Topic 8: Energy production

8.2 – Thermal energy transfer

Understandings:

- Conduction, convection and thermal radiation
- Black-body radiation
- Albedo and emissivity
- The solar constant
- The greenhouse effect
- Energy balance in the Earth surface / atmosphere system

Sun's Properties

- average surface temp = 4500K
- Wein's max wavelength $\lambda_{\max} = \frac{2.90x10^{-3}}{T}$
- most prevalent wavelength is 644nm
- this is in the colour orange on the visible spectrum, but more importantly, closer to the infrared area of the spectrum
- Average Intensity falling on the Earth's surface (I=1380 Wm^{-2}) is 340 Wm^{-2}

(1360-1400 depending on textbook)

Earth's Atmospheric Properties

- three gases, Nitrogen(~80% by weight), Oxygen(~20% by weight), and Argon make up all but 0.04% of the total

- Ozone shields us from UV rays

- Carbon Dioxide (CO_2), Methane (CH_4), Water Vapour (H_2O) and Nitrous Oxide (N_2O) are considered the "green house gases" - they are NOT bad, in fact, they are vital to our existence on this planet

The Greenhouse Effect

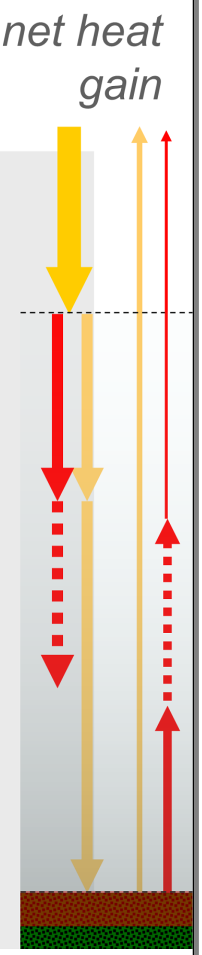
- Oxygen and Nitrogen are very tightly bound, and do not absorb energy from the sun very easily

- the 0.04% that makes up the greenhouse gases (GHG) has a much greater effect

- visible light passes through the GHG while UV and Infrared get absorbed

- the Earth absorbs the visible light, and then re-radiates it in the Infrared range due to the lower surface temperature

- the atmosphere then captures this radiated energy from the surface, and in turn radiates it all directions (effectively trapping some energy in a loop)



The greenhouse effect

- When solar radiation strikes a planet that has a gaseous atmosphere, the gases comprising the atmosphere can absorb infrared radiation (heat).
- The remainder of the incoming radiation then reaches the ground to either be scattered back into the atmosphere, or absorbed.
- Solids can absorb all frequencies of radiation, and convert them to infrared wavelengths.
- The heated ground can then emit infrared radiation back into the atmosphere, which then intercepts more of the energy on the way out.
- The result is that the atmosphere traps heat and causes the temperature of the planet to rise.

Balance

The whole system is in a dynamic equilibrium of absorption and radiation.

Total energy incident on the system from the sun	=	Total energy being radiated away by Earth

The "balance" was established over millions of years, if not billions of years.

About 250 years ago that all changed when man started burning fossil fuels.

The Earth releases CO_2 and sequesters it (absorbs). The forests, ocean, and soil all play a part in this cycle.

As major Earth events have occurred, volcanic eruptions, space impacts, ice ages, etc. biological entities have died, decomposed, and been taken into the soil. As CO_2 was pulled out of the atmosphere, the greenhouse effect changed, new surface temperatures were established. As we burn more fossil fuels we are putting that "locked" away carbon back into the atmosphere and essentially turning the clock back to an earlier atmospheric balance point, where things were much warmer.

The Climate Crisis is fairly easy to define, we are creating an enhanced greenhouse effect by putting more CO_2 into the atmosphere than the Earth can balance. (cutting forests isn't helping either)

The Solution: stop creating so much CO_2 , then work to draw down the legacy load that is currently in the atmosphere. Problem solved, ha!

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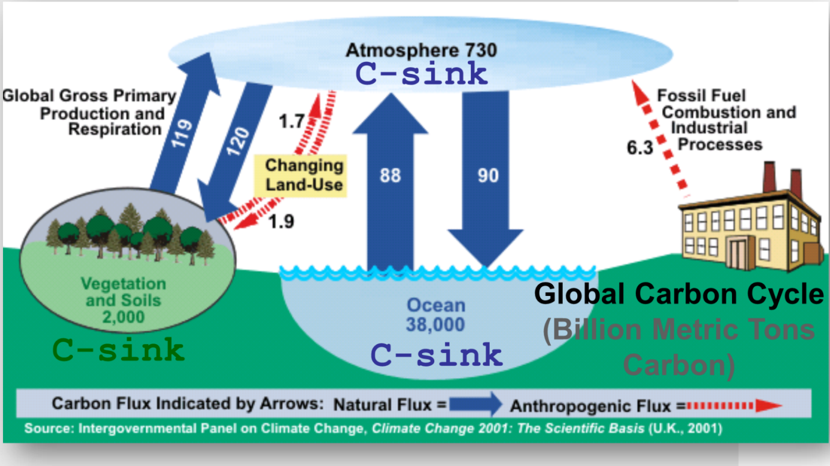
The greenhouse effect

- The process outlined on the previous slide is the so-called **greenhouse effect**.
- The main gases that are particularly effective in absorbing infrared radiation are **methane** (CH_4), **water vapor** (H_2O), **carbon dioxide** (CO_2), and **nitrous oxide** (N_2O).



- Note that there are both **natural** and **man-made** (anthropogenic) contributions and changes.

industrial revolution 1760 - 1820

combustion engine ~ 1860

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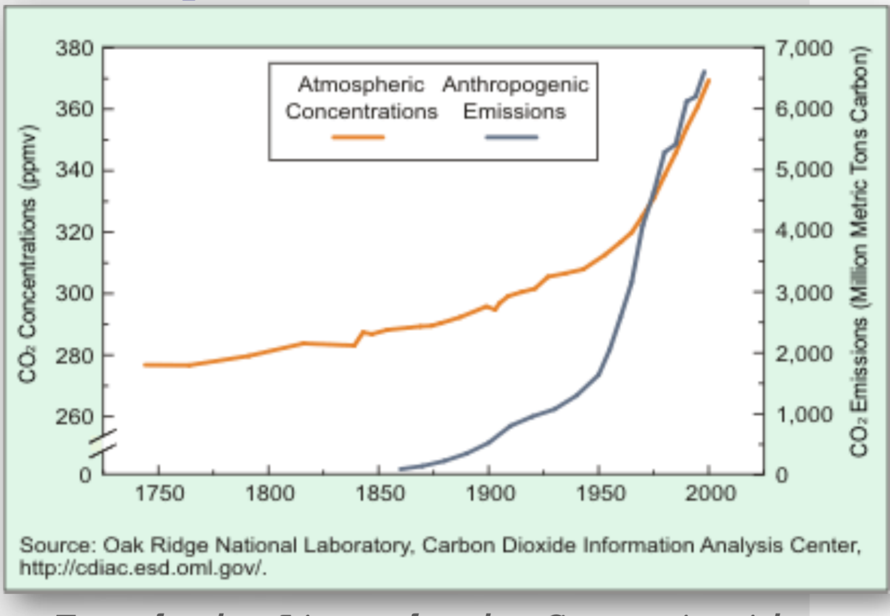
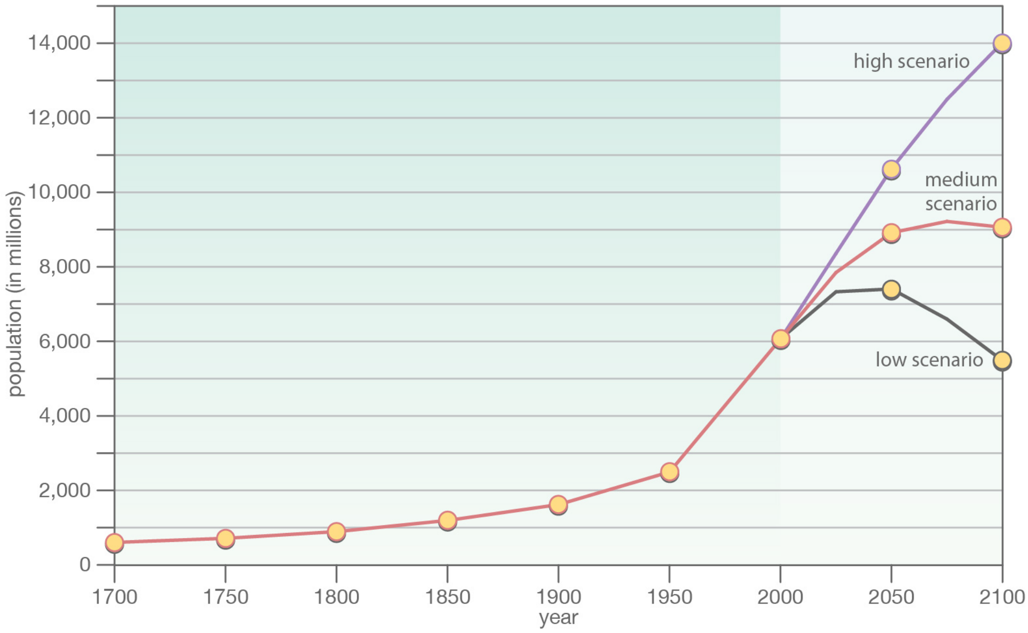
Greenhouse gases – CO_2

- This graph shows the correlation between increasing atmospheric concentration of CO_2 and our fossil fuel emissions of CO_2.
- **Anthropogenic** means "human."



Trends in Atmospheric Concentrations and Anthropogenic Emissions of Carbon Dioxide

World population (1700–2000) and population projections (2000–2100)



Source: United Nations Department of Economic and Social Affairs/Population Division 2004

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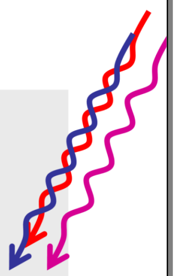
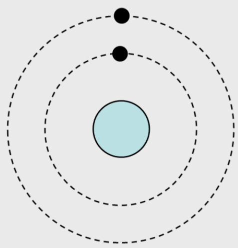


Absorption of infrared radiation by greenhouse gases

- Recall that solar radiation strikes the earth at a rate of $1380\ W\ m^{-2}$ or less, the farther from the equator you are.
- That energy is carried in the form of **photons**, which are quanta of light.
- The atmosphere is made up of gases, which are the first layer of matter that the sun's rays interact with.
- If a photon is at the precise energy for an electron to jump to a different energy level in an atom, it will be absorbed.



Small, medium and large electron jumps may occur, even to the point of ionization

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Absorption of infrared radiation by greenhouse gases

- The excited gases will eventually de-excite and release photons.
- The absorption and release of photons by the gases is called **scattering**.
- Scattering does not produce a net increase in heat energy in the atmosphere.
- However, some of the scattered photons may be in the infrared region – able to be absorbed as internal energy and kinetic energy via the mechanisms illustrated on the next slides:

Resonance on Molecular Level

- recall that resonance occurs when an applied vibration matches the natural frequency of an object; the result is greatly amplified movement

- remember the standing waves created with the slinky on the floor

- Carbon Dioxide has vibrational modes as a molecule - vibration, translation, rotation
(aka; stretching, bending, rotating)

- when the right wavelength hits a CO2 molecule (infrared), resonance can occur making large movements (increased kinetic energy-temperature)

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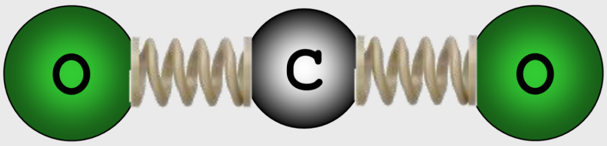
Absorption of infrared radiation by greenhouse gases

- Greenhouse gases are all molecular in nature, (meaning comprised of more than one atom).
- For our purposes we will consider the triatomic molecule CO_2.
- A simple model of CO_2 has springs connecting the two oxygen atoms to the carbon atom:



- Recall that heat energy can be stored in molecules as internal energy in the form of potential (the springs) and kinetic (the vibrations).

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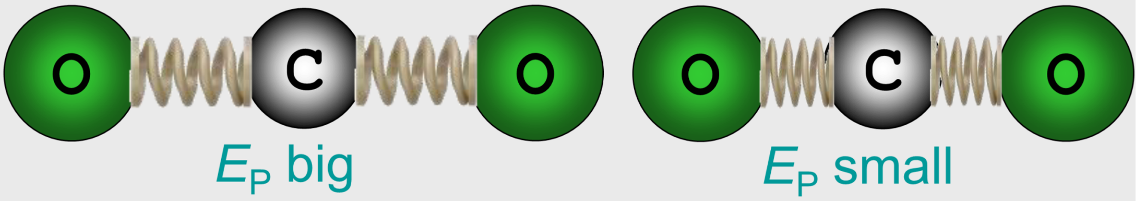
Absorption of infrared radiation by greenhouse gases

- The difference between these two CO_2 molecules is in their internal potential energies:



- The above E_P storage does not contribute to the increase in temperature of the CO_2. Rather, it is the kinetic energy E_K of the molecule that determines its temperature.
- There are three ways an extended molecule such as CO_2 can store kinetic energy: Via **vibration**, via **translation**, and via **rotation**.

Remember- kinetic energy affects temperature

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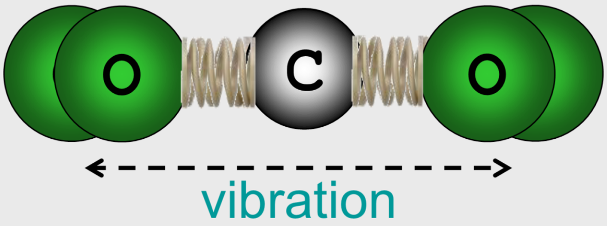
Absorption of infrared radiation by greenhouse gases

- **Vibration** refers to the molecules oscillating in conjunction with the springs:



- The **natural frequency** of greenhouse gases is in the **infrared region** of the spectrum and thus greenhouse gases are prone to absorb such frequencies.

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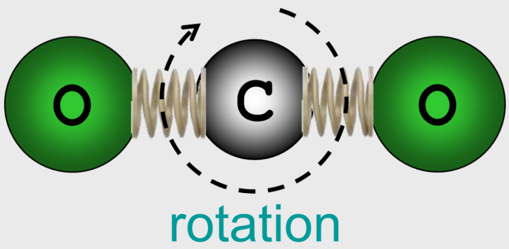
Absorption of infrared radiation by greenhouse gases

- **Translation** refers to the molecule moving as a unit in a straight line:

- **Rotation** refers to the molecule spinning about its center of mass.
- All three E_K modes can absorb and hold **infrared** radiation simultaneously.



As E_k goes up, so does temperature.

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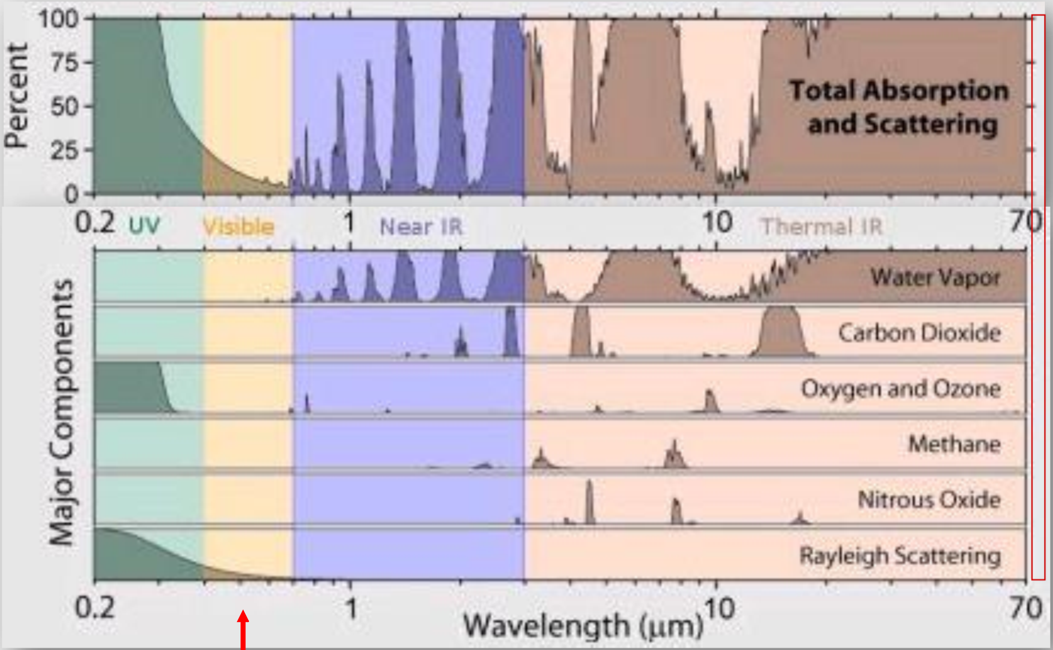
Absorption of infrared radiation by greenhouse gases

- Different gases absorb different wavelengths:



Note, visible doesn't contribute much in the atmosphere.

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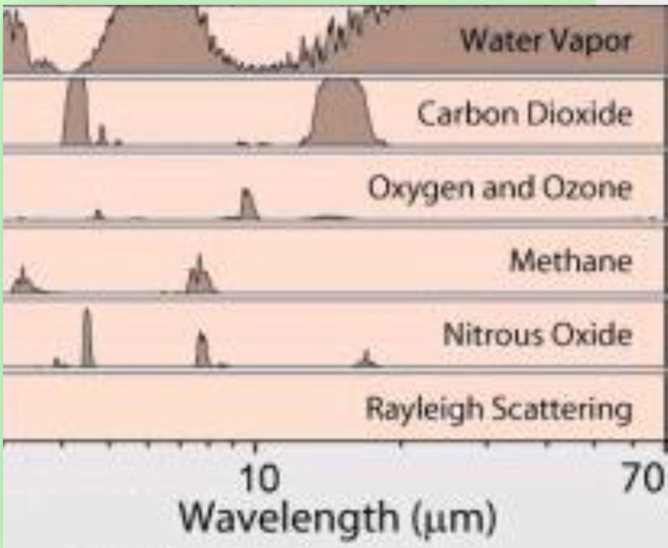
Absorption of infrared radiation by greenhouse gases

PRACTICE: Consider the absorption graphs below:

(a) Which portion of the electromagnetic spectrum is represented?

(b) Which greenhouse gas contributes the most to the greenhouse effect?

(c) Which gas is the least significant contributor?



SOLUTION:

(a) Infrared (heat).

(b) Water vapor!

(c) Oxygen and ozone.

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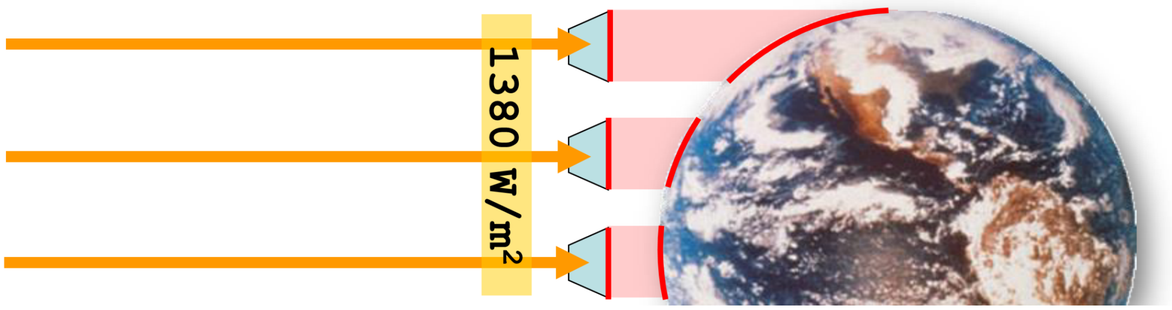
8.2 – Thermal energy transfer

Energy balance in Earth surface / atmosphere system

- Although we calculated the intensity of solar radiation to be 1380 W m^{-2} by the time it reaches Earth, the earth is spherical, and so not all surfaces will receive this intensity.
- We will take the average for our models to be

$I_{AVG} = 340$ W m^{-2} average incident solar radiation



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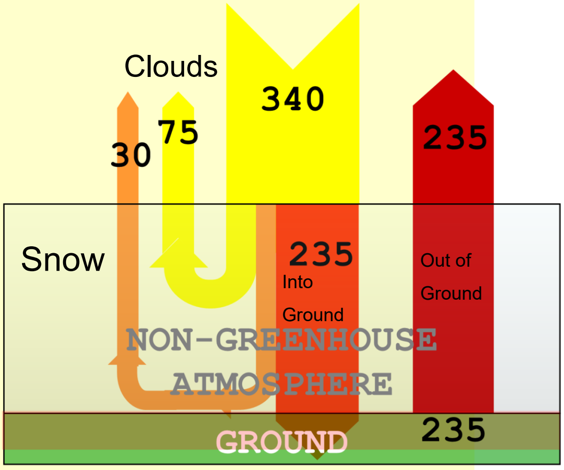
8.2 – Thermal energy transfer

Energy balance in Earth surface / atmosphere system

EXAMPLE: Draw a Sankey diagram for a model of the earth <u>without</u> greenhouse gases.

SOLUTION: First draw Earth/atmosphere blocks:

- Draw incoming solar energy (340 W m^{-2}):
- Draw energy reflected by atmosphere (clouds):
- Draw energy reflected by ground (snow, etc.):
- Draw energy absorbed by ground ($Q = mc\Delta T$):
- Draw energy radiated by ground ($P = \sigma AT^4$):



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8.2 – Thermal energy transfer

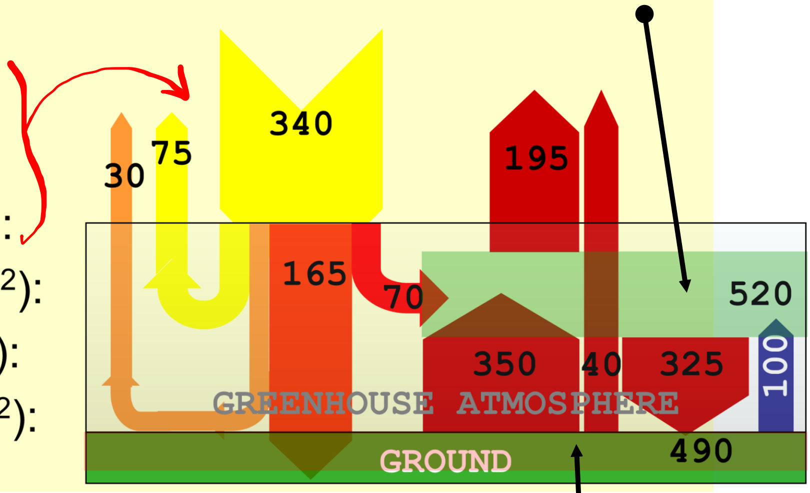
Energy balance in Earth surface / atmosphere system

EXAMPLE: Draw a Sankey diagram for a model of the earth with greenhouse gases.

SOLUTION: Put in the blocks (or sinks) first (**Greenhouse gases**):

- I_{IN} (340 W m^{-2}):
- $I_{REFLECT}$(105 W m^{-2}):
- $I_{GND,abs}$ (165 W m^{-2}):
- $I_{ATMOS,abs}$ (70 W m^{-2}):
- $I_{GND,radiate}$ (390 W m^{-2}):
- $I_{convection}$ (100 W m^{-2}):
- $I_{ATM,radiate}$ (195 W m^{-2}):

in out
Atm (70+350+100=195+325)



Ground In (165+325=490)

Ground Out (350+40+100=490)

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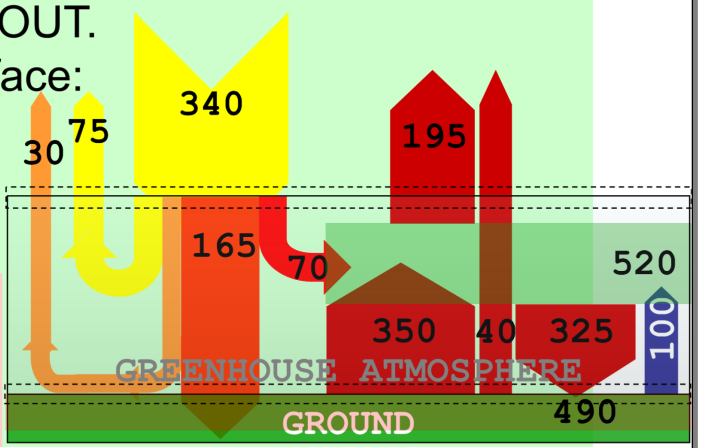
Energy balance in Earth surface / atmosphere system

PRACTICE: Find the net power flow at the space / atmosphere interface and at the ground / atmosphere interface.

SOLUTION:

- Space/atmosphere interface: 340 IN. *Net = 0 W m^{-2}.*
  195 + 75 + 30 + 40 = 340 OUT.
- Ground/atmosphere interface:
  165 + 325 = 490 IN
  350 + 40 + 100= 490 OUT.
  Net = 0 W m^{-2}.



FYI

- This model also shows stable temperatures.

Desirable

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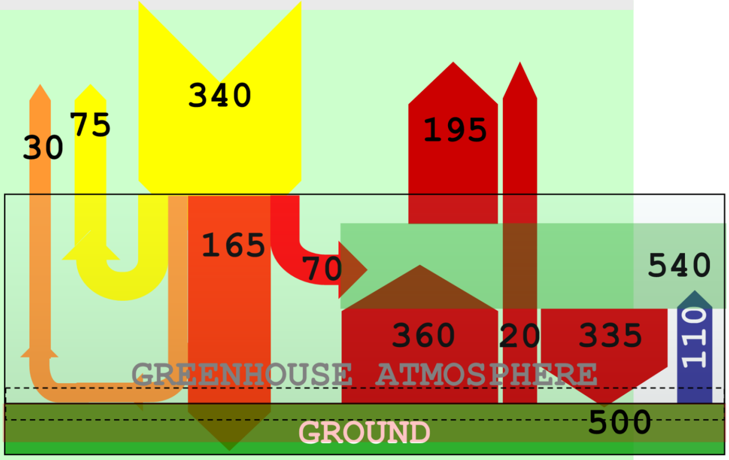
Energy balance in Earth surface / atmosphere system

PRACTICE: Find the net power flow at the ground / atmosphere interface.



SOLUTION:

- We have:

$I_{IN} = 165 + 335$
$= 500\text{ W m}^{-2}$.

$I_{OUT} = 360 + 20 + 110$
$= 490\text{ W m}^{-2}$.

- The net power flow is thus

$I_{IN} - I_{OUT} = 500 - 490 = +10\text{ W m}^{-2}$.

FYI

- This model shows increasing ground temperatures.

Not good for us or the Earth

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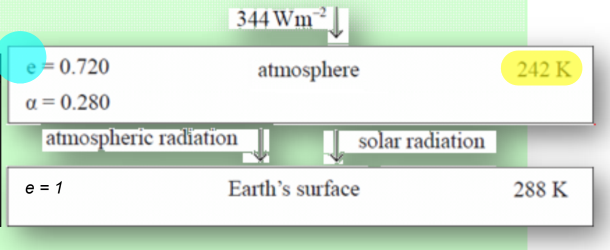
8.2 – Thermal energy transfer

Energy balance in Earth surface / atmosphere system

The diagram shows a simple energy balance climate model in which the atmosphere and the surface of Earth are two bodies each at constant temperature. The surface of the Earth receives both solar radiation and radiation emitted from the atmosphere. Assume that the Earth's surface behaves as a black body.

The following data are available for this model.	
average temperature of the atmosphere of Earth	= 242 K
emissivity, e of the atmosphere of Earth	= 0.720
average albedo, α of the atmosphere of Earth	= 0.280
solar intensity at top of atmosphere	= 344 W m^{-2}
average temperature of the surface of Earth	= 288 K



Use the data to show that the

(i) power radiated per unit area of the atmosphere is 140 W m^{-2}.

- From Stefan-Boltzmann we have $P = e\sigma AT^4$ so that
- Since it is per unit area, $A = 1\text{ m}^2$.

$$\frac{P}{A} = \frac{(0.72)(5.67\times10^{-8})(242)^4}{1} = 140\text{ W m}^{-2}.$$

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Energy balance in Earth surface / atmosphere system

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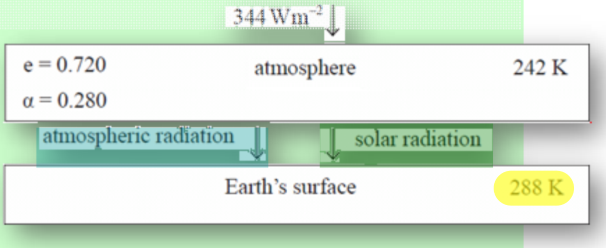

Use the data to show that the

(ii) solar power absorbed per unit area at the surface of the Earth is 248 W m^{-2}.

- $\frac{P}{A} = (1)(5.67\times10^{-8})(288)^4 = 390$ W m^{-2} (amount radiated)
- $\frac{P}{A} = 140$ W m^{-2} (amount absorbed from atmosphere)
- $390 - 140 = 250$ W m^{-2} (amount absorbed from sun).

Without seeing the entire system, conversation rules can be misleading. Use the known information only, for the specific piece of the system you are investigating.

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Energy balance in Earth surface / atmosphere system

The diagram shows a simple energy balance climate model in which the atmosphere and the surface of Earth are two bodies each at constant temperature. The surface of the Earth receives both solar radiation and radiation emitted from the atmosphere. Assume that the Earth's surface behaves as a black body.

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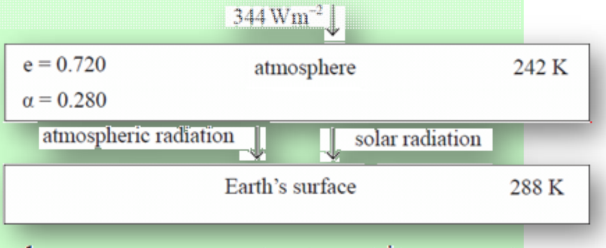

It is hypothesized that, if the production of greenhouse gases were to stay at its present level then the temperature of the Earth's atmosphere would eventually rise by 6.0 K. Calculate the power per unit area that would then be

(iii) radiated by the atmosphere.

- $\frac{P}{A} = (0.72)(5.67\times10^{-8})(242+6)^4 = 154$ W m^{-2}.

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Energy balance in Earth surface / atmosphere system

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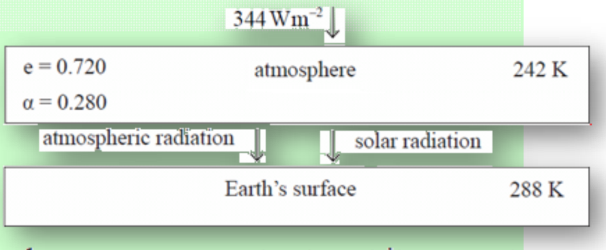

It is hypothesized that, if the production of greenhouse gases were to stay at its present level then the temperature of the Earth's atmosphere would eventually rise by 6.0 K. Calculate the power per unit area that would then be

(iv) absorbed by the Earth's surface.

- Amount absorbed from sun 250 W m^{-2} is still same.
- $\frac{P}{A}$ = 154 W m^{-2} + 250 W m^{-2} = 404 W m^{-2}.

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Energy balance in Earth surface / atmosphere system

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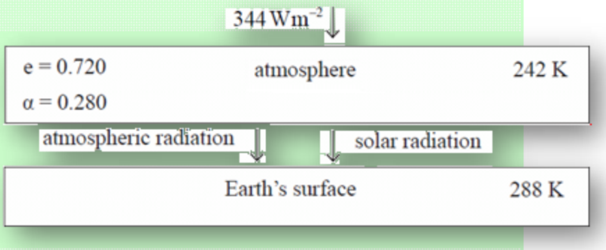

Estimate, using your answer to (iv), the increase in temperature of Earth's surface.

- From Stefan-Boltzmann we have $P = \sigma A T^4$.
- Thus $\frac{P}{A} = \sigma T^4$ or $404 = (5.67\times10^{-8})T^4$, and
- $T = 291$ K, or an increase of $291 - 288 = 3$ K.