DEVIL PHYSICS
THE BADDEST CLASS ON CAMPUS
IB PHYSICS

TSOKOS LESSON 8-2
THERMAL ENERGY TRANSFER


EMISSIVITY DEMO

Essential Idea:

- For simplified modeling purposes the Earth can be treated as a black-body radiator and the atmosphere treated as a grey-body.

Nature Of Science:

- ***Simple and complex modeling:*** The kinetic theory of gases is a simple mathematical model that produces a good approximation of the behavior of real gases. Scientists are also attempting to model the Earth’s climate, which is a far more complex system. Advances in data availability and the ability to include more processes in the models together with continued testing and scientific debate on the various models will improve the ability to predict climate change more accurately.

International-Mindedness:

- The concern over the possible impact of climate change has resulted in an abundance of international press coverage, many political discussions within and between nations, and the consideration of people, corporations, and the environment when deciding on future plans for our planet. IB graduates should be aware of the science behind many of these scenarios.

Theory Of Knowledge:

- The debate about global warming illustrates the difficulties that arise when scientists cannot always agree on the interpretation of the data, especially as the solution would involve large-scale action through international government cooperation.
- When scientists disagree, how do we decide between competing theories?

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

Applications And Skills:

- Sketching and interpreting graphs showing the variation of intensity with wavelength for bodies emitting thermal radiation at different temperatures
- Solving problems involving the Stefan–Boltzmann law and Wien's displacement law

Applications And Skills:

- Describing the effects of the Earth's atmosphere on the mean surface temperature
- Solving problems involving albedo, emissivity, solar constant and the Earth's average temperature

Guidance:

- Discussion of conduction and convection will be qualitative only
- Discussion of conduction is limited to intermolecular and electron collisions
- Discussion of convection is limited to simple gas or liquid transfer via density differences

Guidance:

- The absorption of infrared radiation by greenhouse gases should be described in terms of the molecular energy levels and the subsequent emission of radiation in all directions
- The greenhouse gases to be considered are CH_4, H_2O, CO_2 and N_2O. It is sufficient for students to know that each has both natural and man-made origins.

Guidance:

- Earth’s albedo varies daily and is dependent on season (cloud formations) and latitude. The global annual mean albedo will be taken to be 0.3 (30%) for Earth.

Data Booklet Reference:

$$P = e\sigma A T^4$$

$$\lambda_{\max}(meters) = \frac{2.9x10^{-3}}{T(kelvin)}$$

$$I = \frac{power}{A}$$

$$albedo = \frac{total \sim scattered \sim power}{total \sim incident \sim power}$$

Utilization:

- Climate models and the variation in detail/processes included
- Environmental chemistry (see Chemistry option topic C)
- Climate change (see Biology sub-topic 4.4 and Environmental systems and societies topics 5 and 6)
- The normal distribution curve is explored in Mathematical studies SL sub-topic 4.1

Aims:

- Aim 4: this topic gives students the opportunity to understand the wide range of scientific analysis behind climate change issues
- Aim 6: simulations of energy exchange in the Earth surface–atmosphere system

Aims:

- Aim 8: while science has the ability to analyse and possibly help solve climate change issues, students should be aware of the impact of science on the initiation of conditions that allowed climate change due to human contributions to occur. Students should also be aware of the way science can be used to promote the interests of one side of the debate on climate change (or, conversely, to hinder debate).

Introductory Video

Reading Activity Questions?

Thermal Energy Transfer

- Three Types:
  - Conduction
  - Convection
  - Radiation

Thermal Energy Transfer

- Three Types:
  - Conduction: high temperature on one side of a solid mean electrons have higher kinetic energy and molecules a higher vibrational energy. Electrons pass kinetic energy through collisions, molecules by ‘tugging’ along molecular bonds
  - Convection
  - Radiation

$$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{L}$$

Thermal Energy Transfer

- Three Types:
  - Conduction
  - Convection: heat transfer through a liquid or gas due to expansion
  - Radiation

Thermal Energy Transfer

- Three Types:
  - Conduction
  - Convection
  - Radiation: only transfer method that doesn't require a medium, it involves the emittance and absorption of electromagnetic energy

Black Body Law

- All bodies that are kept at some absolute (Kelvin) temperature radiate energy in the form of electromagnetic waves
- The power radiated by a body is governed by the Stefan-Boltzmann Law

Stefan-Boltzmann Law

- The amount of energy per second (power) radiated by a body depends on its surface area *A*, absolute (Kelvin) temperature *T*, and the properties of the surface (emissivity, *e*)

$$P = e\sigma A T^4$$

- This is the Stefan-Boltzmann Law
- σ is the Stefan-Boltzmann constant

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

Emissivity

Surface	Emissivity
Black body	1
Ocean water	0.8
Ice	0.1
Dry land	0.7
Land with vegetation	0.6

- Dimensionless number from 0 to 1 that states a surface's ability to radiate energy
- For a theoretical perfect emitter, a *black body*, e = 1
- Dark and dull surfaces will have a higher emissivity
- Light and shiny surfaces will have a lower emissivity


EMISSIVITY DEMO

Net Power

- A body that radiates power will also absorb power with the same emissivity values
- Net power is the difference between the two
- At equilibrium, $P_{net} = 0$ and the body loses as much energy as it gains, the temperature remains constant and equal to its surroundings

$$P_{net} = P_{out} - P_{in} = e\sigma A\left(T_1^{\,4} - T_2^{\,4}\right)$$

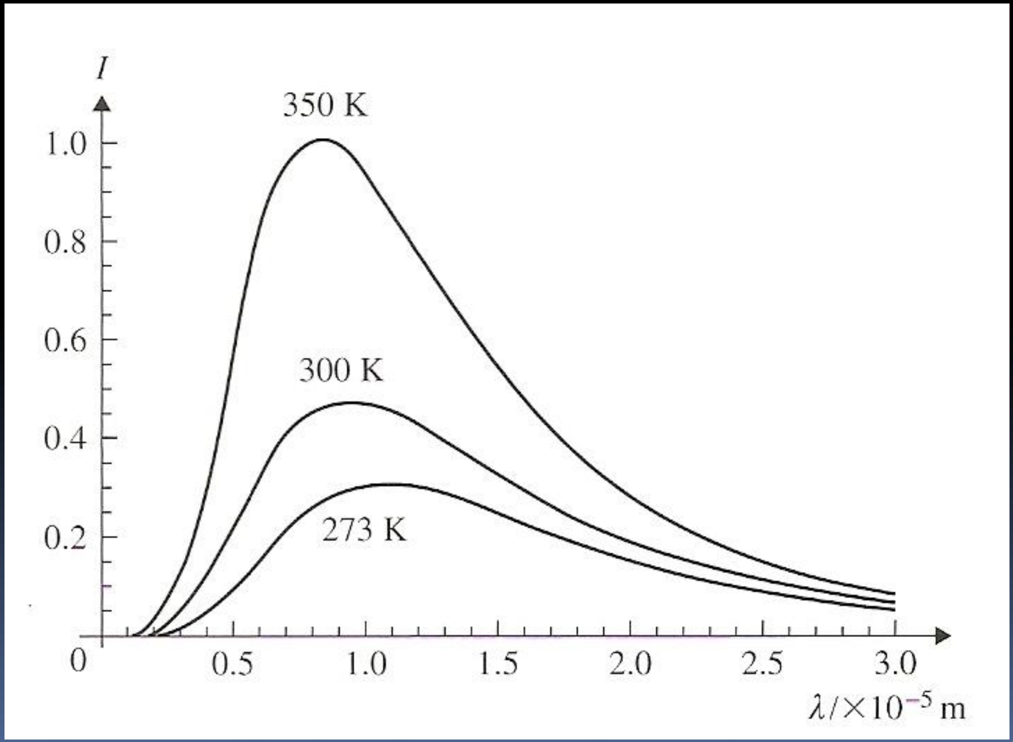
Net Power

- At equilibrium, Pnet = 0 and the earth as a ***system*** maintains constant ***average*** temperature
- If the power absorbed is greater than the power radiated, the earth system increases in temperature

$$P_{net} = P_{out} - P_{in} = e\sigma A\left(T_1^{\,4} - T_2^{\,4}\right)$$

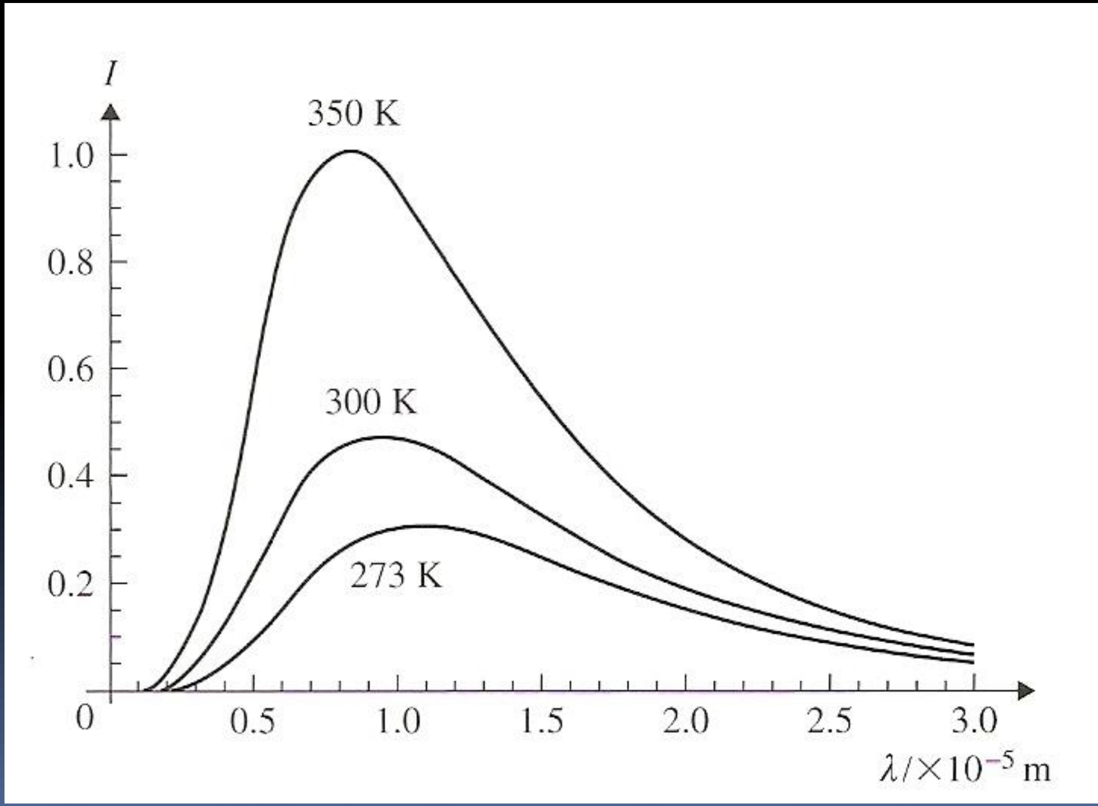
Emitted Radiation Wavelength

- Black-body radiation is emitted over an infinite range of wavelengths, BUT
- Most is emitted at a specific wavelength depending on the body's temperature
- Higher temperature, lower wavelength, higher frequency



Emitted Radiation Wavelength

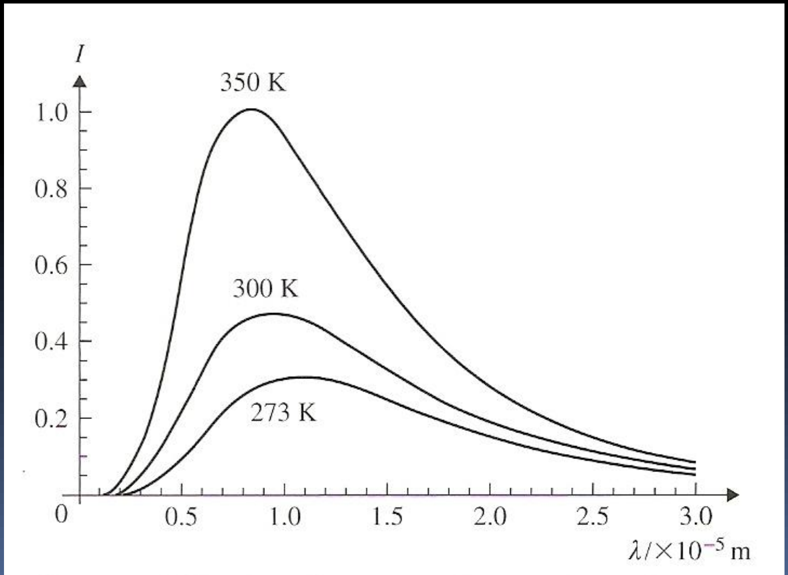
- Most of the energy emitted is an infrared wavelength
- That is why we associate emitted radiation with heat



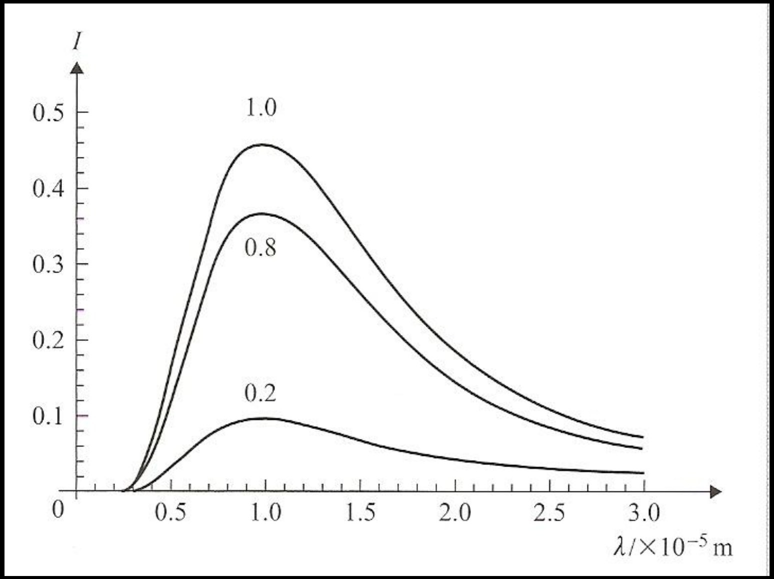
Wien's Law

- The relationship between the peak temperature and the peak wavelength (wavelength at which most of the energy is emitted) is given by

$$\lambda T = 2.90x10^{-3}\, m \cdot K$$



Emitted Radiation vs Emissivity



- Graph of intensity versus wavelength for bodies with the same temperature, but different values of emissivity
- Peak of the curve remains the same, but slope of the curve increases with increased emissivity

Solar Radiation

- Sun is considered a perfect emitter, i.e. a black-body
- Sun’s power output is 3.9×10^{26} W
- The earth receives only a small fraction of this power equal to

$$\frac{a}{4\pi d^2}$$

- Where *a* is the area used to collect the power and d is the earth-to-sun distance

Intensity

- Power of radiation received per unit area of the receiver

$$I = \frac{P}{4\pi d^2}$$

Solar Constant

- Substituting values into the intensity equation we get

$$I = \frac{P}{4\pi d^2}$$

$$I = S = \frac{3.9x10^{26}}{4\pi\left(1.5x10^{11}\right)^2} = 1400Wm^{-2}$$

- Which is the ***solar constant***, S
- $S \approx 1400\ Wm^{-2}$
- ***This is the intensity of the sun reaching the earth's atmosphere, NOT the surface!***

Solar Constant

- If intensity is power per unit area, then power received is equal to intensity times the area of the receiver

$$I = \frac{P}{A}$$

$$P = IA$$

Albedo

- Ratio of radiation power reflected to the power incident on a body

$$\alpha = \frac{total.scattered / reflected.power}{total.incident.power}$$

- Light-colored, shiny objects have a high albedo, dark and dull objects have low albedo
- ***The earth as a whole has an average albedo of 0.3***

Emissivity

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Dry land	0.7
Land with vegetation	0.6

- Dimensionless number from 0 to 1 that states a surface's ability to radiate energy
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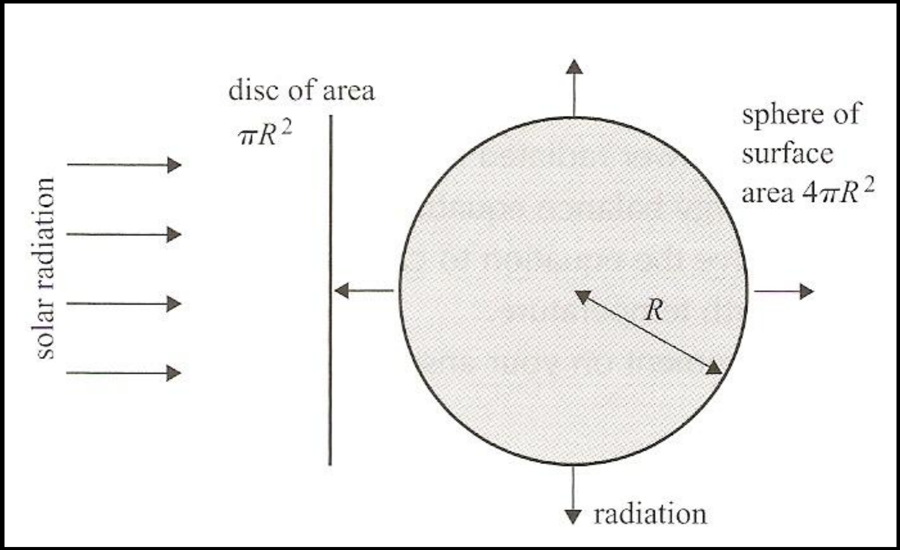
EMISSIVITY DEMO

Intermediate Summary

- A portion of the Sun's power reaches the earth
- Part of that power is reflected, part is absorbed (≈ 30%/70%)
- When a body absorbs energy, the kinetic energy of its molecules increases and temperature increases
- All bodies emit black body radiation which is proportional to temperature
- Constant temperature occurs when $P_{net} = 0$

Radiation Reaching the Earth

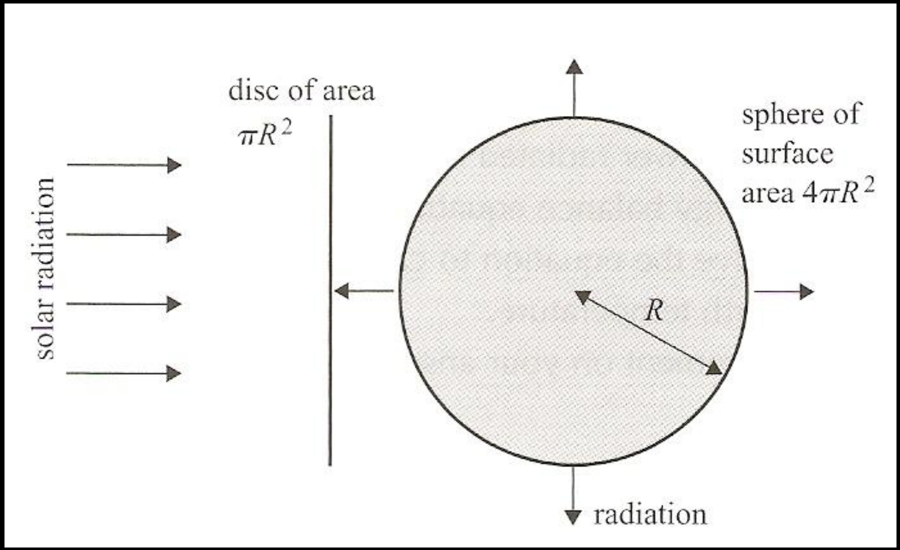
- The solar constant, S = 1400 W/m², is the amount of solar power striking a given area of the atmosphere



- At any given time, the area of the earth's surface exposed to this radiation is equal to the area of a circle, πR^2, using the radius of the earth

Radiation Reaching the Earth

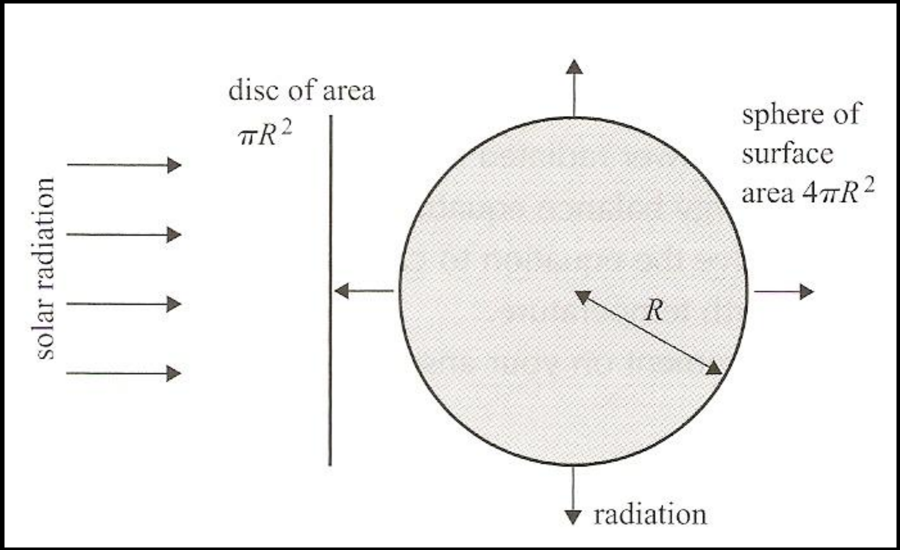
- The total surface area of a sphere is $4\pi R^2$, so the 'exposure' area is only 1/4th the surface area of the earth
- Therefore, the radiation received per square meter on the surface of the earth at any given time is,



$$\frac{S}{4} = 350 W / m^2$$

Radiation Reaching the Earth

- Since 30% of this energy is reflected (albedo = 0.3, the actual radiation the Earth's surface receives at any given moment is



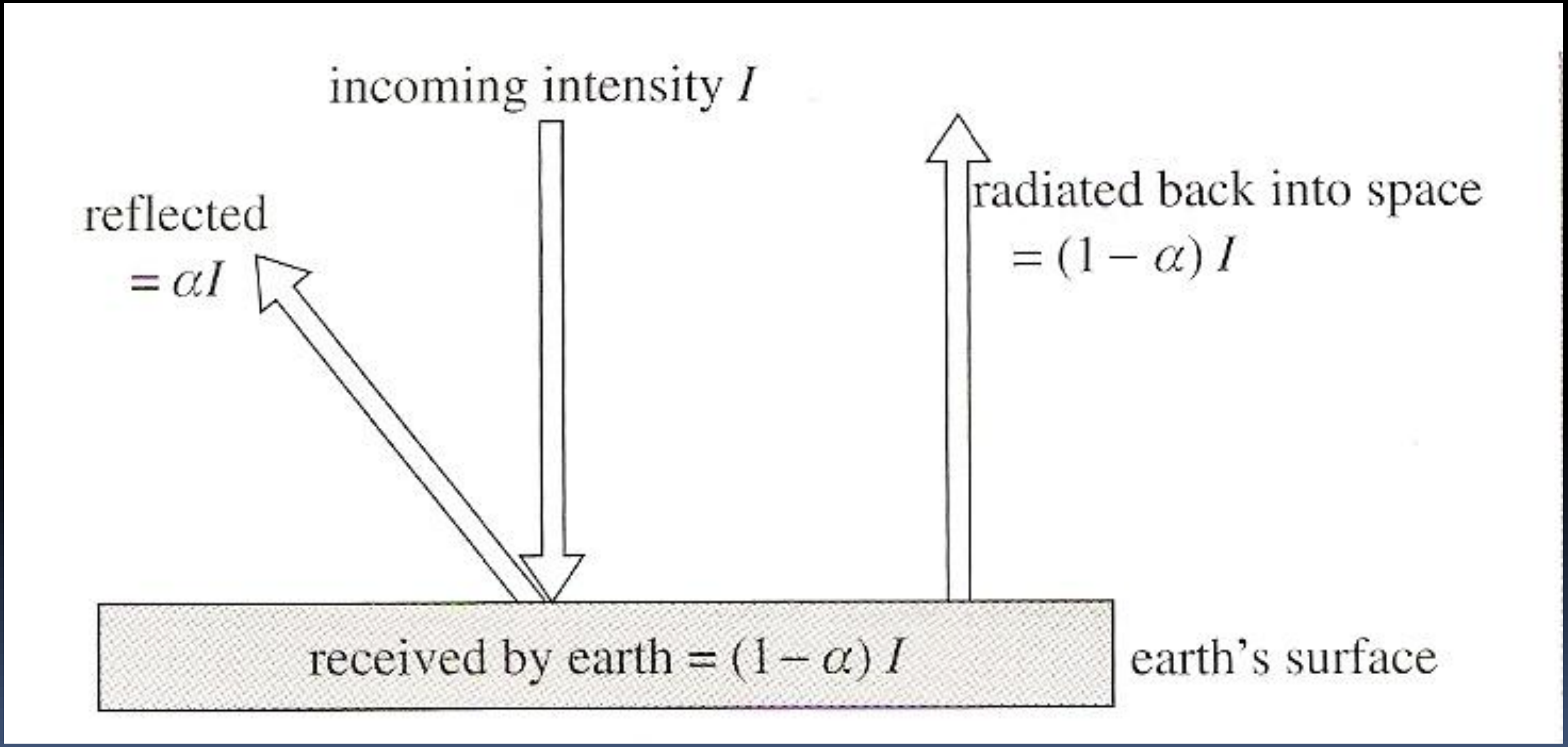
$$350x0.70 = 245W / m^2$$

Energy Balance

- The earth has a more or less constant average temperature and behaves like a black body
- Therefore, the energy input to the earth must equal (balance) the energy radiated into space

Energy Balance

- Simplified Energy Diagram



Energy Balance

- Problems with the Simplified Energy Diagram
  - Not all of the earth's radiated energy escapes the atmosphere
  - Some of the energy is absorbed by the atmosphere and re-radiated back toward the earth (this is the greenhouse effect)

Energy Balance

- Problems with the Simplified Energy Diagram
  - Model fails to consider other interactions with the atmosphere:
    - Latent heat flows
    - Thermal energy flows in oceans by currents
    - Thermal energy transfers (essentially conduction) between the surface and the atmosphere due to temperature differences

Greenhouse Effect

- Most of the solar radiation reaching earth is in the visible wavelength band
- The atmosphere only reflects about 30% of this
- The average temperature of the earth's surface is 288K
- Using Wien's Law, the radiation emitted by the earth is in the infrared wavelength range

Greenhouse Effect

- Remember from the photoelectric effect and quantum physics that energy is dependent on wavelength and molecular energy absorption and emission are dependent on energy levels
- Certain gases in the atmosphere (***greenhouse gases***) will allow the sun's visible light to pass through, but will absorb the earth's radiated infrared energy (emission/absorption spectrum)

Greenhouse Effect

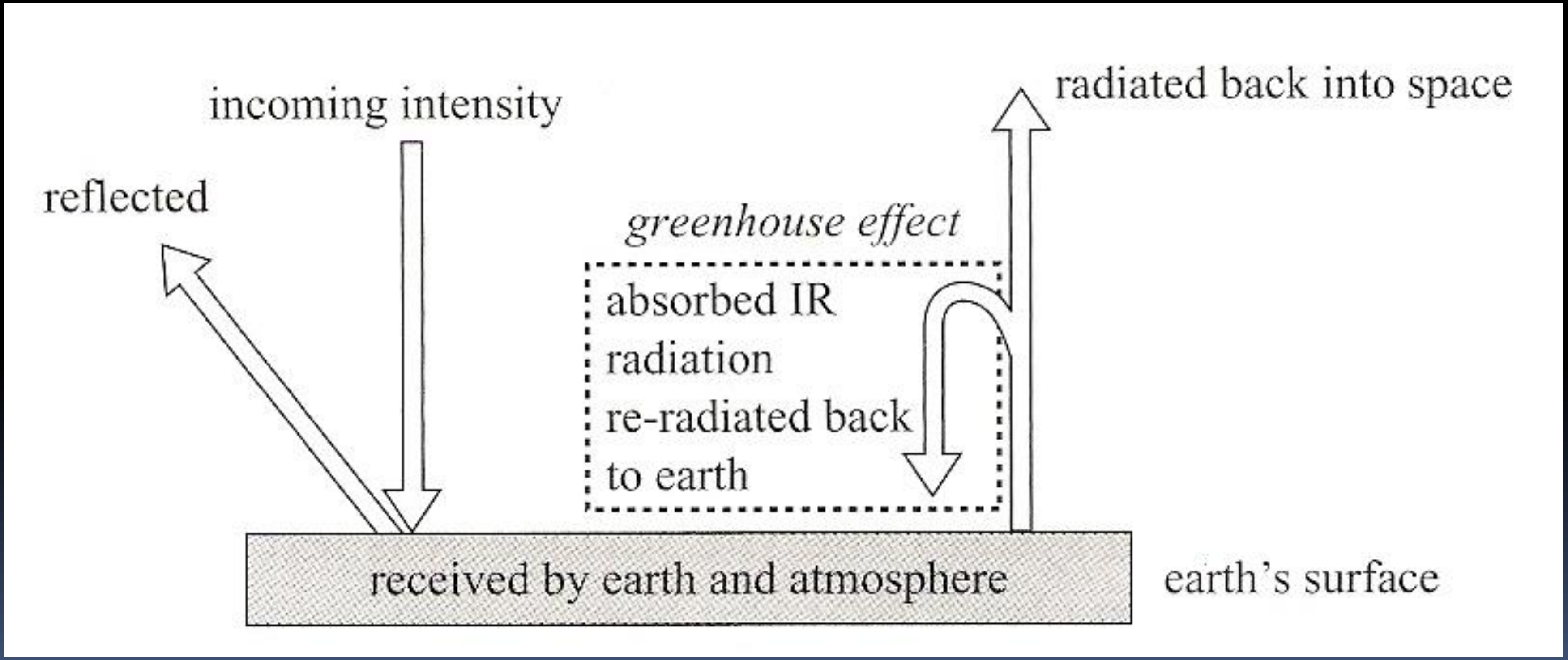
- The absorbed energy is quickly re-radiated in all directions (as from a sphere)
- Some of that energy is re-radiated back to the earth’s surface providing added warmth

Greenhouse Effect

- The Greenhouse Effect is a good thing
  - With the greenhouse effect the average temperature is 288 K / 15°C / 59°F
  - Without the greenhouse effect the average temperature is estimated to be 256 K / -17°C / 1°F
- Primary greenhouse gases are water vapour, carbon dioxide, methane and nitrous oxide

Greenhouse Effect

- Energy Diagram Including Greenhouse Effect

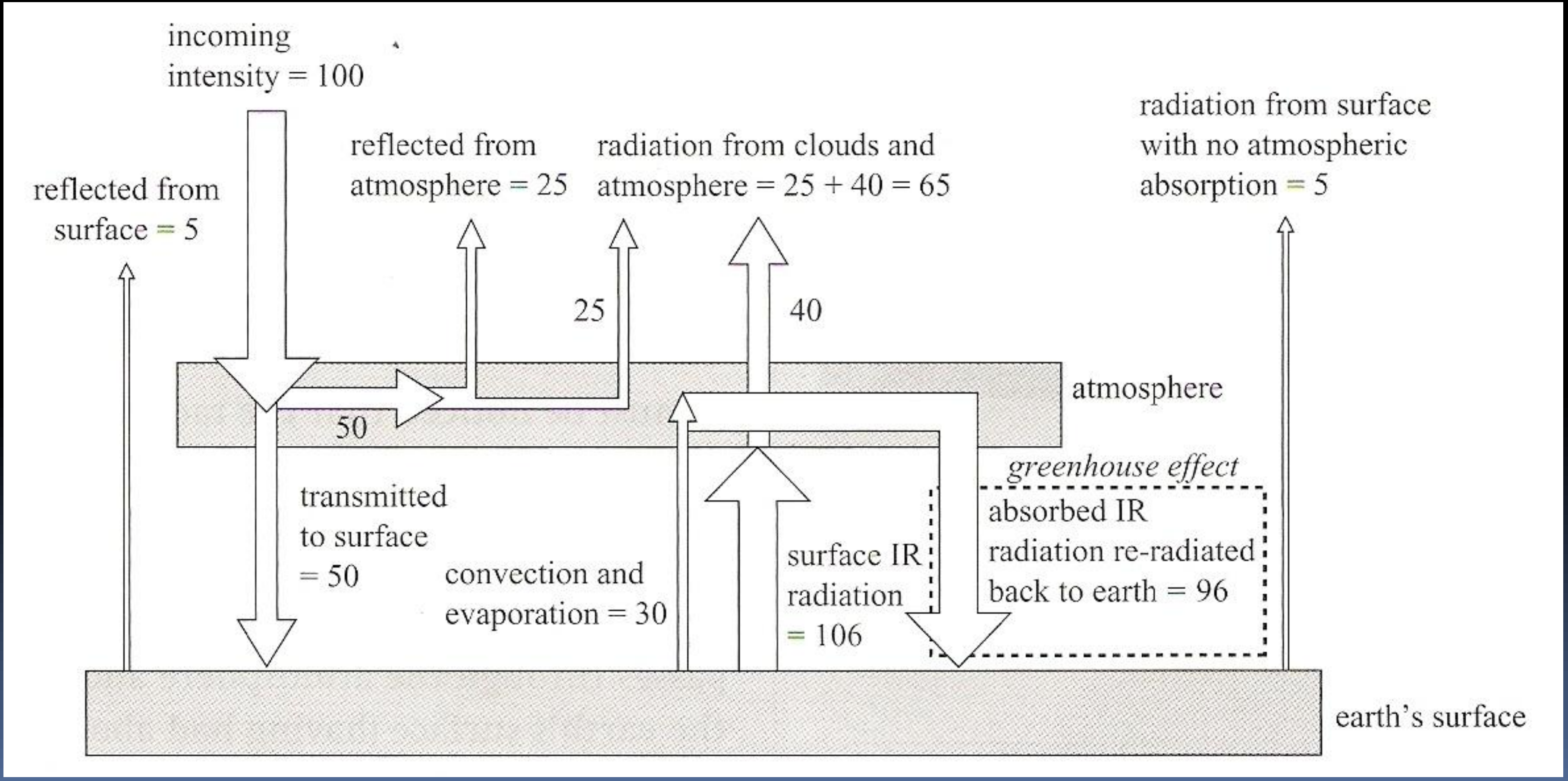


Greenhouse Effect

- Even this diagram doesn't include:
  - Latent heat flows
  - Thermal energy flows in oceans by currents
  - Thermal energy transfers (essentially conduction) between the surface and the atmosphere due to temperature differences

Greenhouse Effect

- All-Encompassing Energy Diagram



Enhanced Greenhouse Effect

- Unlike laundry detergent, enhanced is not necessarily better
- Greenhouse gases keep the earth warm and toasty, but if we increase the amount of greenhouse gases, the place gets downright hot
- More greenhouse gases means more energy radiated from the atmosphere back to the earth which means higher temperatures

Enhanced Greenhouse Effect

- Greenhouse gases have natural as well as ***anthropogenic*** (geek speak for *man-made*) sources

Enhanced Greenhouse Effect

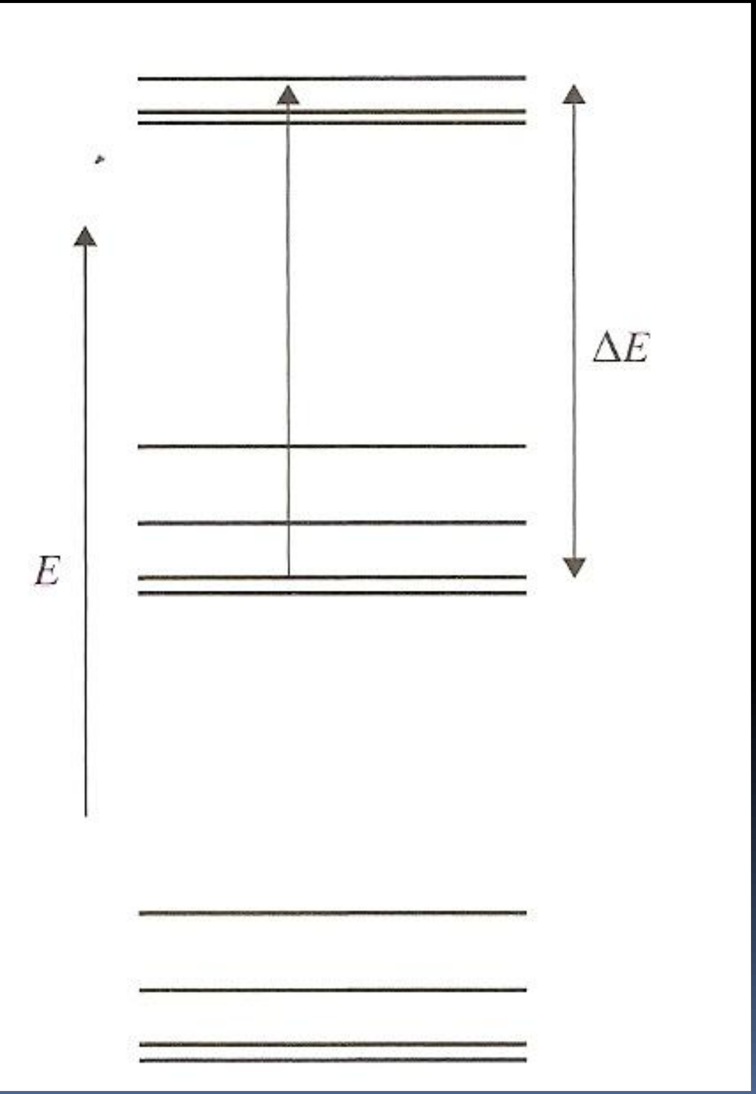
Greenhouse gas	Natural sources	Anthropogenic sources
H_2O (water vapour)	evaporation of water from oceans, rivers and lakes	
CO_2 (carbon dioxide)	forest fires, volcanic eruptions, evaporation of water from oceans	burning fossil fuels in power plants and cars, burning forests
CH_4 (methane)	wetlands, oceans, lakes and rivers	flooded rice fields, farm animals, termites, processing of coal, natural gas and oil, and burning biomass
N_2O (dinitrogen oxide, nitrous oxide)	forests, oceans, soil and grasslands	burning fossil fuels, manufacture of cement, fertilizers, deforestation (reduction of nitrogen fixation in plants)

Enhanced Greenhouse Effect

- On the upside, there are ***sinks*** (mechanisms for removal) for greenhouse gases
  - Carbon dioxide absorbed by plants during photosynthesis and dissolved in oceans
  - Methane is destroyed in lower atmosphere by chemical reactions with hydroxyl radicals
  - Nitrous oxide destroyed in the atmosphere by photochemical reactions

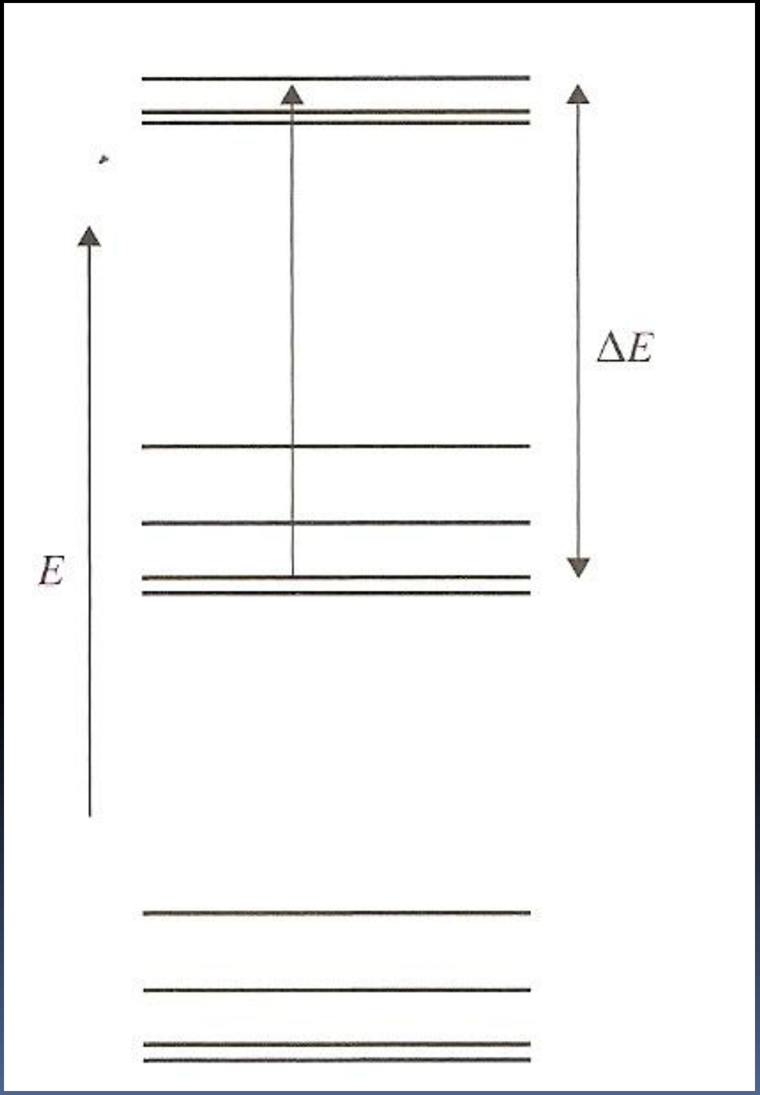
Mechanism of Photon Absorption

- Energy of molecules due to their vibrational and rotational motion is quantized like the energy levels of electrons
- In greenhouse gases, the energy levels of the molecules corresponds to the energies of the infrared photons



Mechanism of Photon Absorption

- Molecules will absorb these photons and be excited to higher energy levels
- GG molecules, however, are a lot like an IB student on a Saturday morning, i.e. they prefer the lower energy state and emit the photon back out into the atmosphere



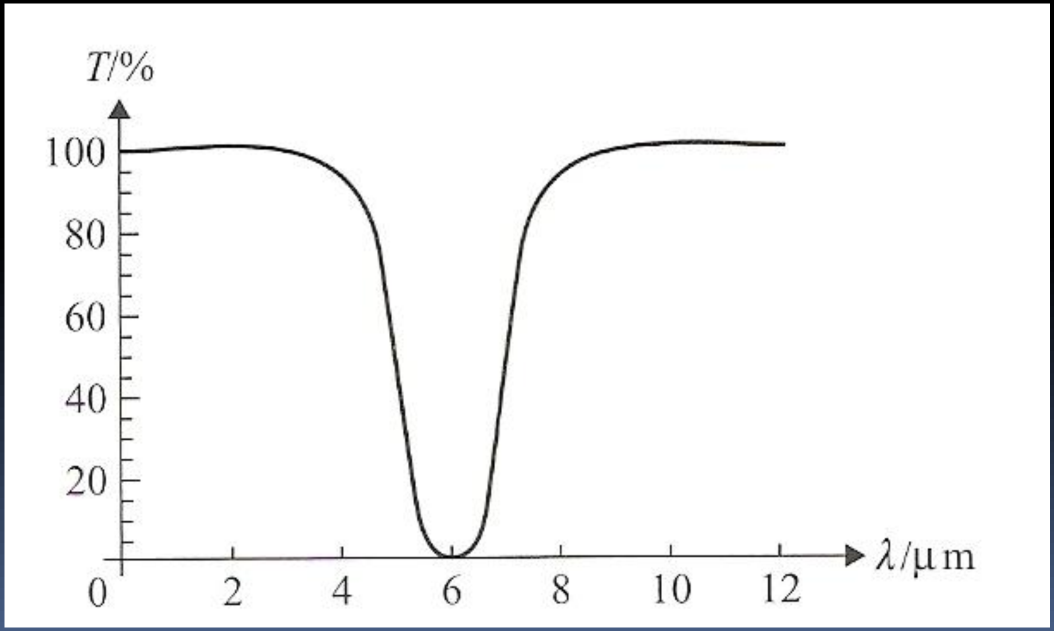
Mechanism of Photon Absorption

- The atoms of a GG molecule can be thought of as being connected by bi-directional springs
- The molecules oscillate back and forth at their ***natural frequency***
- Photons traveling (wave properties) with a frequency close to the natural frequency of a molecule will be absorbed

REMAINING SLIDES ARE EXTENDED INFORMATION – TIME PERMITTING

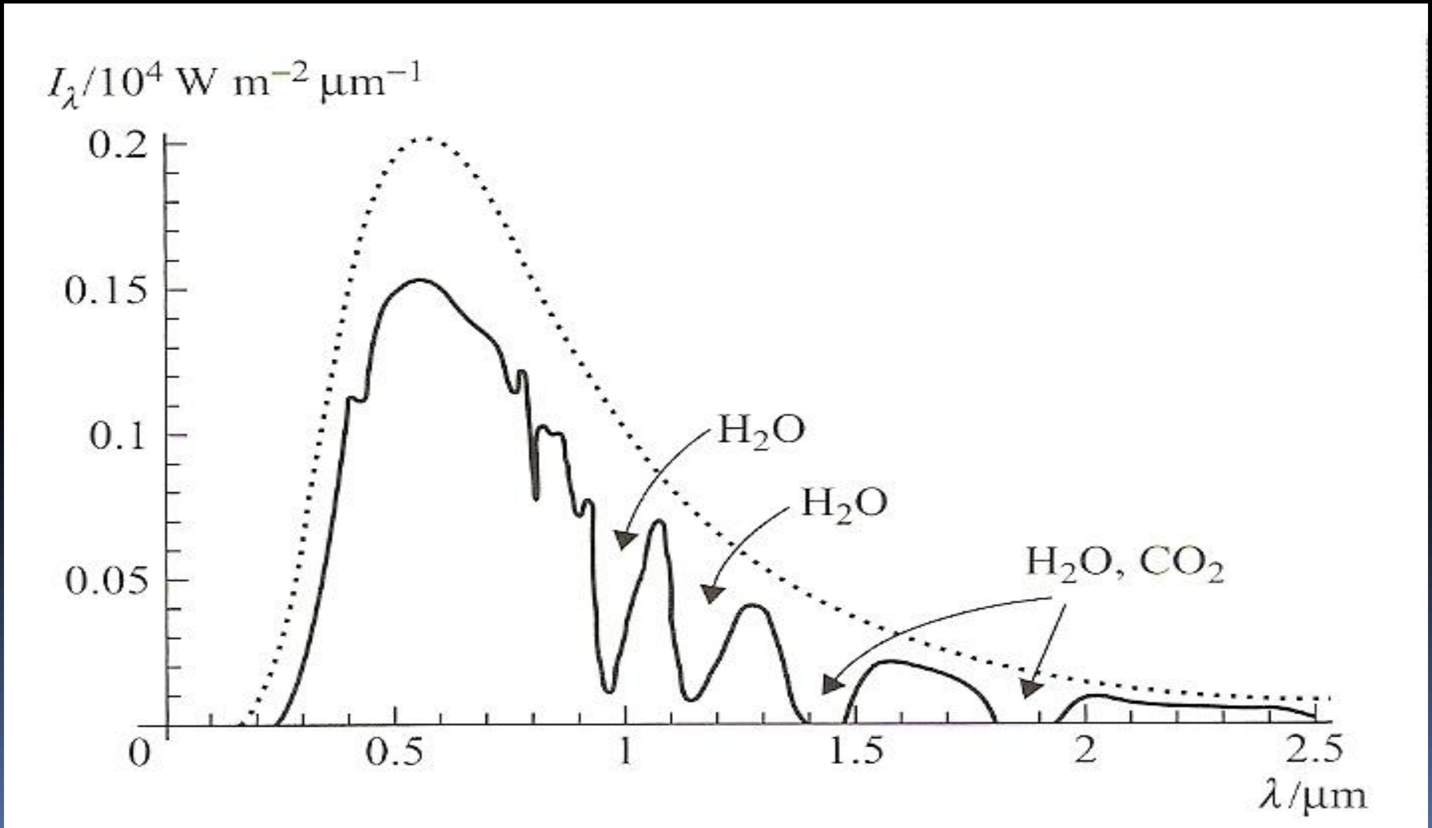
Transmittance Curves

- Transmittance curves show what percent of radiation will be transmitted through a gas without absorption for a given wavelength



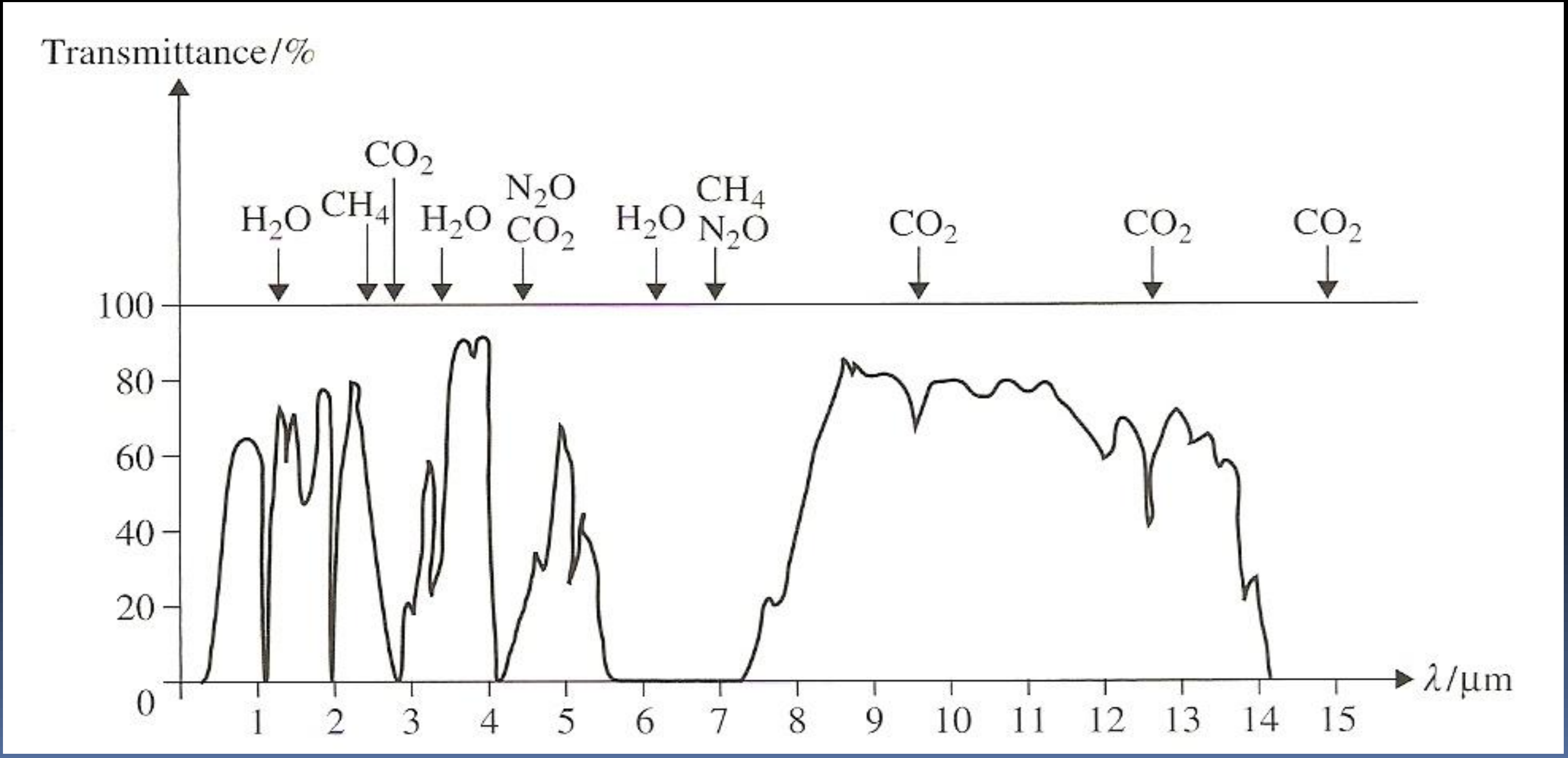
Transmittance Curves

- This curve shows the sun's intensity that is incident on the atmosphere (dotted line) and what is actually observed on the earth surface (solid line)



Transmittance Curves

- This curve shows the transmittance of the earth's infrared radiation and the gases that absorb the energy at various wavelengths



Surface Heat Capacity (C_S)

- The energy required to increase the temperature of **1 m²** of a surface by 1 K

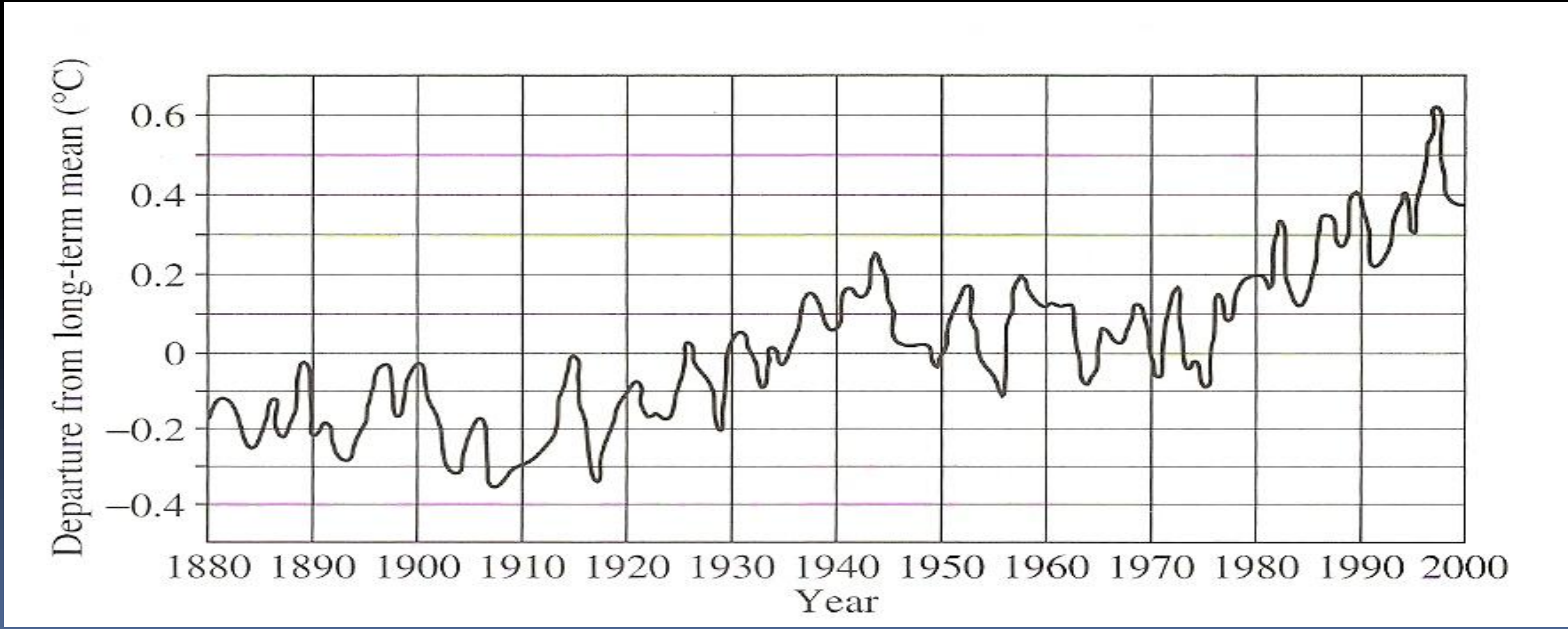
$$Q = AC_S \Delta T$$

$$\Delta T = \frac{(I_{in} - I_{out})t}{C_S}$$

$$\frac{dT}{dt} = \frac{(I_{in} - I_{out})}{C_S}$$

Global Warming

- Graph below shows deviation of the earth's global average surface temperature from the ***expected long-term average***

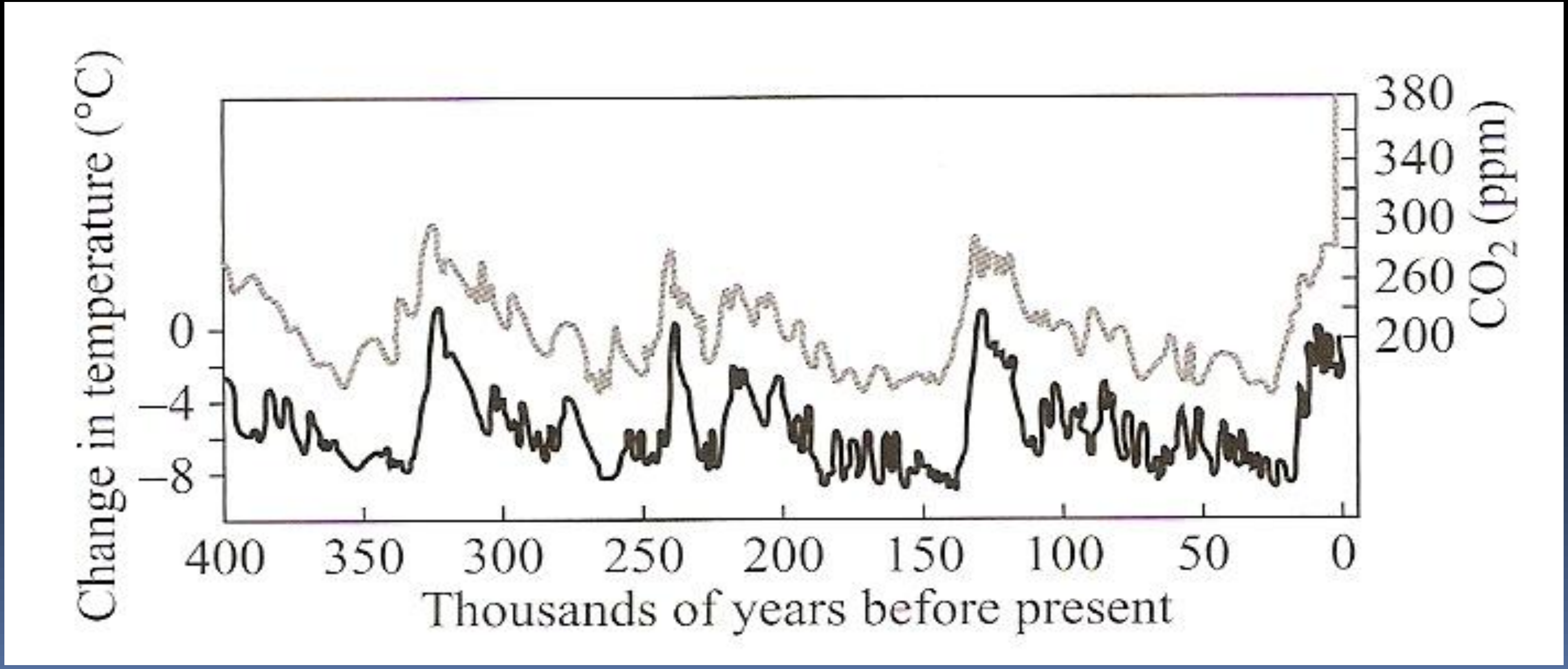


Global Warming

- The graph shows that concentrations of carbon monoxide, methane, and nitrous oxide in the atmosphere have shown a dramatic increase
- This corresponds to the temperature increases shown in the previous slide
- This data is supported by analysis of ice cores from Antarctica and Greenland that show a correlation between greenhouse gas concentrations and atmospheric temperature

Global Warming

- The graph below shows global average temperatures and CO2 concentrations over the last 400,000 years relative to present temperatures and levels



Global Warming - Questions

- *What is the best estimate for the temperature increase over a given period of time?*
- *What will be the effects of a higher temperature on the amount of rainfall?*
- *How much ice will melt?*
- *What will be the rise in sea level?*
- *Will there be areas of extra dryness and drought and if so, where will they be?*

Global Warming - Questions

- *Will the temperature of the oceans be affected and if so, by how much?*
- *Will ocean currents be affected and if so, how?*
- *Will there be periods of extreme climate variability?*
- *Will the frequency and intensity of tropical storms increase?*
- *What is the effect of sulphate aerosols in the atmosphere? Do they offset global warming?*

Global Warming - Questions

- *What are the feedback mechanisms affecting global climate?*
- *Can the observed temperature increase be blamed on greenhouse gases exclusively?*
- *Given the long lifetime of carbon dioxide in the atmosphere, can the process of global warming be reversed even if present emissions are drastically reduced?*

Global Warming - Questions

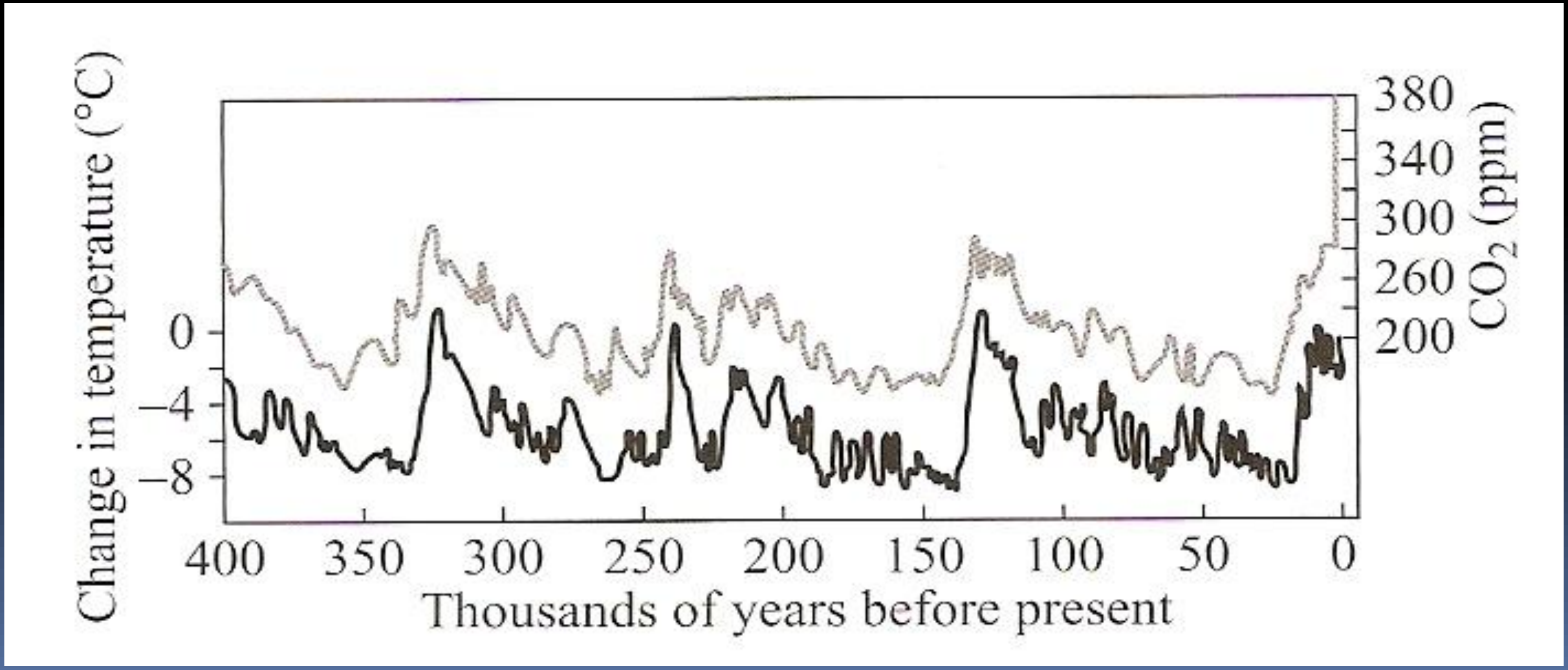
- *What are the ecological implications of the expected changes in the habitats of many species?*
- *What will be the effects on agriculture?*
- *Will there be more diseases?*
- *What are the social and economic effects of all of the above?*
- *Will it be enough to keep people from Ohio from coming to Florida to complain?*

Global Warming – Other Possibilities

- Increased solar activity
- Increased greenhouse gases due to volcanic activity
- Changes in the earth's orbit (both eccentricity and tilt)

Global Warming – Other Possibilities

- Spike in the cycle



Sea Level

- Sea level varies naturally due to:
  - Atmospheric pressure
  - Plate tectonic movements
  - Wind
  - Tides
  - River flow
  - Changes in salinity
  - Etc.

Sea Level

- *Changes in sea level affect the amount of water that can evaporate and the amount of thermal energy that can be exchanged with the atmosphere.*
- *In addition, changes in sea level affect ocean currents.*
- *The presence of these currents is vital in transferring thermal energy from the warm tropics to colder regions.*

Melting Ice

- Important to distinguish between land ice and sea ice
  - Melting sea ice will not change sea levels (thanks Mr. Archimedes)
  - Land ice will result in an increase in sea level
- Overall, warmer temperatures result in a rise in sea level due to melted land ice and the expansion of water due to warmer temperatures

Melting Ice

- Remember the anomalous behavior of water between 0° and 4°C?
- As it is heated from 0° to 4°C, it will contract, then expand as temperature exceeds 4°C
- The change in volume of a given mass of water is given by,

$$\Delta V = \gamma V_0 \Delta \theta$$

Melting Ice

- The change in volume of a given mass of water is given by,

$$\Delta V = \gamma V_0 \Delta \theta$$

- The coefficient of thermal expansion, γ, for water is dependent on temperature
- Thus, the change in volume will be different, even if the temperature change ($\Delta\theta$) is the same depending on the initial temperature

Effects of Global Warming on Climate

- Higher average global temperature means a higher sea level
- Higher sea level means greater area covered by water (low albedo), less area covered by land (higher albedo)
- This lowers the overall earth albedo which means more energy is absorbed which in turn increases temperature
- This is an example of a positive feedback mechanism

Effects of Global Warming on Climate

- Higher sea level means increase in evaporation rate
  - Cooling of earth's surface due to more energy removed for evaporation process
  - More cloud cover which means more reflected energy which means more cooling
  - More precipitation – may promote more vegetation
- Another example of a negative feedback mechanism

Effects of Global Warming on Climate

- Higher water temperatures decreases ability of sea water to dissolve carbon dioxide
- More carbon dioxide in the atmosphere enhances the enhanced greenhouse effect and increases temperature

Effects of Global Warming on Climate

- Do we really need to save the rainforests?
  - Rainforests absorb carbon dioxide
  - But that carbon dioxide is released when the trees die and decompose
  - Rainforests produce methane which is a greenhouse gas that enhances the enhanced greenhouse effect
  - In general, cutting down a rainforest will increase albedo which will lower temperatures

Measures to Reduce Global Warming

- Focus is on reducing carbon dioxide
  - Fuel efficient, hybrid and electric cars
  - Increase efficiency of coal-burning power plants
  - Replace coal-burning with natural gas-fired power plants
  - Consider methods of capturing and storing the carbon dioxide produced in power plants
  - Increasing the amounts of power produced by wind and solar generators
  - Increased use of nuclear power

Measures to Reduce Global Warming

- Focus is on reducing carbon dioxide
  - Being energy conscious with buildings, appliances, transportation, industrial processes and entertainment
  - Stopping deforestation

Fool-Proof Methods of Reducing Greenhouse Gas Production

- Global Ban on Mexican Food
- Global Ban on all Forms of Exercise
- Limit Political Speeches to 2 minutes
- Increase sleep rates by 80%
- Eliminate undesirables

And the measure with the highest potential for success . . .

Fool-Proof Methods of Reducing Greenhouse Gas Production

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- ***World-Wide Hold Your Breath Day***

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Essential Idea:

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QUESTIONS?

Homework

#26-44