

The Big Idea:

The observed global warming on Earth is a manifestation of the Second Law of Thermodynamics. The Earth operates like any heat engine. The input heat in from solar radiation and the exhaust heat (terrestrial radiation) largely determine the operating temperature (global surface temperature). Over geological periods this heat exchange reaches equilibrium and the temperature is stable. If the input heat increases or the exhaust heat decreases the temperature rises and vice versa. Natural processes over geologic time have changed the input and affected both output heat and temperature. In the present era the quantity of exhaust heat is being rapidly restricted by the *greenhouse effect* and consequently the temperature must rise to reach a higher equilibrium temperature. How much higher depends entirely on human activity.

The input heat, solar energy received, is a function of solar activity and oscillations in characteristics of the Earth's orbit

The quantity of exhaust heat, terrestrial radiation, is largely a function of the presence of certain gases in the atmosphere that absorb outgoing infrared radiation. This is known as the *greenhouse effect*. The greenhouse effect is due to the differential absorption of certain wavelengths of solar as compared to terrestrial radiation.

The solar energy reaching the surface of the Earth is concentrated in short wavelengths, which can easily penetrate the greenhouse gases, such as Carbon Dioxide and Methane. The Earth, however, is cooler than the sun and it radiates its heat in the form of energy in the far infrared range. These longer wavelengths are partially absorbed by the greenhouse gases and some of the solar heat is returned to Earth. At a certain temperature these processes are in equilibrium and the surface temperature of the Earth is stable. However, if more greenhouse gases are put in the atmosphere the amount of trapped terrestrial radiation increases, leading to an increase in global temperature.

Currently the heating effect of extra greenhouse gases (since the start of the industrial revolution) is equal to about 1.0 W/m². Thus the recent period has recorded parallel increases in concentration of carbon dioxide and average global temperature. As more greenhouse gases are put into the atmosphere the temperature will increase further. There are certain effects of a warmer Earth (discussed below) which could accelerate the process, even if no more greenhouse gases are put into the atmosphere (an unlikely prospect for the foreseeable future).



The Key Concepts (Possible Effects That Can Accelerate Global Warming):

1. **Time Lag:** The excess energy warms the ocean very slowly, due to water's high heat capacity. Even in the unlikely event that no more greenhouse gases are added to the atmosphere the temperature increase already measured will be almost doubled.

2. **The Effect of Water Vapor:** Increasing temperatures will lead to more evaporation and more water vapor in the atmosphere. Water vapor is a greenhouse gas and its increased presence may cause further warming in a positive feedback loop. On the other hand if the water vapor results in more clouds more solar radiation will be reflected, a possible negative feedback.

3. **Albedo** is the amount of light reflected by a surface. Sea ice has an albedo of .85, meaning 85% of light is reflected back from its surface (and leaves the Earth) and 15% is absorbed and stays in the Earth; ice-free water has an albedo of .07. (93% of the solar energy is absorbed.) Thus the observed melting of sea ice could amplify the effect of global warming

4. The **melting of the Artic Permafrost** also has an amplifying effect by releasing carbon dioxide and methane that is normally trapped in the tundra.

5. Warmer oceans are hostile to **algae and cytoplankton**, which are the most important absorbers of carbon dioxide. The loss of the these two photosynthesizers would remove the most important natural CO_2 sink.

6. Loss of Rain Forests would have a similar effect. Global warming is likely to lead to desertification of the habitats of rain forests. The rain forest is the second most important CO_2 sink.

The Key Concepts (Physics Laws and Observations):

1. The relationship between temperature of a body and its radiation wavelength is given by **Wien's Law**: For any body that radiates energy the wavelength of maximum energy radiated is inversely related to the temperature.

2. The effect of global warming on the solubility of Carbon Dioxide (CO_2) and methane (CH4) is governed by two laws that partly contravene each other. **Henry's Law:** The solubility of a gas is directly proportional to the partial pressure of that gas. The constant of proportionality is Henry's Law Constant. This constant of proportionality is temperature dependent and decreases as temperature increases. Therefore as carbon dioxide increases in the atmosphere the partial pressure of CO_2 increases and more of it tends to dissolve in the oceans, but as the temperature

increases the constant decreases and less of it tends to dissolve. The net effect at a given temperature will have to be calculated.

3. The **Solar Radiation** peaks at 610 nm; there is 61.2% of solar radiation is in the visible band (400-750 nm) with less than 9% in the uv band and about 30 % in the near infra red. Some 99% is radiated between 275 and 5000 nm. This band largely is unabsorbed



by any atmospheric gases. The most significant of the greenhouse gases are H_2O and CO_2 . The plot above details the absorbance of various wavelengths of radiation by atmospheric gases in the shortwave region.

4. The **Earth's radiation** peaks at 11,000 nm, with an intensity of .04 W/cm². Some 99% is radiated between 40,000 nm and 3000 nm in the longer infrared regions. This band is unabsorbed by nitrogen, oxygen and argon (99%) of the Earth's current atmosphere), but partially absorbed by carbon dioxide, methane, water vapor, nitrous oxide and some minor gases. The gases that absorb this band of radiation are called *greenhouse gases*.

5. **Earth Orbital Changes:** There are three principal variations in orbit that are collectively known as the Milankovitch Cycles:

- a. precession of the rotational axis (period: 23,000 years)
- b. variation in tilt of rotational axis from 21.5° to 24.5° (period: 41,000 years)
- c. eccentricity of the elliptical orbit (period: 100,000 years)

Atmospheric concentrations of methane closely followed this cycle historically and on a larger time frame so have concentrations of CO_2 .

6. **Departures from the historical cyclical trend** began 8000 years ago with the development of agriculture. This led to a temperature rise of 0.8 °C above expected trends and concentrations of CO_2 rising 30 ppm above expected trends with the concentration of methane 450 ppb above natural trends. In the last 100 years of industrialization these departures from normal have accelerated with temperature rising an additional 0.8 °C and CO_2 concentrations rising to 370 ppm, which is 90 ppm higher than the recorded CO_2 concentrations at the warmest points in the interglacial periods. Methane concentrations are at 1750 ppb, 1000 ppb above historical highs. Over 70% of the extra greenhouse gases were added after 1950. CO_2 is emitted whenever anything is burned, from wood to coal to gasoline. Methane is produced by animal husbandry,

agriculture, and by incomplete combustion or leakage of natural gas. As more greenhouse gases are put into the atmosphere the temperature will increase further. The co-variation of CO_2 concentrations and temperature has been demonstrated not only by recent observation, but by records of the last 700,000 years from Antarctic ice cores. There are many possible effects and feedback mechanisms that are currently being studied and modeled to better predict possible outcomes of this global trend. Many of these are identified above and in the following sections.

The Key Applications:

1. Changing quantity of CO_2 in oceans will lead to a **change in Ph of the oceans**; changing its suitability as a habitat for some species of oceanic life.

2. Human health problems are associated with warmer temperatures including a projected 10-fold rise in mosquito populations and the diseases they bring as well as the already documented spread of malaria and dengue fever into areas in which these diseases were hitherto unknown.
3. Loss of water supply: A large part of human and other animal water supply is supplied from glaciers or melting snow-packs. This dependable supply will be disrupted or curtailed for many people. Especially vulnerable are Southeast Asia and India, which depend on the Himalayas, and much of South America, which depends on the Andes; in the US California and the West stand to have a curtailed water supply in the summer months as a result of global warming.

4. Weather changes:

a. Global Warming seems to cause the North Atlantic Oscillation to become stuck in the positive mode. The effect is to have warmer weather in Alaska, Siberia and western Canada, but colder weather in eastern Canada, Europe, and northeast US.

b. The same effect likely will lead to dry windy conditions in Europe and North America and dry conditions in much of Africa.

c. Models show global warming leading to droughts in most of the northern hemisphere, particularly in the grain belts of North America, Europe, and Asia.

d. At the same time there is predicted to be increased rain overall, but coming in the form of severe storms and consequent flooding.

e. The conditions that lead to hurricanes and tornadoes are powered by solar energy. More solar energy in the ocean may lead to more severe hurricanes. There is some evidence to support that this has already occurred. The combination of warm Gulf waters and windy plains cause tornadoes. Both of these conditions will be increased by global warming.

5. Melting of the land glaciers will lead to **rising sea levels**. The Greenland ice sheet is moving into irreversible melting, which together with the loss of other land ice raise the ocean levels 8 meters in a century. Thermal expansion of water would add several tens of centimeters to this rising sea level.

6. Ecosystems under stress: When temperature changes occur over thousands of years plants and animals adapt and evolve. When they happen over decades adaptation is not always possible. The first flowering days of 385 plant species were on average 4.5 days earlier in 1991-2000 than normal. This can lead to lack of pollination and loss of fruiting.

A study in the Netherlands showed that weather changes caused oak buds to leaf sooner, causing winter moth caterpillars to peak in biomass earlier. The birds that depend on the caterpillars to feed their chicks have not delayed their egg laying. This leads to a mismatch of 13 days between food availability and food needs for these birds.

The Key Equations:

1. $T\lambda_{max} = A$; where A = 2.8978 m-K; Wien's Law

2. $C = kP_{partial}$; Where k is temperature dependent and gas dependent; $CO_2 @ 20^\circ = 3.91 \times 10^{-3}$ molal/atm, $CO_2 @ 25^\circ = 3.12 \times 10^{-2}$ molal/atm; $CH_4 @ 20^\circ = 1.52 \times 10^{-3}$ molal/atm. The concentration is given in molals (Molal is moles of solute/kg of solvent) The partial pressure is given in atmospheres. Henry's Law

3. Energy imbalance of 12 watt/m²-year leads to deglaciation that raises sea levels 1 meter.

4. Climate Sensitivity: Energy imbalance of 1 W/m² \rightarrow .75° C ± .25° C change in average global temperature

5. Present Energy Imbalance = about 1 W/m² (\pm .5 W/m²)



6. The picture above shows the normal energy balance of the Earth. Note that normally the 342 W/m² incoming is balance by 235 W/m² outgoing + 107 W/m² reflected radiation. At present the atmospheric window allows only 39 W/m² out resulting in total of 234 W/m² outgoing and an energy surplus of 1 W/m² that results in temperature increases. (These figures are \pm .5 W/m²). 7. 1kwh = .68 kg CO₂ (EPA estimates)

8. 10,000 kWh = 1.4 cars off the road = 2.9 acres of trees planted (EPA estimates)

Problem Set Chapter 26

1. One W/m² energy imbalance may not seem much. (In the following calculations assume for the sake of significant digits that this is an exact number. It is in fact ± 0.5 W/m²)

a. Calculate the total watts received by Earth. Surface area of a sphere is $4\pi r^2$.

b. Convert to energy in kWh.

c. How many joules of extra energy are received by Earth in a year.

d. To estimate the contrasting energy of an atomic bomb, assume 100 kg of U^{235} , isotopic mass if 235.043924, is split into Xe¹⁴², isotopic mass of 141.929630, Sr⁹⁰, isotopic mass of 89.907738 and 3 neutrons, each with mass of 1.008665. All masses are given in amu's. First find the mass difference between reactant and products. Then converting to kilograms and using $E = \Delta mc^2$ find the energy in joules of an atomic bomb.

e. How many atomic bombs would have to be set off to equal the extra energy the Earth receives in one year from global warming.

2. It is estimated that 12 W/m² energy imbalance leads to sufficient melting of land ice to cause the sea levels to rise one meter.

a. How many joules is that? b. What mass of ice is melted? The heat of fusion of water is $3.33 \times 10^5 \text{ J/kg.}$ c. What volume of water is that? ($\rho = 1000 \text{ kg/m}^3$) d. From the above result you should be able to estimate the surface area of the world's oceans and check the given

estimate.



3. Given the uncertainty of \pm 0.5 W/m², give the high and low estimates of global sea level rise in a century. Draw two new world maps using this data. Draw maps of your state, if it is a coastal state, 100 years from now given these estimates. (Perhaps your inland state will become a coastal state.)

4. Given the following table, involving the growth in concentration of greenhouse gases:

year	[CO ₂] ppm	[CH ₄] ppb
1940	310	1100
1960	315	1250
1980	335	1550
2000	370	1750
2020 (IPCC* projection)	420	2150

*Intergovernmental Panel on Climate Change

a. Graph this data with time on the horizontal axis

- b. Determine the rate of increase in the concentrations of the two gases
 - i. 1940 2000
 - ii. 1960 2000
 - iii. 1980 2000
 - iv. the instantaneous rates of change in 2000
 - v. the instantaneous rates of change projected for 2020

5. Climate forgings can come from a variety of sources besides methane and carbon dioxide. Determine whether the following are positive feedbacks (contribute to global warming) or negative. You may have to do some research on this.

- a. Black Carbon soot
- b. Reflective Aerosols
- c. Chlorofluorocarbons
- d. Nitrous Oxide
- e. Ozone
- f. Cloud Droplet Changes

6. An overlooked area of additional global warming is the traditional cook stove. The soot smoke produced from this stove in one Honduran study absorbed 65% of terrestrial radiation that then goes into warming the atmosphere. There 400 million such cook stoves worldwide, which emit 1.5g of soot per kilogram of wood burned. The average daily use of wood is 7.5 kg per stove. Calculate the mass of soot released through cook stoves per day, per year.



For Problems 7 - 10 use the following tables:

Electricity Emission Rates: (EPA)

State or region	CO ₂ in kg/ Mwh	CH ₄ in kg/Mwh	N ₂ O in kg/Mwh
California	364.8	.00304	.00168
Michigan	740.1	.00662	.0133
New York City	494.3	.00367	.00404
Oregon	304.3	.00149	.00154

Global Warming Potential of Gases Compared to Carbon Dioxide (IPCC):

Greenhouse gas	Multiplier
Carbon dioxide CO ₂	1
Methane CH ₄	23
Nitrous Oxide N ₂ O	296
A/C refrigerant HFC-143a	4300
Auto A/C refriger HFC-134a	1300
SF ₆	22,000
C_2F_6	11,900

7. A typical household air conditioner draws about 20 a from a 240 v line.

a. If used for 8 hours how many kwh does it use?

b. In the course of a 120 day summer how many Mwh is that?

c. Calculate the mass of carbon dioxide one summer's use of ac contributes. (Pick a state or region from above.)

d. Calculate the mass of methane and N₂O emitted.

e. Using the global warming multipliers for the latter two gases calculate the global warming potential in equivalent kg of CO_2 for all 3 gases.



8. If you "shut down" your computer, but the LED light is still on, it consumes about 4 w of power. Suppose you do that for every weekend (60 hours) every week of the year. Repeat the calculations in problem 7 to find out the global warming potential in kg of CO_2 .

9. In 2006 Natomas High School in California used 1692 Mwh of electricity, repeating the calculations above find the kg of carbon dioxide emitted.

10. A large car or SUV typically carries 1.0 kg of refrigerant for the a/c.

a. If this were released into the atmosphere calculate the equivalent of carbon dioxide released.

b. Repeat this calculation for a residential air conditioner (capacity is 2.8 kg.), using HFC-143a.

c. Your school has a commercial chiller maybe (1000 ton) with a refrigerant capacity of 1225 kg.

If it uses HFC-134a calculate the equivalent of CO_2 emitted, if the chiller is decommissioned.

Emissions of Carbon Dioxide for Different Fuels

Fuel	Kg of carbon dioxide emitted/gallon
gasoline	8.78
California reformulated gasoline, 5.7% ethanol	8.55
ethanol	6.10
Diesel #2	10.05
biodiesel	9.52
Jet fuel	9.47
propane	5.67
Natural gas/gasoline gallon equivalent	6.86

11. Compare the carbon "footprint" of the following:

- a. a hybrid car (45 mpg) that drives 21,000 mile per year in Calif.
- b. an SUV (17 mpg) that drives 21,000 miles per year also in Calif.
- c. a mid-size car (24mpg) that uses ethanol and drives 21,000 miles per year
- d. a commercial flatbed (11 mpg) that drives 21,000 miles per year and uses bio diesel

12. Research some typical mileages, type of fuel used, and miles covered in a year and determine the carbon footprint for:

- a. a tractor-trailer truck
- b. a commercial airliner
- c. a corporate jet
- d. a bus
- e. Amtrack



13. Looking at the above problems another way, suppose you want to travel from California to New York find your carbon footprint for the trip using:

- a. Amtrack
- b. a jet plane
- c. a bus
- d. an SUV
- e. a hybrid

Assume 90% full loads on the commercial transports and 2 passengers on the cars. You will have to go on-line to find the loads of the commercial transports.

14. China is putting two coal-fired electrical plants in operation each week. These plants do not typically use any scrubbing or pollution controls. Research the typical Mwh output, and, using either the table for problem 7 (Michigan depends more on coal than the other states listed.) or a more direct source for CO_2 emissions for a coal plant, find the gain in greenhouse gas emissions each year from this source alone. Compare to the results in problem 4 and determine if the IPCC is underestimating the problem.