Mon Oct 20

Announcements:
- bring calculator to class from now on
  - > in-class activities
  - > midterm and final
-

Today:
- radiation and temperature (cont)
- sun-earth geometry
- energy balance >> conceptual model of climate change

Tues: T_e (as opposed to T_s) and the greenhouse effect
energy budget, balance at different levels

Wed: atmospheric composition and structure
greenhouse gas chemistry (why do these molecules absorb IR?)

Thurs: multiple roles of clouds in energy balance
local energy balance

upcoming talks

Monday 20 October:
3:30 310 ATG
Prof Jim Tillman, UW
Climate Mars: Viking Lander and next generation

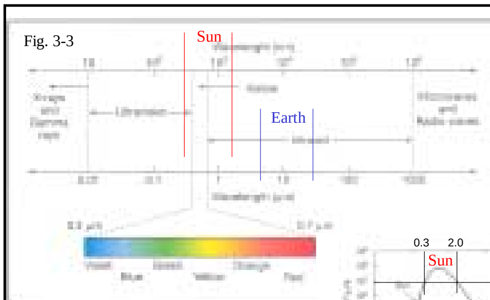
TUESDAY 21 October
12:30 ATG 310c, Weather discussion, Rick Steed

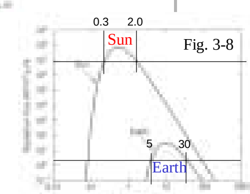
FRIDAY 24 October:
3:30 14 OTB (Oceanography Teaching Bldg)
Dr. Ralph Keeling
Scripps Institute of Oceanography
"Fate of anthropogenic CO2 and changing biogeochemistry of the oceans"

Radiation/Wavelength note

1. Electromagnetic radiation:
   - propagates through space
   - has a characteristic wavelength,
     for now just two types:
     SW: shortwave (mostly visible)
     LW: longwave

SW and LW ... not same meaning as radio !





Radiation vs Wavelength

Stefan-Boltzmann Law

Hotter objects emit more total energy:

Stephan-Boltzmann Law: $E = \sigma T^4$

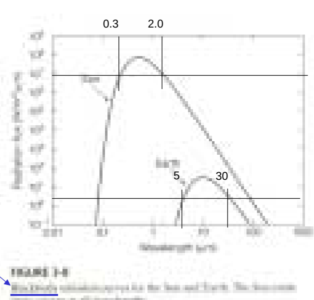
σ = 5.67e-8 [a constant]

T is temp in Kelvin, the absolute temperature scale

T(K) = T(C) + 273

Applies to an ideal material known as a "blackbody".

(The emissions from most physical objects are close to this ideal.)



Kelvin (absolute) Temperature Scale

T(K) = T(C) + 273

Reference Point	Celcius Scale (C)	Kelvin Scale (K)
water boils	100	373
water freezes	0	273
????	-273	0

What is the meaning of "absolute zero" temperature?

Consider...
- Hotter objects emit more total energy
- Can there be a negative temperature on the Kelvin scale?
- What is the meaning of "temperature", anyway?

Kelvin/Boltzmann applications

Stephan-Boltzmann Law: $E = \sigma T^4$

where σ = 5.67e-8, E is in W/m^2, and T is in Kelvin (K)

Kelvin vs Celcius scale: T(K) = T(C) + 273

The average surface temperature of the Earth is 15C.
Express this in degrees Kelvin.

An object warms from 0C to 10C.
What is the fractional increase in temperature?
What is the fractional increase in emitted, radiative energy?

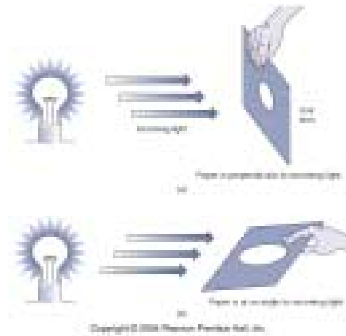
If the Sun were to warm up by 10%, by how much would the solar constant increase?
(i) fractional increase, (ii) absolute increase

T_{SUN} ~ 6000 K, T_{EARTH} ~ 255 K
What is the ratio of energy flux, E (W/m^2) from the Sun to that from the Earth?

Sun-Earth Geometry: flux on an angled surface

overhead sun, tropics

sun low in the sky, high latitudes



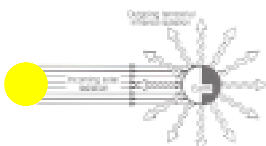
Sun-Earth Geometry: factor of 4

Define the solar constant, S_0: the flux of solar energy passing through space at the Earth's orbital distance.

S_0 = 1370 W/m^2

The earth intercepts the same amount of solar energy as flat disc of area πr^2

The earth emits LW radiation over the surface area of a sphere, $4\pi r^2$



$E_{IN} = E_{OUT}$

$S_0(1\text{-}A)\,\pi r^2 = \sigma T_e^4\, 4\pi r^2$

Energy balance

$E_{IN} = E_{OUT}$

$S_0(1\text{-}A)\,\pi r^2 = \sigma T_e^4\, 4\pi r^2$

Now divide both sides by the surface area of the Earth, $4\pi r^2$.
This will give the energy fluxes averaged over the Earth's surface.

$$\frac{S_0}{4}(1\text{-}A) = \sigma T_e^4$$

In-class activity: S_0 = 1370 W/m^2
the average albedo of the Earth is 0.30
>> calculate E_{IN} <<

E_{IN} = 240 W/m^2
The average flux of solar energy absorbed by the Earth system.
(averaged over entire surface, including day/night)

Tues Oct 21

Announcements:
- bring calculator to class from now on
  - > in-class activities
  - > midterm and final
-

Today:
- conceptual model of climate change: forcing > feedback > response
- "effective radiating temperature", T_e
- greenhouse effect (property of a planet's atmosphere)
- energy budget: needs to balance at every level
- [everything you need for HW#2 by end of today]

Energy Balance and Climate Change

Energy balance equation (E is energy flux, W/m^2)…

E_{IN}	=	E_{OUT}
energy absorbed by Earth		energy emitted by Earth

"Energy Balance Theory of Climate Change"

if $E_{OUT} < E_{IN}$ [imbalance]

then $T_{surface}$ will go up until balance is restored

Energy Balance Theory of Climate Change

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

ΔF: forcing, change in energy balance (W/m^2)
ΔT_s: response, change in surface temperature (K)
λ: feedbacks, climate sensitivity {$K/(W/m^2)$}

What are the characteristics of each of these terms?

ΔF: imposed changes on the climate system;
increasing GHGs, changed surface albedo, increasing aerosols

ΔT_s: climate response in terms of GAAST;
can be measured and predicted for the past (test of understanding)

λ: involves full complexity of the climate system; requires climate models; involves feedbacks, mainly (i) water vapor, (ii) ice-albedo, (iii) clouds

Energy Balance Theory of Climate Change

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

ΔF: forcing, change in energy balance (W/m^2)
ΔT_s: response, change in surface temperature (K)
λ: feedbacks, climate sensitivity {$K/(W/m^2)$}

There are two important terms left out of the above equation.
What are they?

Response time of the climate system

Natural variability of the climate system

(We will incorporate these later.)

Effective Radiating Temperature -1

$$E_{IN} = E_{OUT}$$

$$\frac{S_0}{4}(1-A) = \sigma T_e^4$$

where S_0 is the solar constant
A is the planetary albedo
σ is the Stephan-Boltzmann constant
and T_e is the "effective radiating temperature"

Given values for S_0, A, and σ, we can solve for T_e:

$$T_e^4 = \frac{S_0}{4\sigma}(1-A)$$

$$T_e = \left[\frac{S_0}{4\sigma}(1-A)\right]^{0.25}$$

Effective Radiative Temperature -2

$$T_e = \left[\frac{S_0}{4\sigma}(1-A)\right]^{0.25}$$

σ = 5.67e-8 [universal constant]
For Earth: S_0 = 1370 W/m^2
A = 0.30
Calculate T_e ???

T_e = 255 K (or -18 C)
"The Earth radiates as if it were a blackbody at 255 K."

but...
the Earth's surface temperature (T_s) is 288 K (or +15 C).

???

Greenhouse Effect

If the Earth had no atmosphere (and still had an albedo of 0.30), its surface temperature would be 255 K.

The atmosphere acts like a blanket, trapping heat near the surface and keeping it much warmer than it would otherwise be.

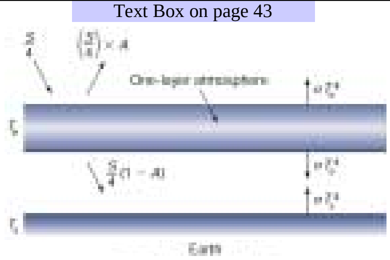
The magnitude of this "greenhouse effect" (ΔT_g) is:

$$\Delta T_g = T_s - T_e = 288\text{ K} - 255\text{ K}$$

$$\Delta T_g = 33\text{ K}$$

ΔT_g is a property of the atmosphere.
(Should really be called "the atmosphere effect".)

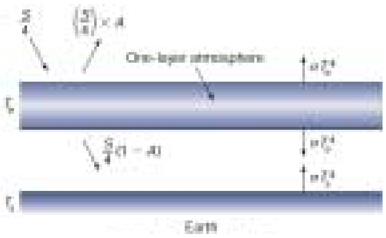
Text Box on page 43



What are the assumptions of this model?

- Atmosphere is a separate "layer" with temperature T_e.
- Atmosphere does not absorb any SW radiation.
- Atmosphere completely absorbs the LW radiation emitted by the surface.

Text Box on page 43



Good: Atmosphere acts like a blanket.
Simple numerical model of the greenhouse effect.

BAD: Calculation is not very accurate (ΔT_g = 48 K)
Includes a misleading, incorrect equation:

~~$T_s = 2^{1/4} T_e$~~

Sister planets

In fact, you cannot "predict" T_s from knowledge of T_e.

T_e is a function of S_0 and A

$T_s = T_e + \Delta T_g$

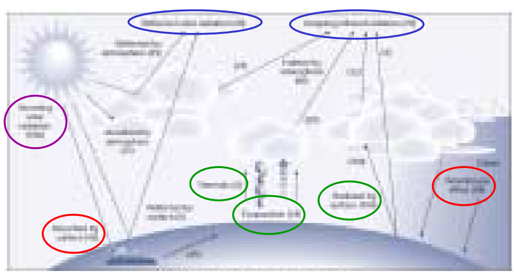
where, ΔT_g is a property of the <u>atmosphere</u> of a planet

Venus (runaway greenhouse) | Earth ("just right") | Mars (virtually no greenhouse)

Note: formula from the Text Box on page 43 gives wildly inaccurate estimates of greenhouse effect for Venus and Mars.

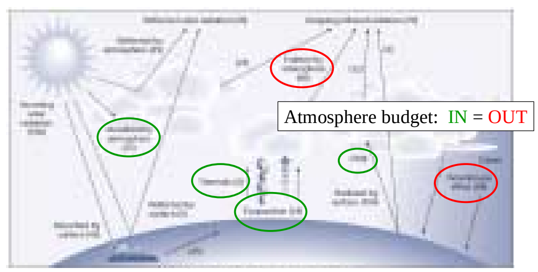
Energy Budget: TOA and surface

Top-of-Atmosphere budget: IN = OUT



Surface budget: IN = OUT

Energy Budget: atmosphere

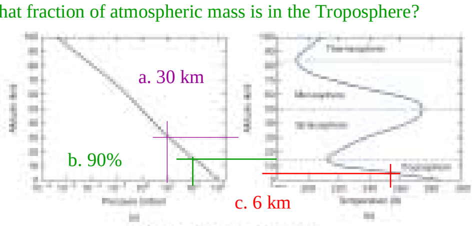


Vertical structure of the atmosphere

<u>Pressure:</u> the weight of air overhead (e.g. psi or lbs/in^2)
Note log scale on pressure graph.

a. At what height are you above 99% of the atmospheric mass?

b. What fraction of atmospheric mass is in the Troposphere?

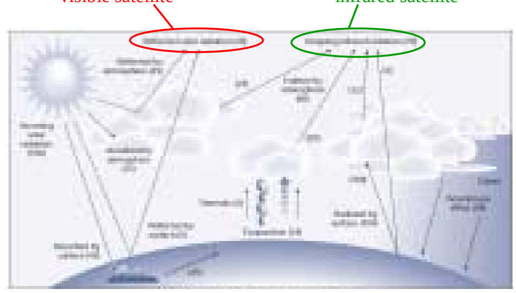


<u>Lapse rate:</u> The rate at which temperature changes with height in the atmosphere. A measure of vertical stability.

c. What height corresponds to T_e?

Satellite View of Energy Budget

visible satellite | infrared satellite



Wed Oct 22

Announcements:
- HW#2 due Thursday at beginning of class
- Monday's record rain

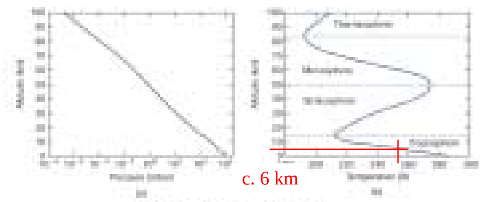
Today:
- vertical structure, "lapse rate"
- atmospheric composition
- greenhouse gas absorption - how does it work?
- dual role of clouds

Speaking of atoms...

Vertical structure of the atmosphere

Pressure: the weight of air overhead (e.g. psi or lbs/in^2)

a. At sea level, P = 15 psi. Why don't we feel it?
b. At what depth underwater is pressure doubled?



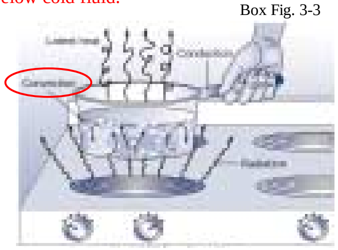
Lapse rate: The rate at which temperature changes with height in the atmosphere. A measure of vertical stability.
c. What height corresponds to T_e?

Lapse rate and convection

Lapse rate: The rate at which temperature changes with height in the atmosphere. A measure of vertical stability.

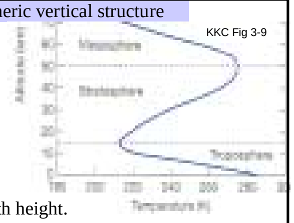
Stable: Warm fluid on top of cold fluid.
Unstable: Warm fluid below cold fluid.

Box Fig. 3-3



A dialectic on atmospheric vertical structure

KKC Fig 3-9



Weather (clouds, rain) happens in the Troposphere because the Troposphere is unstable.

Why is the troposphere unstable?

Because temperature decreases with height.

Yes, but why does temperature decrease with height?

Because it is heated from below.

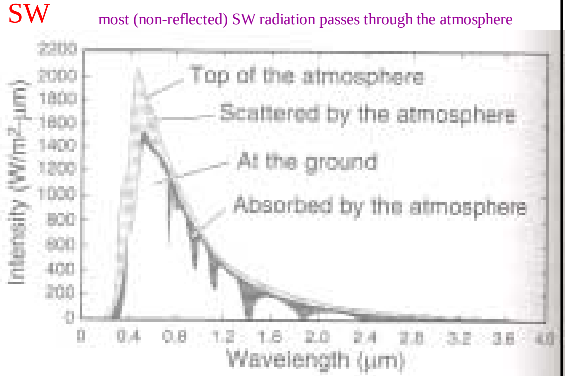
Yes, but how does it come about that it is heated from below?

Because the atmosphere is mostly transparent to solar (or, SW) radiation.

spectral absorption by the atmosphere

SW

most (non-reflected) SW radiation passes through the atmosphere

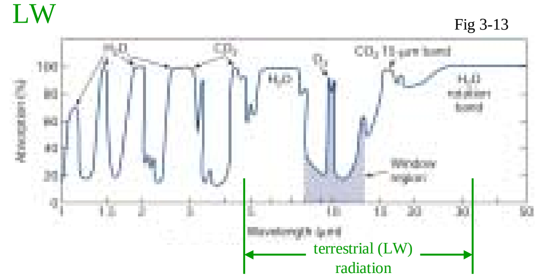


spectral absorption by the atmosphere

most LW radiation emitted by the surface is absorbed by the atmosphere

LW

Fig 3-13



Atmospheric constituents

- **main gases** (O_2, N_2, Ar are 99.9% of dry volume of atmosphere)
- **variable gas** (water vapor)
- **trace gases** (CO_2, O_2, CFC's, SO_2, etc, etc, etc)
- **particles** (dust, seasalt, sulfate, soot, organics)

TABLE 3-2

Major Constituents of Earth's Atmosphere Today

Name and Chemical Symbol	*Concentration (% by volume)*
Nitrogen, N_2	78
Oxygen, O_2	21
Argon, Ar	0.9
Water vapor, H_2O	0.00001 (South Pole)–4 (tropics)
Carbon dioxide, CO_2	0.037*

*In 2002

Greenhouse gases

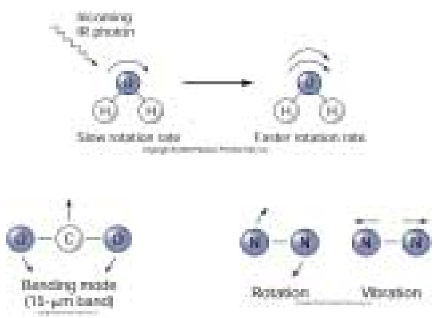
ppmv, parts per million by volume:
molecules of trace substance per million molecules of air

TABLE 3-3

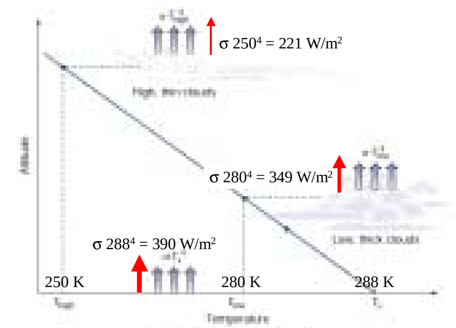
Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	*Concentration (ppm by volume)*
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	370
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	0.00054

GHG absorption



hi-lo cloud: Bad Figure!



upcoming talks

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FRIDAY 24 October:
  3:30 14 OTB (Oceanography Teaching Bldg)
  Dr. Ralph Keeling
  Scripps Institute of Oceanography
  "Fate of anthropogenic CO2 and changing biogeochemistry
       of the oceans"
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Thur Oct 23

Announcements:
- HW #2 due today
- Readings for next week are on the web
  - Modeling chapter from new edition of book
  - Lorius et al. article on ice-ages and climate sensitivity
- midterm next Friday
- paper #1 due next Friday

Today:
- multiple role of clouds in energy balance
- local energy balance, diurnal effects

Tomorrow (Friday):
- guidance on papers
- review/questions
- supplementary topics

Heat-trapping by clouds

calculate the heat-trapping (W/m2) by the cloud

Cloud:

E_{OUT} = σT^4
= 5.67e-8*270^4
= 301 W/m^2

Surface:

E_{OUT} = σT^4
= 5.67e-8*288^4
= 390 W/m^2

Heat-trapping
= 390 - 301
= 89 W/m^2

301 W/m^2

T_{top}=270 K — Cloud

89 W/m^2 "trapped" within Troposphere

390 W/m^2

$T_{surface}$ = 288 K

What assumptions underlie this calculation?

- All LW radiation is absorbed by cloud.
- Cloud emits according to cloud-top temperature.

Greenhouse role of clouds

LW — The previous slide demonstrates that clouds are a major participant in the Earth's greenhouse effect. — warming

SW — But...
We know from previous lectures that clouds are a major player in controlling Earth's albedo. — cooling

net — Question...
What is the net effect of a cloud on the energy balance? — ???

Local Energy Balance

calculate E_{IN}, E_{OUT}, and net energy effect for each cloud type

High thin cloud
T=250 K A=0.20

E_{IN} = S_0/4(1-A)
= 1370/4*0.8
= 274 W/m^2

E_{OUT} = σT^4
= 5.67e-8*250^4
= 221 W/m^2

E_{NET} = E_{IN} - E_{OUT}
= 274 - 221
= +53 W/m^2

E_{IN} = S_0/4(1-A)
= 1370/4*0.4
= 137 W/m^2

E_{OUT} = σT^4
= 5.67e-8*280^4
= 349 W/m^2

E_{NET} = E_{IN} - E_{OUT}
= 137 - 349
= -212 W/m^2

T=280 K A=0.60
Low, thick cloud

Multiple roles of clouds in the energy budget

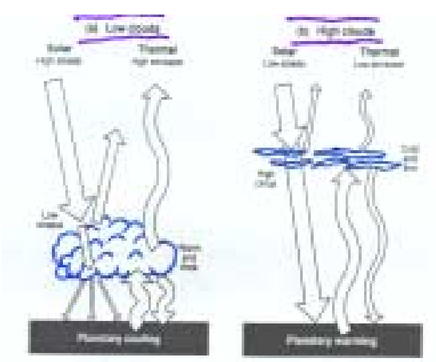
SW: Clouds are <u>the</u> major player in the Earth's albedo

LW: Clouds are a major player in heat-trapping (greenhouse effect)

high clouds:
- modest albedo (small SW effect)
- lots of "heat-trapping"
  - complete IR absorption
  - cold, so have low IR emission

low clouds:
- high albedo (big SW effect)
- modest "heat-trapping"
  - complete IR absorption
  - almost as warm as the surface, so emit almost as much IR upwards

High vs Low Clouds graphic



Home Weather record

Where on these plots do you see the SW effect of clouds?
Where do you see the LW effect of clouds?