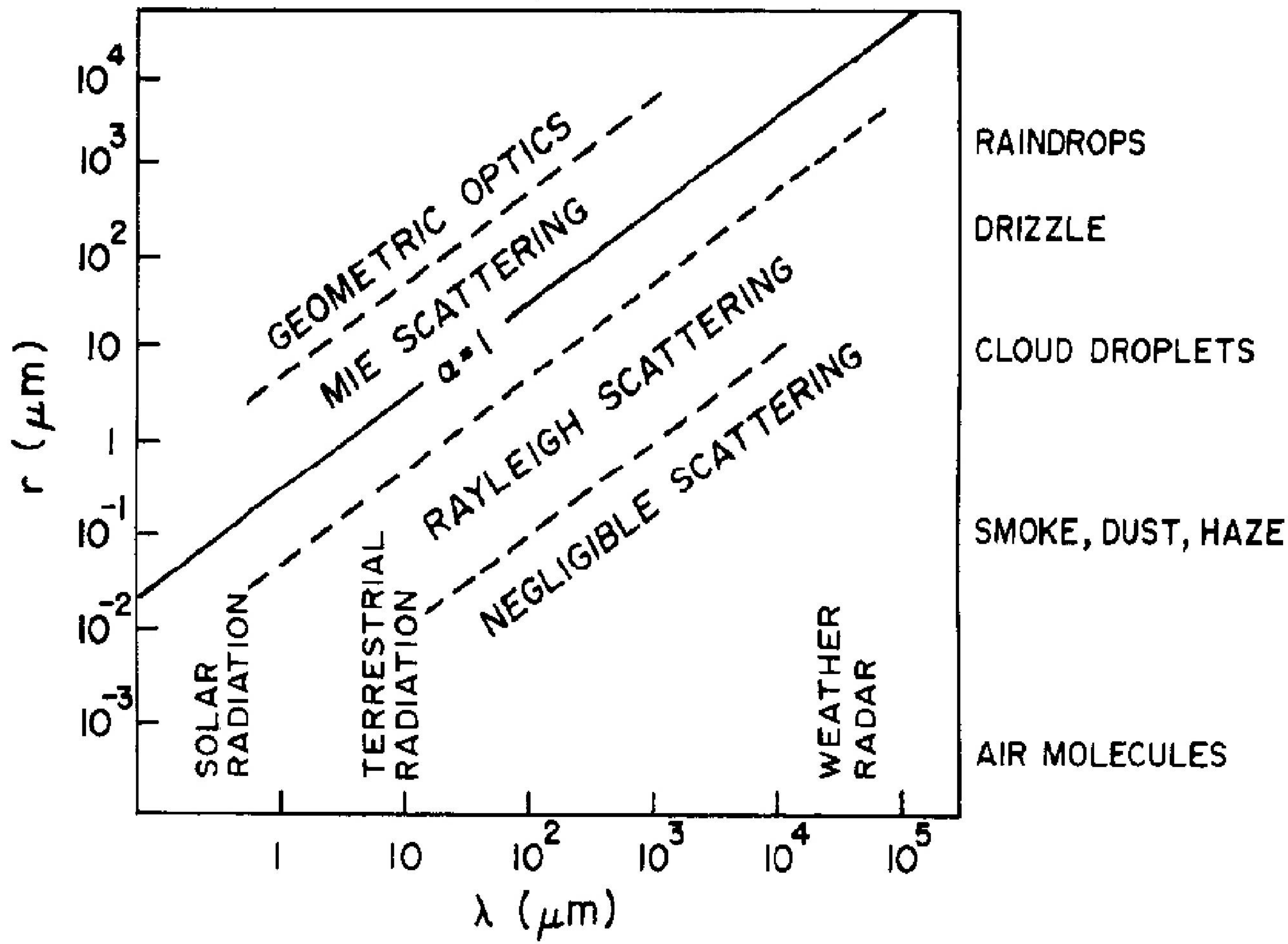
$$\boxed{\alpha = 2\pi d / \lambda}$$

with d the diameter of the particle assumed to be spherical

- This ratio is called Mie parameter (α).

TYPES OF SCATTERING

- The type of scattering depend very much on the Mie parameter:
- $\alpha << 1$ Rayleigh scattering (particle small compared with the wavelength)
- $\alpha \simeq 1$ Mie scattering (particle of about the same size as the wavelength)
- $\alpha >> 1$ Geometric scattering (particle large compared with the wavelength)


GEOMETRIC OPTICS
MIE SCATTERING
α=1
RAYLEIGH SCATTERING
NEGLIGIBLE SCATTERING
SOLAR RADIATION
TERRESTRIAL RADIATION
WEATHER RADAR
RAINDROPS
DRIZZLE
CLOUD DROPLETS
SMOKE, DUST, HAZE
AIR MOLECULES
r (μm)
λ (μm)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
1
10
10^2
10^3
10^4
10^5

SCATTERING AND VISIBILITY REDUCTION

- Visibility is reduced when there is significant scattering because particles in the atmosphere between the observer and the object scatter light from the sun and other parts of the sky through the line of sight of observer.

- This light decreases the contrast between the object and the background sky, thereby reducing visibility.

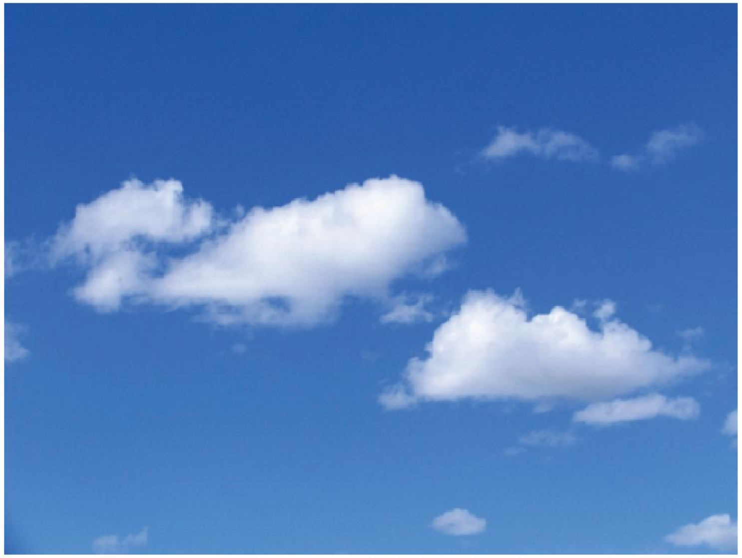
- Visibility reduction is greatest at high relative humidity. Why???

SCATTERING AND PERTURBATION TO CLIMATE

- Scattering of solar radiation by aerosols increases the earth's albedo because a fraction of the scattered light is reflected back to space.

- Volcanic eruptions, such as that of Mount Pinatubo in 1991, inject large amounts of aerosols into the atmosphere resulting in cooling of the earth's surface.

How can Rayleigh scattering explain why the sky is blue? Or why a sun set is red?



Blue Sky/ Red Sunset

- Viewed from space the sky is black and sun is white
- Rayleigh scattering: shorter wavelengths are scattered by air molecules more effectively than longer wavelengths.
- Blue light (λ ~0.42μm), Red light (λ ~0.65μm)
- Therefore, blue light scattered five times more than red light
- Therefore, blue light arrives at the Earth's surface as diffuse radiation emanating from all directions, the mixture of scattered colours appears blue.
- Conversely glancing at the sun, the longer wavelength colours that were not scattered away are visible (red, yellow)
- When the sun is near the horizon (sunset) the volume of air through which the sunlight must pass is greater, therefore virtually all the blue light is scattered by Rayleigh scattering, the remaining light is the orange/red of the sunset.

SUMMARY

- Radiation can be absorbed, emitted or scattered.
- The type of scattering depends on the Mie parameter.
- Significant scattering reduces visibility and perturbs the earth climate system.

CLOUD AND AEROSOL RESPONSE TO CLIMATE CHANGE

GOALS

- Radiative properties of clouds
- Cloud radiative feedback
- Greenhouse effect
- One-two-layered model of greenhouse effect
- Radiative forcing and climate change
- Climate change models due to natural and anthropogenic forcing

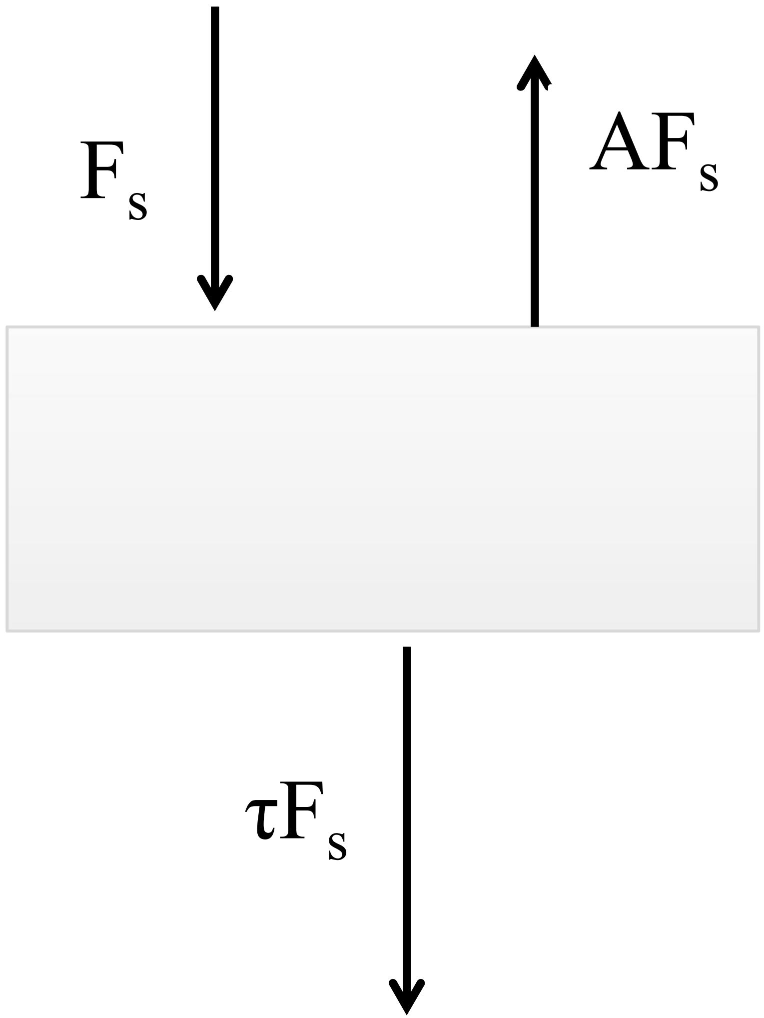
RADIATIVE PROPERTIES OF CLOUDS

- On average clouds approximately 50% of the earth's surface.

- They have large influence on both outgoing and incoming radiation.

- Solar radiation is modified on its passage through the atmosphere.

MODIFICATION OF SOLAR RADIATION BY CLOUDS



- F_s is the incident solar flux at the top of the clouds
- AF_s is the scattered/ upward flux at the top of the clouds
- τF_s is transmitted/ downward flux flux below the clouds.
- A and τ are the albedo and transmissivity of the clouds

- The amount of the incident solar flux absorbed by the clouds is given by:

$$\text{Absorbed} = F_s\,(1 - A - \tau)$$

- For a typical stratus cloud and radiation integrated over the whole spectrum, $A = 0.5$ and $\tau = 0.3$

ABSORPTION STRENGTH OF CLOUDS

- Clouds are strong absorbers of terrestrial radiation. Why?

- Clouds mostly contain liquid water and ice. Liquid water and ice are absorb strongly through out the infra red region, hence clouds absorb the long wave radiation emitted by the earth.

CLOUD RADIATION FEEDBACK

- Clouds interfere with the transfer of radiation in the atmosphere in two ways:

1. They reflect a proportion of the solar radiation back to space. (reflectivity effect)

2. They absorb thermal radiation emitted by the earth's surface. (blanket effect).

- When clouds reflect some amount of solar radiation back to space, they reduce the total amount of energy available to the earth system.

- When the clouds absorb the terrestrial radiation, they emit radiation in the infra red radiation (thermal radiation).

  - They act to reduce the heat lost to space from the surface.

- The effect that is dominant in a particular cloud depends on

1. the cloud's height , hence on the cloud's height
2. those properties (optical properties) which determines the cloud's reflectivity to solar radiation and its interaction with thermal radiation.

OPTICAL PROPERTIES OF CLOUDS

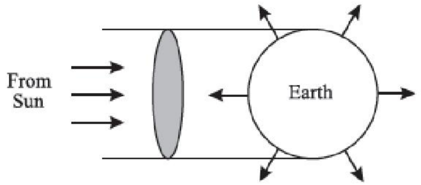
- The optical properties of the clouds depend on;

1. liquid - ice content
2. Average size of the particle.

- In general, the reflectivity effect is dominant in low clouds.
- The "blanket effect" is dominant in high clouds.

GREENHOUSE EFFECT

Total solar irradiance (TSI): $F_s = 1370\ Wm^{-2}$



Illustrating the calculation of the temperature of the Earth, ignoring any absorption of radiation by the atmosphere. The parallel arrows indicate solar radiation, confined within a tube of cross-sectional area πa^2. The radial arrows indicate outgoing thermal radiation from the total surface area $4\pi a^2$ of the Earth.

Reflected back to space: $AF_s\pi a^2$,

A=albedo = 0.3

Power emitted per unit area = σT^4 , σ= Stefan-Boltzmann constant

Total power emitted = $4\pi a^2\ \sigma T^4$

Thermal equilibrium: incoming and outgoing power balance

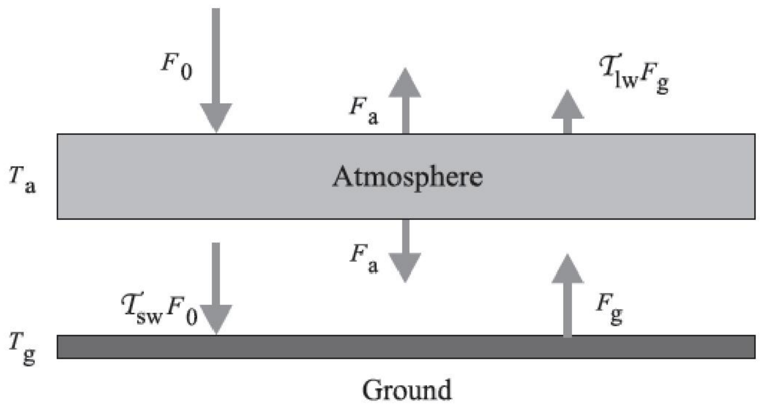
$$(1-A)F_s\pi a^2 = 4\pi a^2\ \sigma T^4$$

substitute the values:T=255K, **BUT** actually T=288K.

The radiation-trapping effect of the atmosphere

or '***Greenhouse Effect***'

A SIMPLE MODEL OF GREENHOUSE EFFECT



A simple model of the greenhouse effect. The atmosphere is taken to be a layer at temperature T_a and the ground a black body at temperature T_g. Various solar and thermal irradiances are shown.

- T_a : Temperature of atmosphere
- T_g : Temperature of ground
- T_{sw} : Solar short-wave radiation
- T_{lw} : Thermal long-wave radiation
- F_0 : unreflected incoming solar irradiance at the top of atmosphere
- F_g : upward irradiance emitted by ground

Assuming radiative equilibrium:

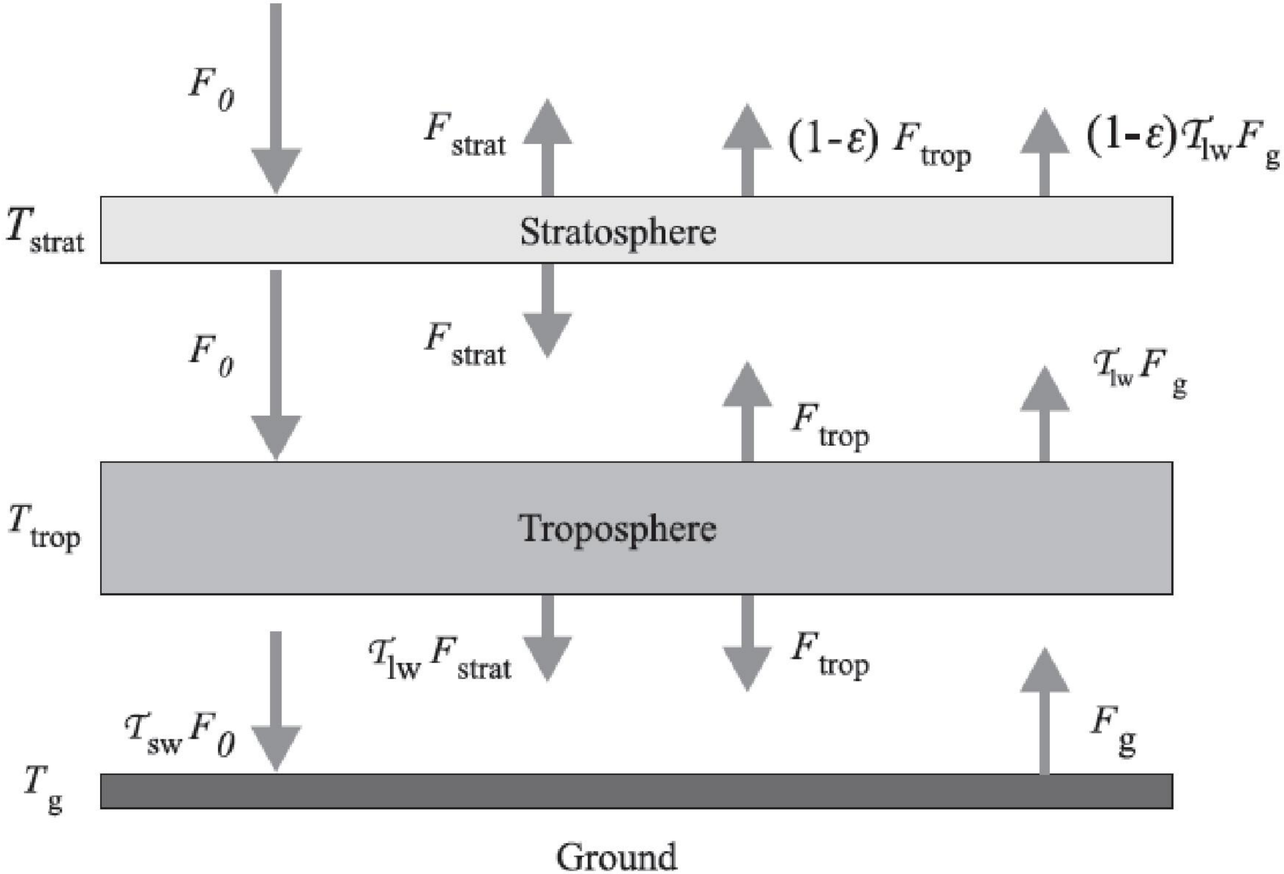
- above the atmosphere: $F_0 = F_a + T_{lw}F_g$
- between atmosphere and ground: $F_g = F_a + T_{sw}F_0$

Eliminating F_a: $$F_g = \sigma T_g^4 = F_0 \frac{1 + \mathcal{T}_{sw}}{1 + \mathcal{T}_{lw}}.$$

$T_{sw} = 0.9$ (strong transmittance and weak absorption of solar radiation)
$T_{lw} = 0.2$ (weak transmittance and strong absorption of thermal radiation)

Applying T_{sw} and T_{lw} above gives T_g of ~ 286K
(this is much closer to the observed 288K than the previous 255K)

A TWO-LAYER MODEL OF THE GREENHOUSE EFFECT



Two-layer model atmosphere, including an optically thin stratosphere at temperature T_{strat}, a troposphere at temperature T_{trop} and the ground at temperature T_g. See text for further details.

This model provides a simple example of the **greenhouse effect:**

• less absorption (greater transmittance) for solar radiation

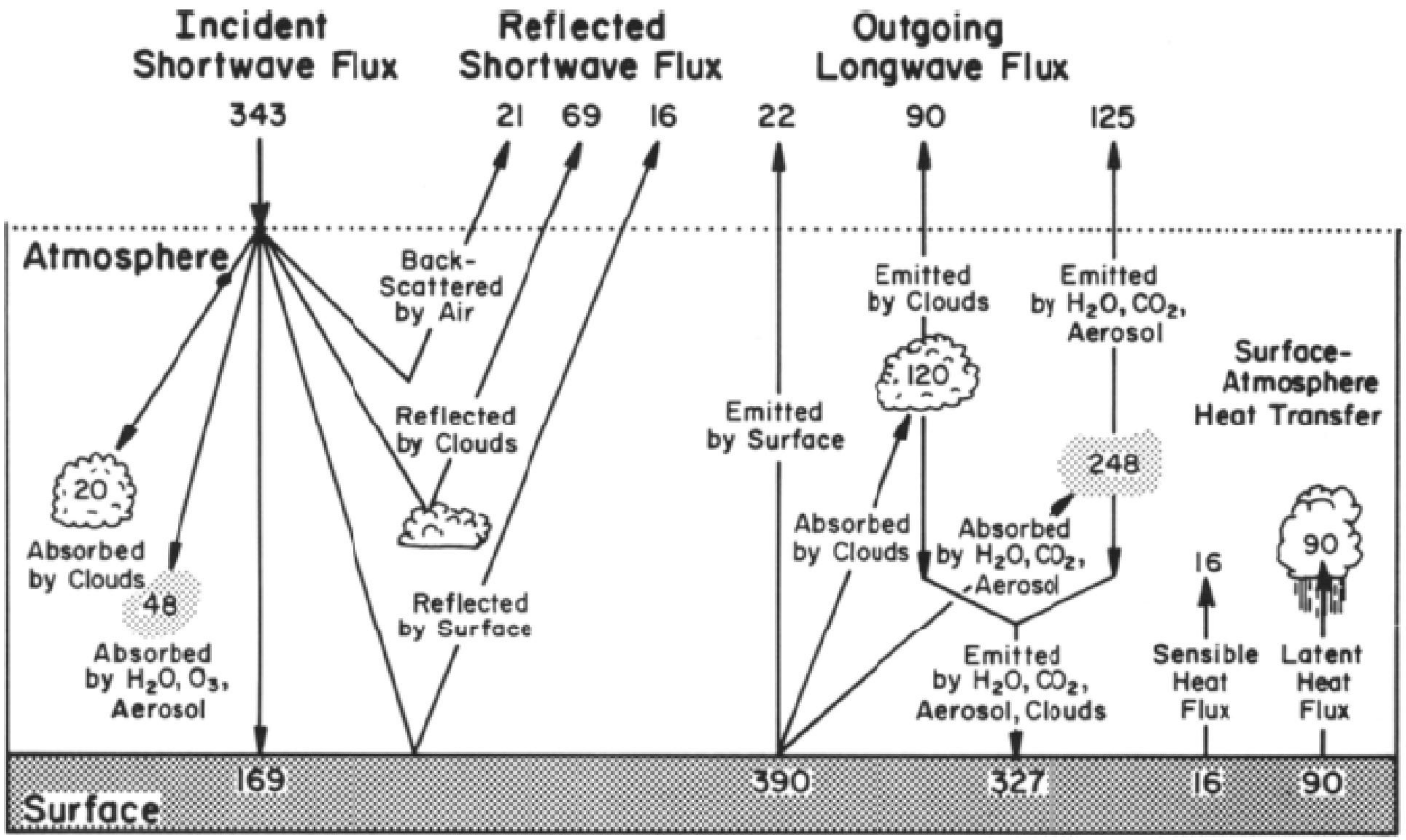
• more absorption (less transmittance) for thermal radiation

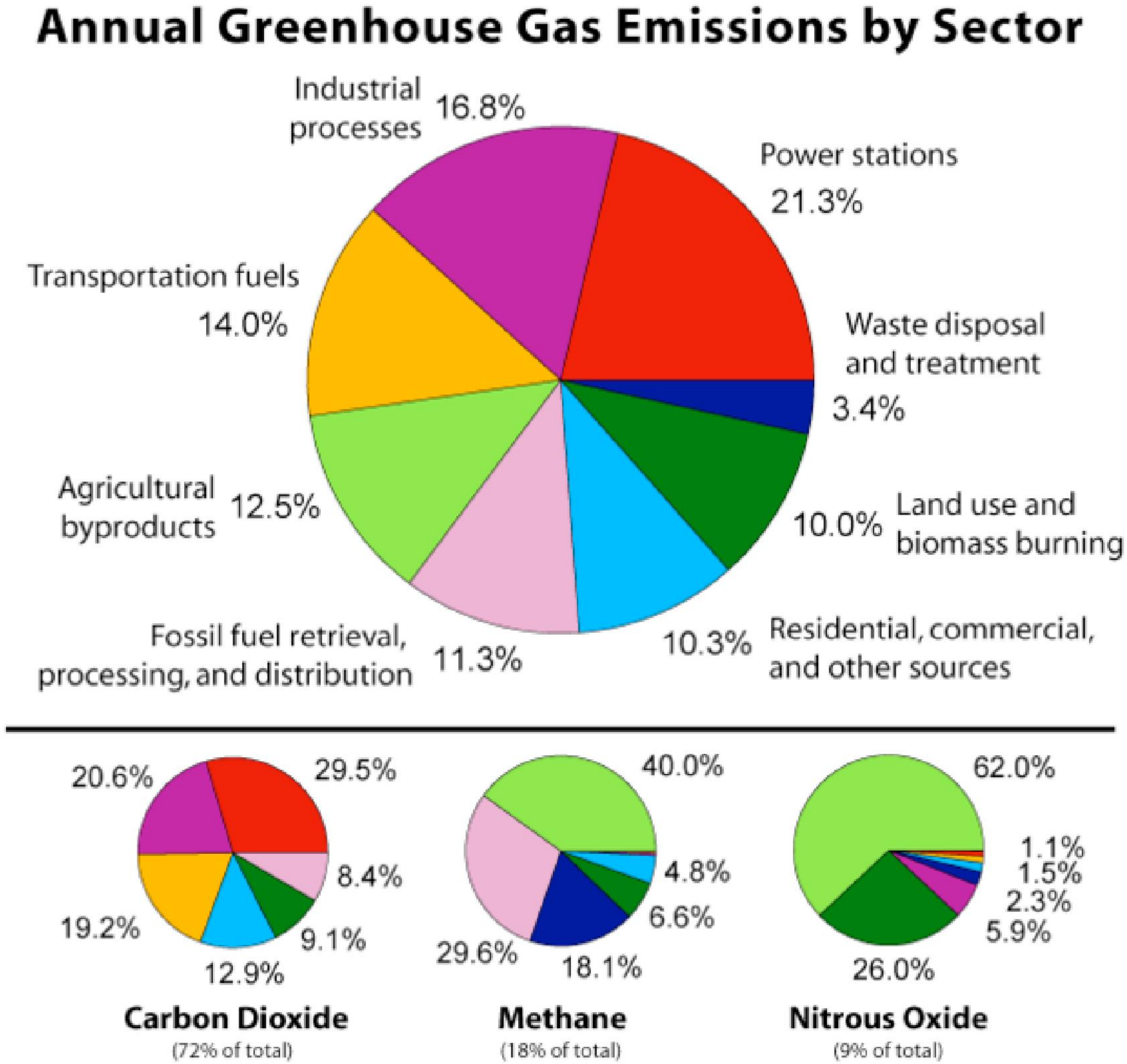
• Therefore, the atmosphere readily transmits solar radiation but traps thermal radiation, thus accounting for the raised temperature at the Earth's surface.

• Atmospheric gases which absorb and emit infrared radiation but allow solar radiation to pass add to this effect and called **greenhouse gases.**

• The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide and ozone

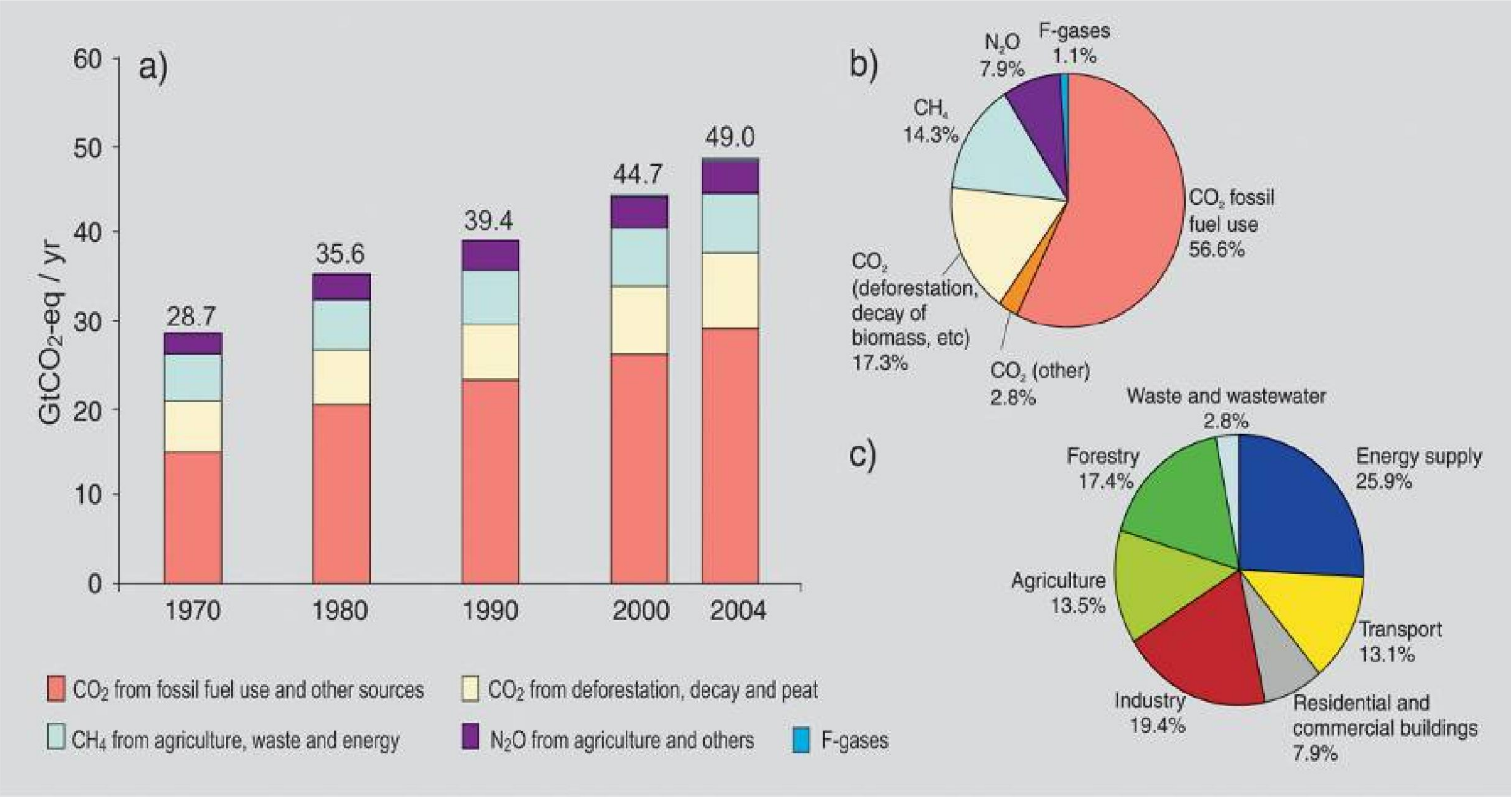
: GLOBAL-MEAN ENERGY BUDGET (WM^{-2}). UPDATED FROM M. L. SALBY 1996)



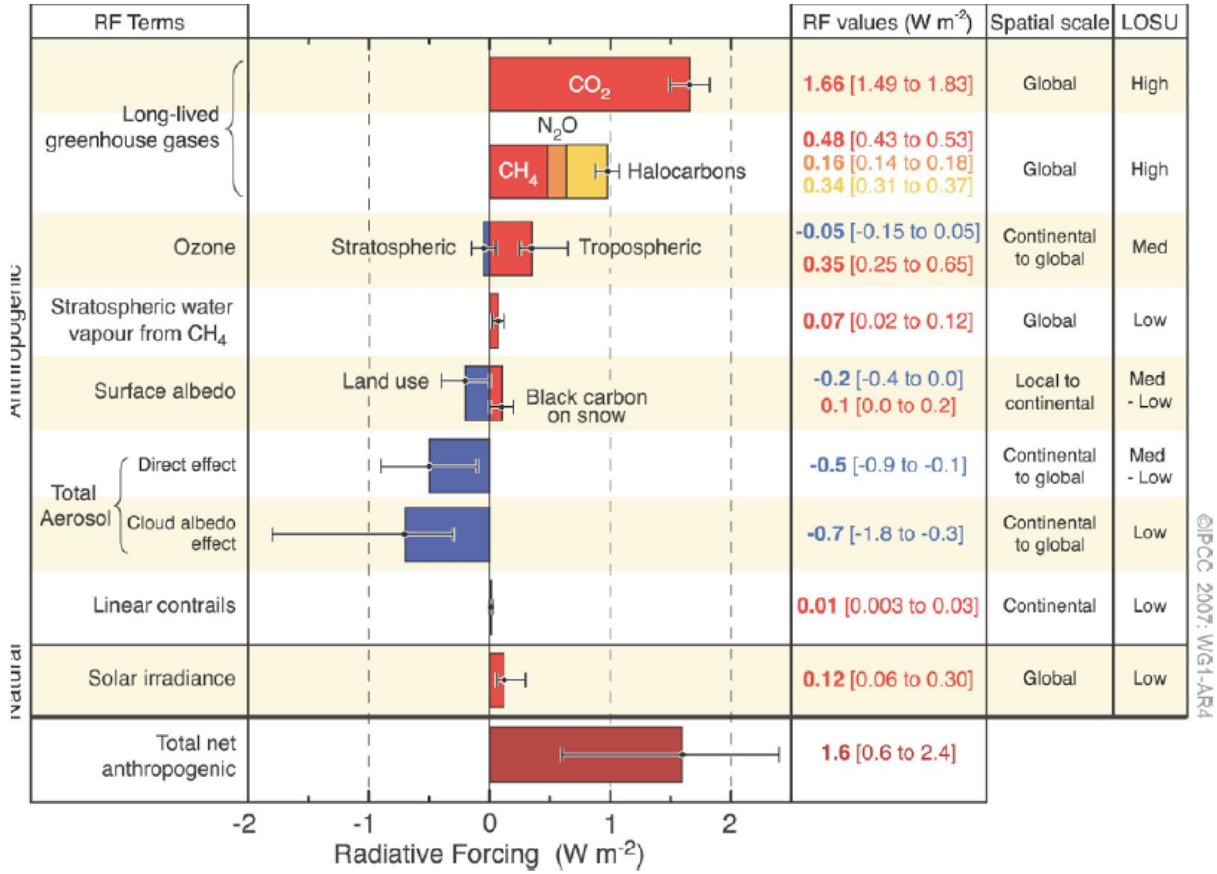


Source: IPCC 2007

GREEN HOUSE GASES AND CLIMATE CHANGE



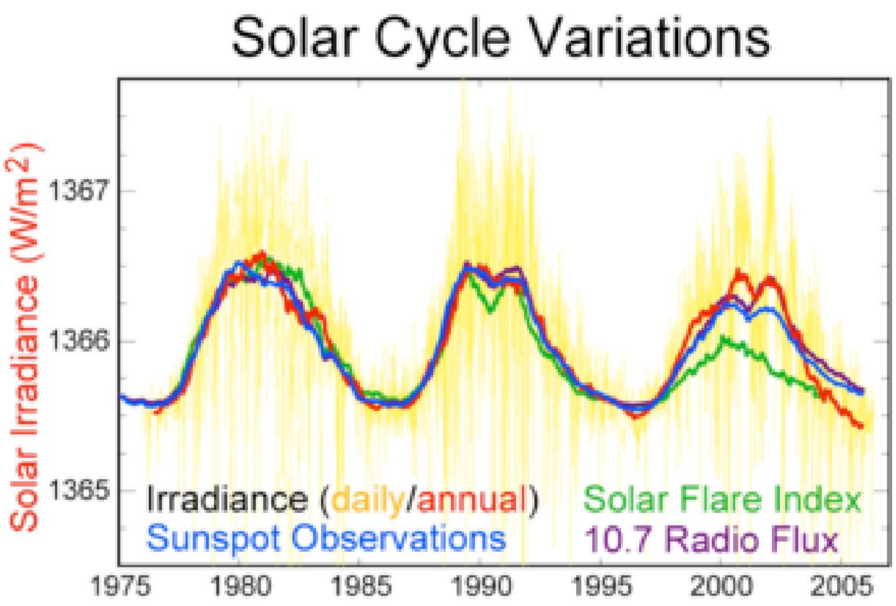
RADIATIVE FORCING



Radiative Forcing: the net decrease of the upward irradiance at the tropopause due to a change in some climate-change driver, such as a specified increase in the amount of a gaseous absorber

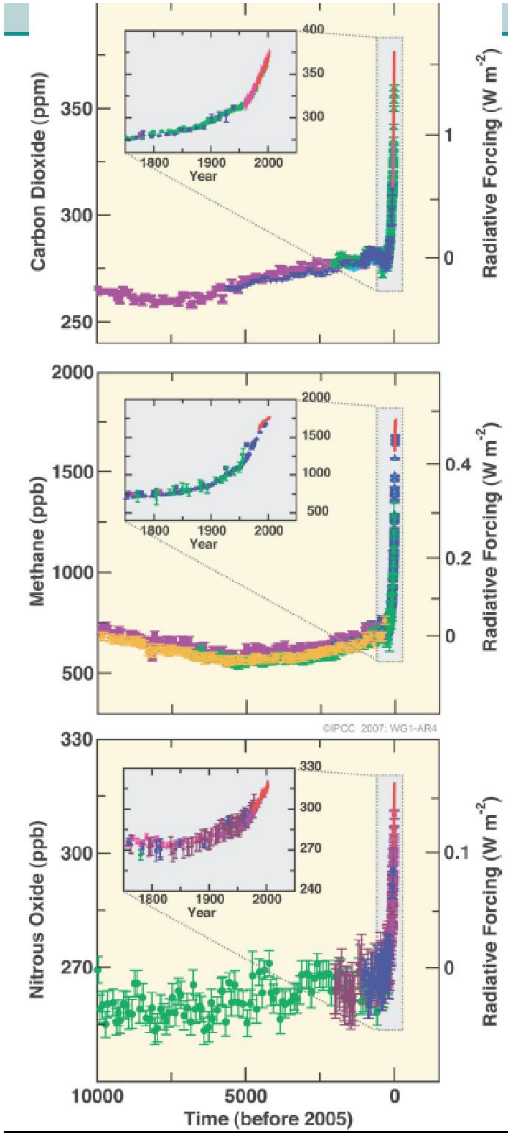
CLIMATE CHANGE

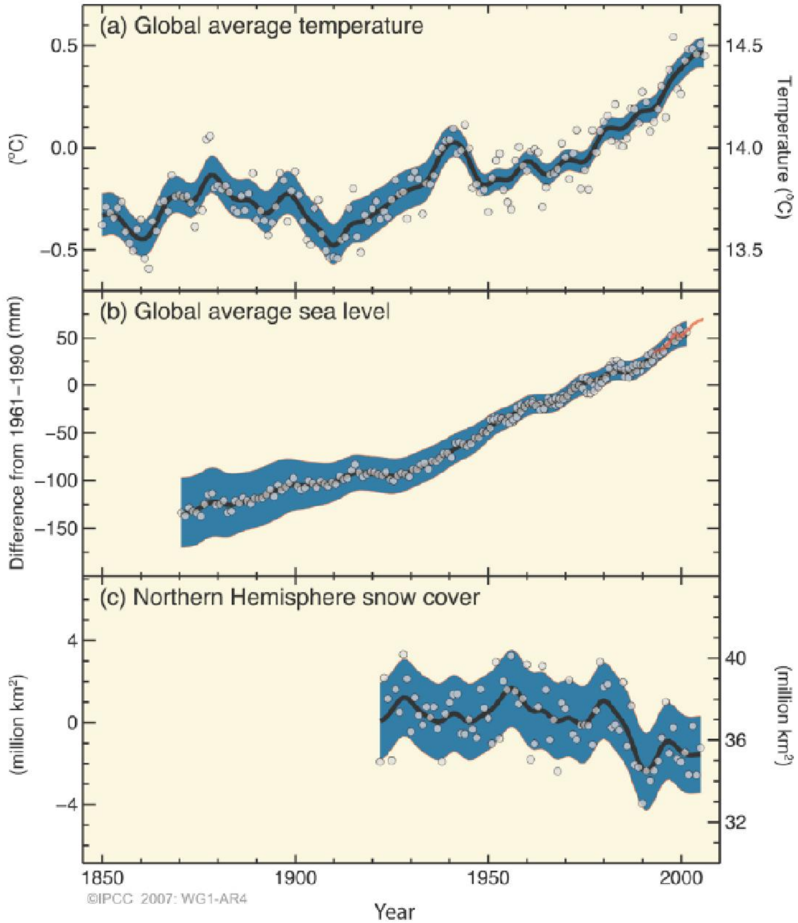
Climate change is a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years.
It may be a change in average weather conditions or the distribution of events around that average (e.g., more or fewer extreme weather events).



Factors that can shape climate are called climate forcings or "forcing mechanisms". These include processes such as variations in solar radiation, deviations in the Earth's orbit and changes in greenhouse gas concentrations.

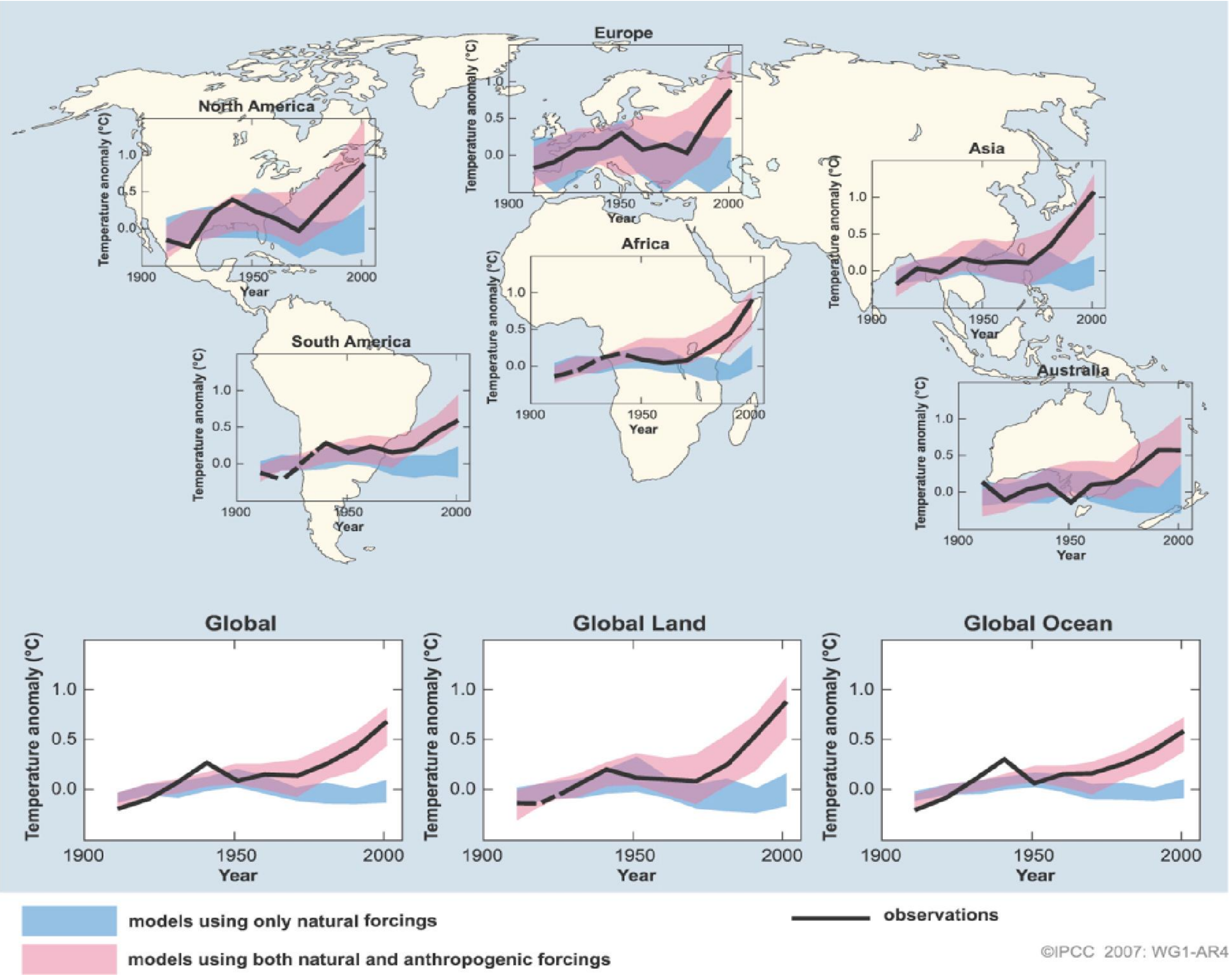
Intergovernmental Panel on Climate Change (IPCC)



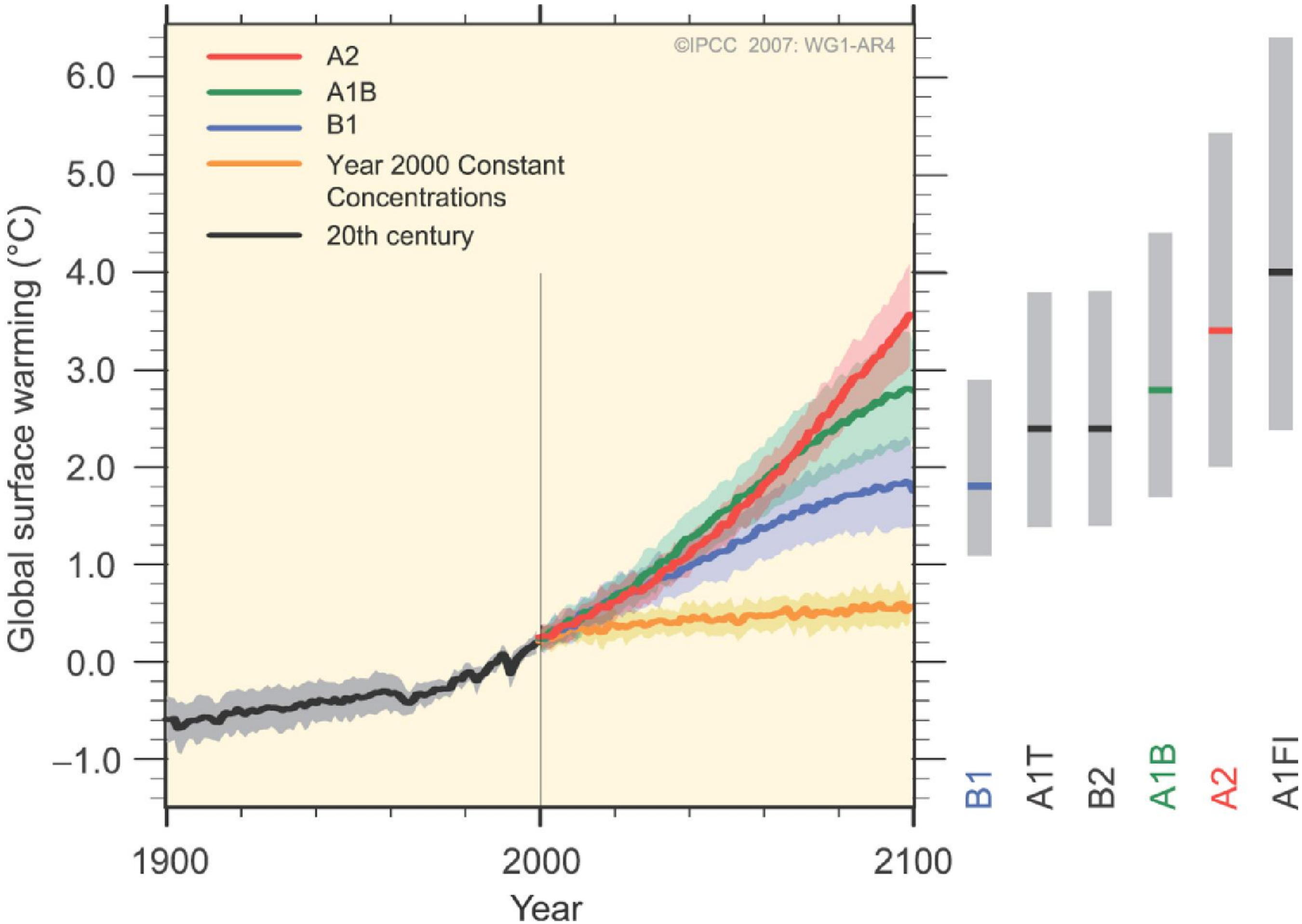


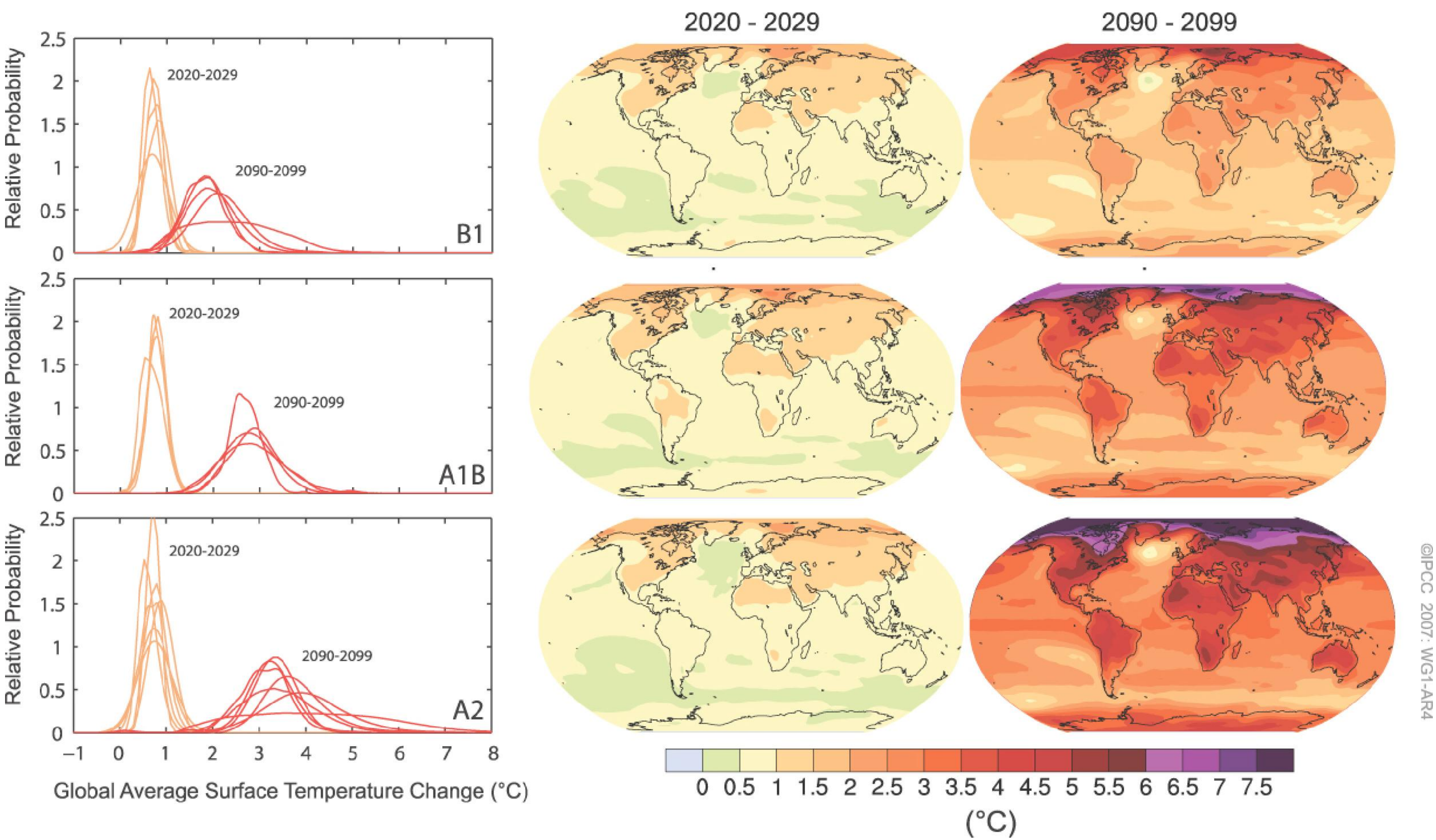
http://www.ipcc.ch/publications_and_data/

CLIMATE CHANGE- NATURAL AND ANTROPOGENIC EFFECT



CLIMATE CHANGE - ANALYSIS FROM DIFFERENT MODELS




2020 - 2029
2090 - 2099
Relative Probability
2020-2029
2090-2099
B1
A1B
A2
Global Average Surface Temperature Change (°C)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5
(°C)
©IPCC 2007: WG1-AR4

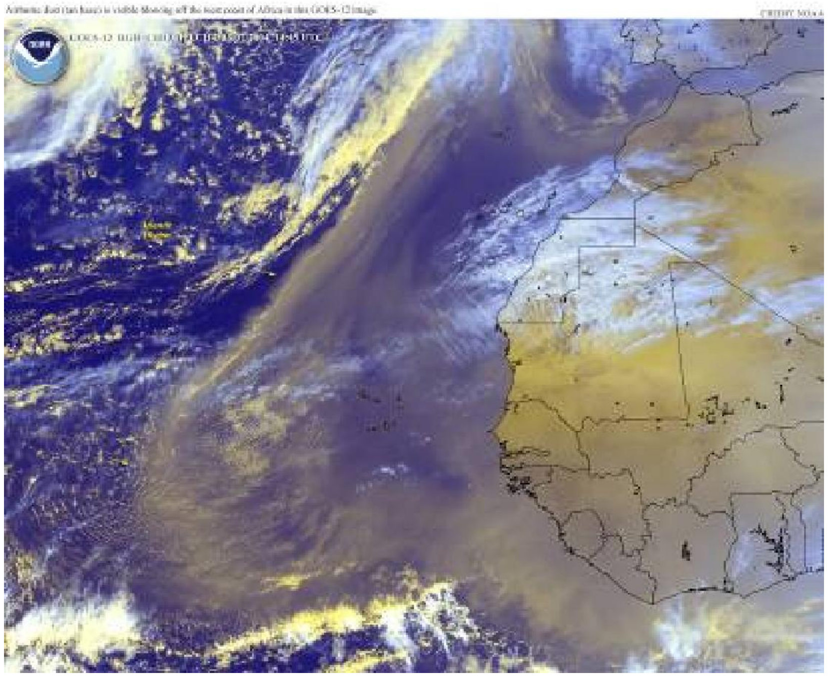
THE ROLE OF CLOUDS AND AEROSOLS IN CLIMATE

- Radiative transfer is modified importantly by clouds.

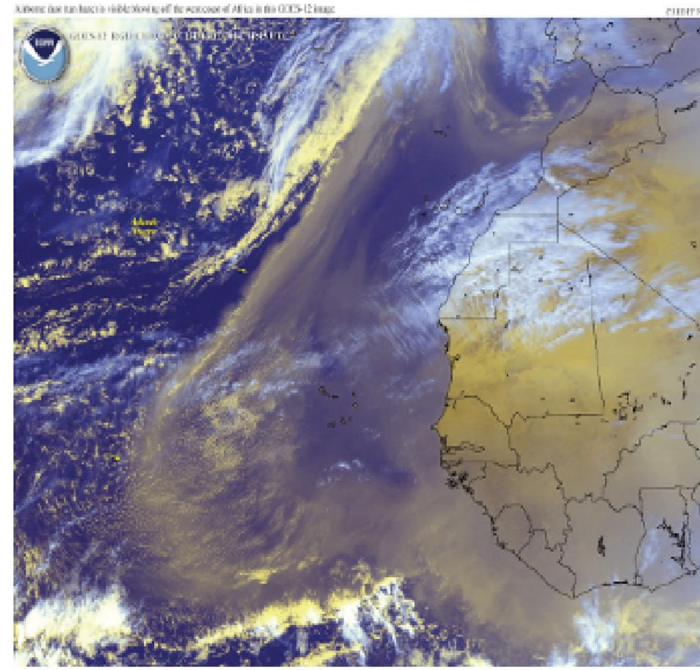
- Owing to their high reflectivity in the visible, clouds shield the earth-atmosphere system from solar radiation and thus represent cooling in the shortwave (SW) energy budget.

- Conversely, the strong infrared (IR) absorptivity of water and ice particles sharply increases the optical depth of the atmosphere, which magnifies the greenhouse effect and represents warming in the longwave (LW) energy budget.

- Atmospheric aerosol has optical properties similar to clouds.



Influence of Aerosol



- Atmospheric aerosol (e.g. desert dust) has a similar but weaker effect to clouds.
- Depending on its composition and the underlying surface, aerosol can either enhance or diminish albedo.

- Convection can carry desert aerosol as high as 500 hPa. Dust absorbs SW radiation, so it reduces the albedo over a highly reflective surface, like desert or shallow stratus, to introduce warming in the SW energy budget.
- However, dust changes the albedo over a dark surface like ocean only slightly- because both absorb strongly. The LW energy budget is influenced by desert aerosol in a manner similar to clouds. When it is convective to great heights, desert aerosol can reduce the effective emission temperature significantly.

- Aerosols are central to cloud formation, a role that is even more important than their direct radiative effect. Outbreaks of Saharan dust alter both the amount and type of cloud, with stratiform being favoured. Therefore, changes in the concentration, size or composition of atmospheric aerosol can introduce important changes in cloud cover and radiative energetics.

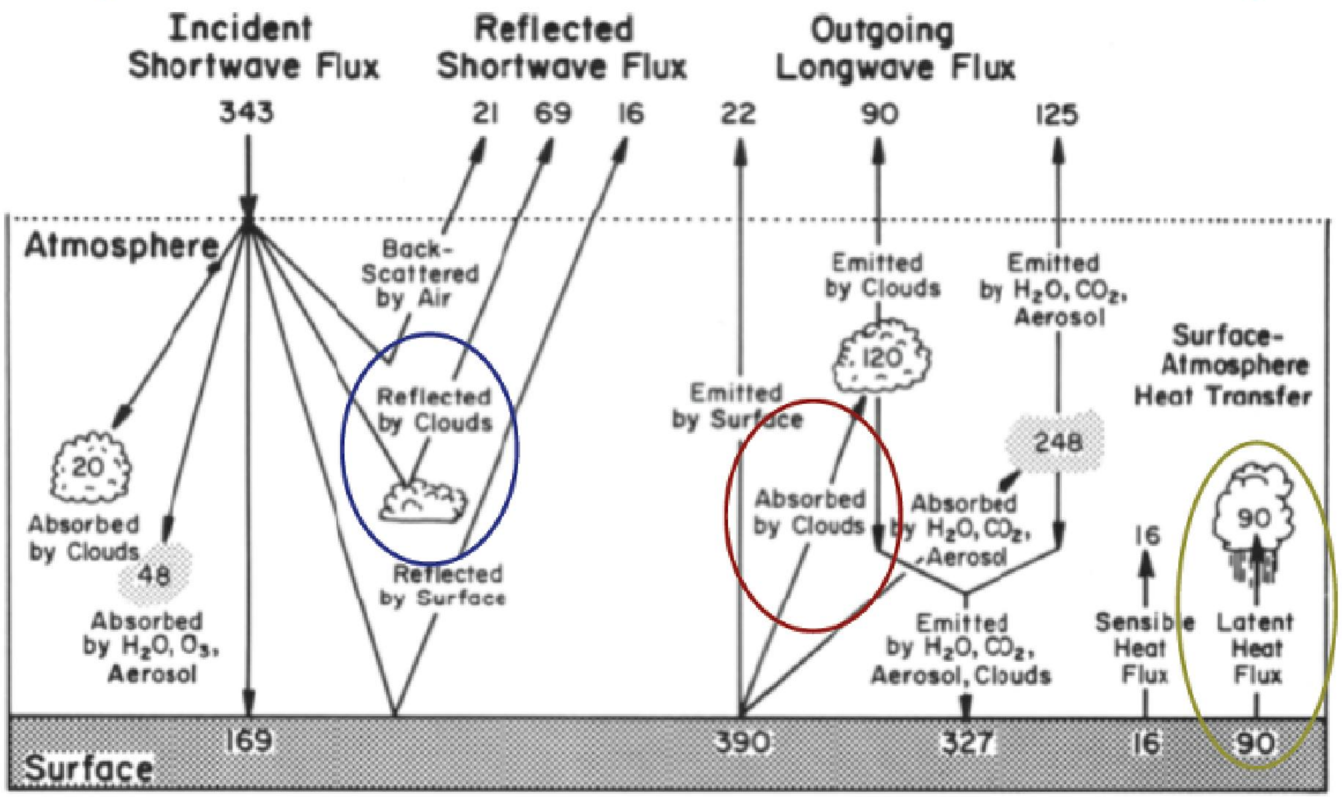
Clouds: forcing in the radiative energy balance

For SW radiation, the high reflectivity of clouds decreases the incoming solar flux, which favours reduced surface temperature.

For LW radiation, the large opacity of clouds increases the optical depth of the atmosphere, which promotes increased surface temperature by enhancing the greenhouse effect.

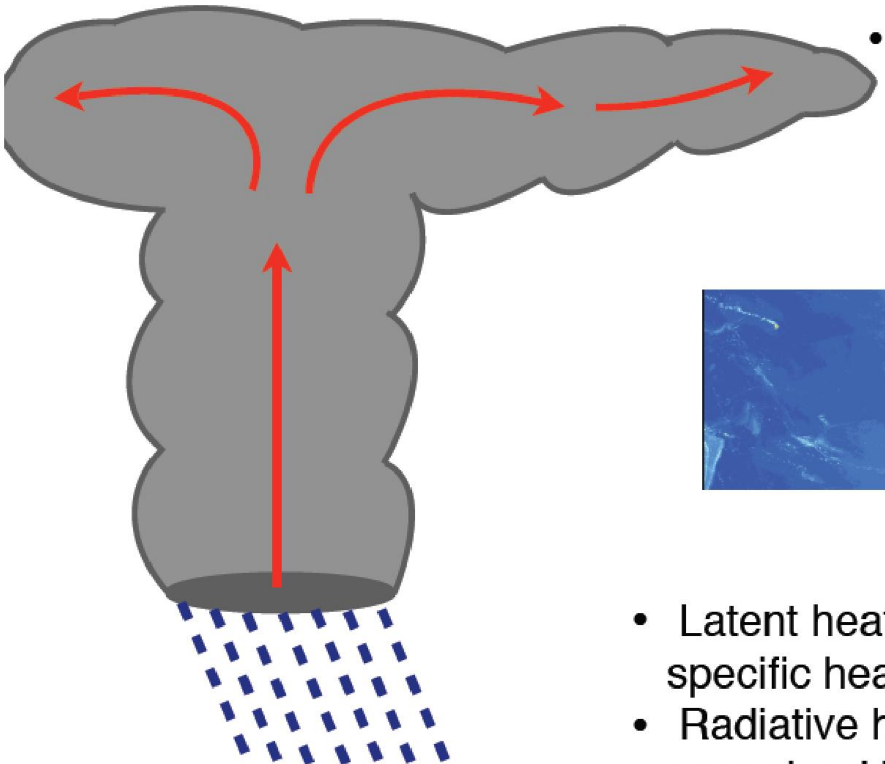
⇒Cooling

⇒Warming

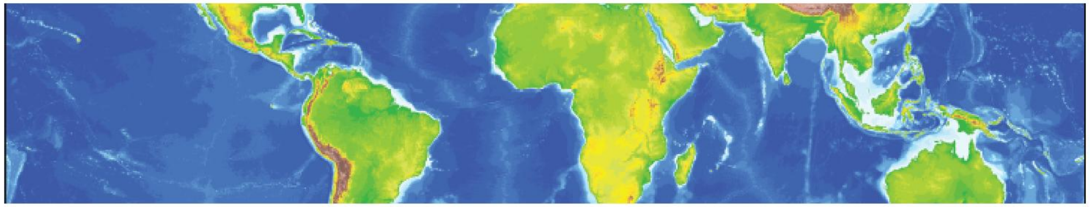


Latent Heating

Latent Heat in deep tropical convection



- Clouds introduce heating through the release of latent heat. Precipitation leads to a net transfer of heat from the oceans to the atmosphere.
- Latent heating is particularly important for organised deep cumulus clouds, which produce large volumes of precipitation in the tropics.



- Latent heat release inside tropical convection leads to a specific heating rate of order 10 K/day.
- Radiative heating and cooling can exceed this value near cloud boundaries, but the deep distribution of latent heat makes it a key source of energy for the tropical troposphere.

SUMMARY

- Clouds modify the global energy balance by altering the absorption and scattering properties of the atmosphere.
- Convection also supports large transfers of sensible and latent heat from the Earth's surface, which represent another important heat source for the atmosphere.
- Similar radiative effects are introduced by aerosol which controls cloud formation through microphysical process.