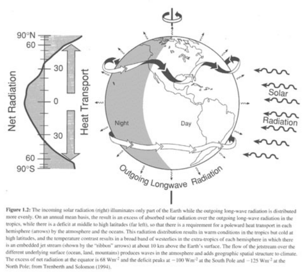
Lecture 2: Global Energy Cycle



(from *Climate Change 1995*)

- **Planetary energy balance**
  Energy absorbed by Earth = Energy emitted by Earth
- **Role of the atmosphere**
  Greenhouse effect
- **Role of oceans**
  Polarward energy transport
- **Role of land surface**
  not significant due to its low heat capacity

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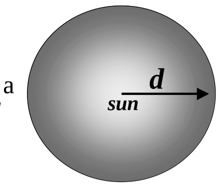
Solar Flux and Flux Density

- Solar Luminosity (L)
  the constant flux of energy put out by the sun

  $L = 3.9 \times 10^{26}$ W

- Solar Flux Density (S_d)
  the amount of solar energy per unit area on a sphere centered at the Sun with a distance d

  $S_d = L / (4 \pi d^2)$ W/m^2



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Solar Flux Density Reaching Earth

- Solar Constant (S)
  The solar energy density at the mean distance of Earth from the sun (1.5×10^{11} m)

$$S = L / (4 \pi d^2)$$
$$= (3.9 \times 10^{26}\ \text{W}) / [4 \times 3.14 \times (1.5 \times 10^{11}\ \text{m})^2]$$
$$= 1370\ \text{W/m}^2$$

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Solar Energy Incident On the Earth

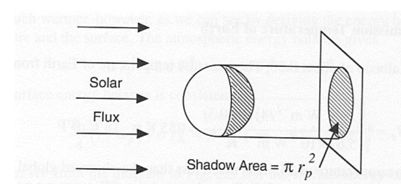

Fig. 2.2 Diagram showing the shadow area of a spherical planet.

- Solar energy incident on the Earth
  = total amount of solar energy **can be** absorbed by Earth
  = (Solar constant) x (Shadow Area)
  = $S \times \pi R^2_{Earth}$

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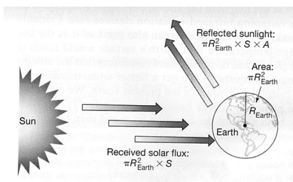
Solar Energy Absorbed by Earth



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 x πR^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.

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What Happens After the Earth Absorbs Solar Energy?

- ❑ The Earth warms up and has to emit radiative energy back to the space to reach a equilibrium condition.
- ❑ The radiation emitted by the Earth is called "terrestrial radiation" which is assumed to be like blackbody radiation.

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Blackbody Radiation

- ❑ Blackbody
  A blackbody is something that emits (or absorbs) electromagnetic radiation with 100% efficiency at all wavelength.
- ❑ Blackbody Radiation
  The amount of the radiation emitted by a blackbody depends on the absolute temperature of the blackbody.

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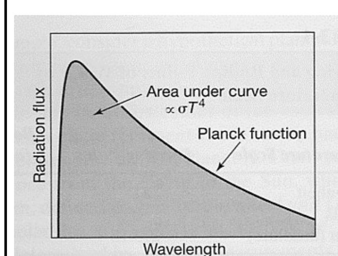
Energy Emitted from Earth



(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/m^2/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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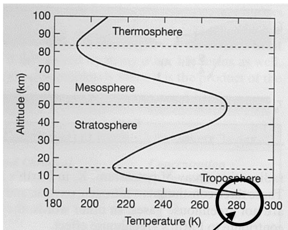
Planetary Energy Balance



(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 *blackbody* temperature**

T_e = 255 K (-18C)

Earth's *surface* temperature

T_S = 288 K (15C)

greenhouse effect (33C) !!

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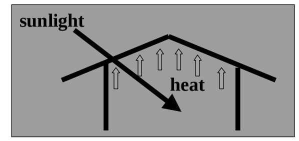
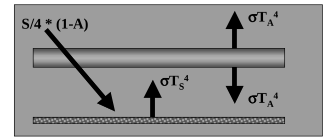
Greenhouse Effect

Greenhouse



- allow sunlight to come in
- trap heat inside the house

Atmosphere



At the top of the atmosphere:

$S/4*(1\text{-}A) = \sigma T_A^4$ ➔ $T_A = T_e$ = **255K**

For Earth's surface:

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

➔ $T_S = 1.19 T_A$ = **303K**

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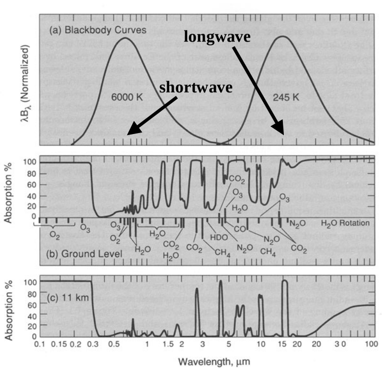
Different Wavelengths of Solar and Earth's Radiation

Normalized Planck Function



(from *Climate System Modeling*)

Planck Function

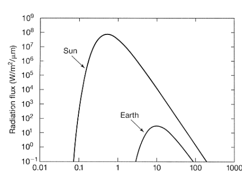


FIGURE 3-8
Blackbody emission curves for the Sun and Earth. The Sun emits more energy at all wavelengths.

(from *The Earth System*)

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Greenhouse Gases

Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	*Concentration (ppm by volume)*
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	360
Methane, CH_4	1.7
Nitrous oxide, N_2O	0.3
Ozone, O_3	0.01 (at the surface)
Freon-11, CCl_3F	0.00026
Freon-12, CCl_2F_2	0.00047

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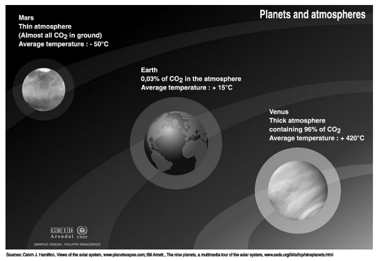
Earth, Mars, and Venus



Planet	Distance to the Sun	Radius	Planetary Albedo	Mean Surface Temperature
Venus	0.72 AU	12,104 km	0.80	730°K
Earth	1.00 AU	6,370 km	0.30	288°K
Mars	1.52 AU	6,794 km	0.22	218°K

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Three Factors To Determine Planet Temperature

- ❑ Distance from the Sun
- ❑ Albedo
- ❑ Greenhouse effect

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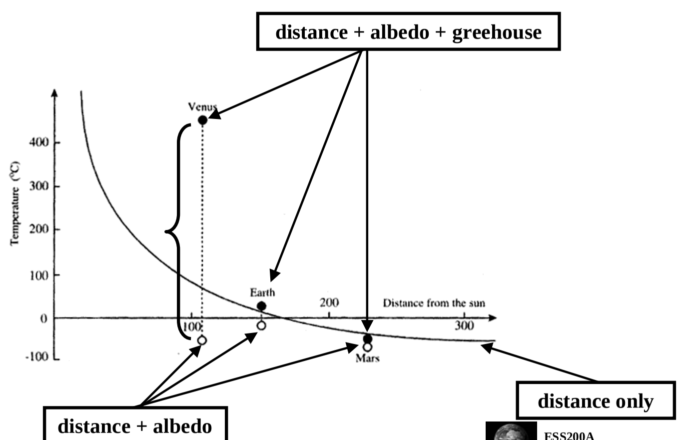
Global Temperature



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Greenhouse Effects

- ❑ On Venus ➔ 510°K (very large!!)
- ❑ On Earth ➔ 33°K
- ❑ On Mars ➔ 6°K (very small)

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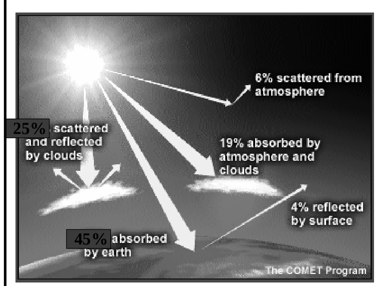
Why Large Greenhouse Effect On Venus?

- ❑ **Venus is too close to the Sun**
- ➔ Venus temperature is very high
- ➔ Very difficult for Venus's atmosphere to get saturated in water vapor
- ➔ Evaporation keep on bringing water vapor into Venus's atmosphere
- ➔ Greenhouse effect is very large
- ➔ A "run away" greenhouse happened on Venus
- ➔ Water vapor is dissociated into hydrogen and oxygen
- ➔ Hydrogen then escaped to space and oxygen reacted with carbon to form carbon dioxide
- ➔ **No water left on Venus (and no more chemical weathering)**

Why Small Greenhouse Effect on Mars?

- ❑ **Mars is too small in size**
- ➔ Mars had no large internal heat
- ➔ Mars lost all the internal heat quickly
- ➔ No tectonic activity on Mars
- ➔ Carbon can not be injected back to the atmosphere
- ➔ Little greenhouse effect
- ➔ **A very cold Mars!!**

Where Does the Solar Energy Go?

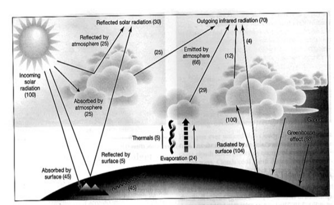


(from NCAR/COMET website)

Incoming solar energy (100)

- 70% absorbed
  - 45% by Earth's surface (ocean + land)
  - 25% 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?

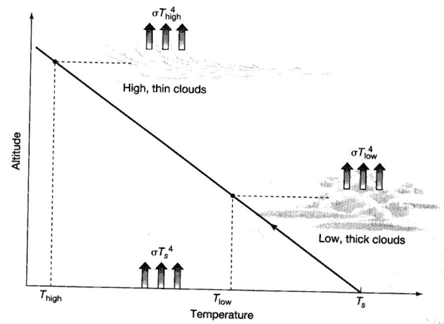


(from *The Earth System*)

Radiation back to Space (70 Units)

- 70 (units) radiation back to space
  - 66% by the atmosphere
  - 4% by surface (through clear sky)
- Greenhouse emission (back to surface)
  - 88% (of solar radiation)

Important Roles of Clouds In Global Climate



(from The Earth System)

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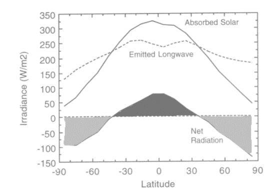
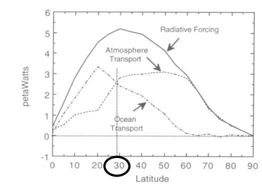
Polarward Energy Transport

Annual-Mean Radiative Energy



Polarward heat flux is needed to transport radiative energy from the tropics to higher latitudes

Polarward Heat Flux



The atmosphere dominates the polarward heat transport at middle and high latitudes. The ocean dominates the transport at lower latitudes.

(1 petaWatts = 10^{15} W)

(figures from *Global Physical Climatology*)

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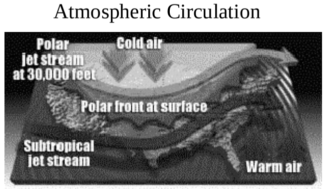
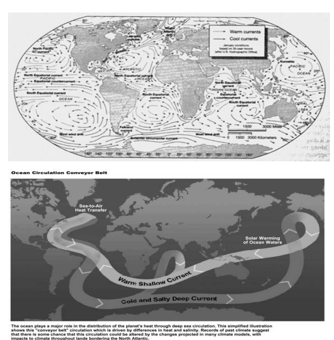
How Do Atmosphere and Ocean Transport Heat?

Atmospheric Circulation



(from USA Today)

Ocean Circulation



(top from *The Earth System*)
(bottom from USGCRP)

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