FINAL EXAM SOLUTIONS

1. Briefly describe the Montreal Protocol's major features, including the agreement on developing country participation. (10 points)

2. Briefly describe the different population scenarios generated by the United Nations and explain why the scenarios are so divergent. (10 pts)

3. In your opinion, which energy technologies are most likely to have a significant impact on reducing carbon emissions over the next 20 to 50 years? Why? (10 points)

4. A reporter asks you to explain, briefly and in simple terms, how stratospheric ozone is destroyed. A previous interview with an atmospheric chemist left him particularly confused about the difference between "homogenous" and "heterogeneous" reactions. (10 points)

5. What is the objective of the Framework Convention on Climate Change? What must be done to achieve this objective? (10 points)

6. The Exxon Valdez spilled 11 million gallons of crude oil into Prince William Sound (PWS), which has an area of 8,800 km^2 and an average depth of 300 m.

   A. Six of the 11 million gallons were recovered in the vicinity of the ship. Before tidal currents began to flush the oil out to sea, about half the area of PWS was covered with the remaining oil. What was the average thickness of the slick? (5 points)

$$\left[5\cdot 10^6\ \text{gal}\right]\left[\frac{3.75\ \text{L}}{\text{gal}}\right]\left[\frac{\text{m}^3}{10^3\ \text{L}}\right]\left[\frac{1}{4400\ \text{km}^2}\right]\left[\frac{\text{km}^2}{10^6\ \text{m}^2}\right]\left[\frac{10^3\ \text{mm}}{\text{m}}\right]=\mathbf{0.004\ mm}$$

   B. In reality, by the time the slick covered half of PWS wave action mixed the oil into the top 10 meters of water. What was the average concentration of oil in these surface waters, in parts per billion by weight? Alaska's water quality standard is 10 ppb; concentrations above 100 ppb are toxic to most marine life. (6 points)

$$\frac{\left[5\cdot 10^6\ \text{gal}\right]\left[\frac{3.75\ \text{L}}{\text{gal}}\right]\left[\frac{\text{m}^3}{10^3\ \text{L}}\right]\left[\frac{0.7\ \text{t}_{\text{oil}}}{\text{m}^3}\right]}{\left[4400\ \text{km}^2\right]\left[\frac{10^6\ \text{m}^2}{\text{km}^2}\right]\left[10\ \text{m}\right]\left[\frac{1\ \text{t}_{\text{H}_2\text{O}}}{\text{m}^3}\right]}=3\cdot 10^{-7}\ \frac{\text{t}_{\text{oil}}}{\text{t}_{\text{H}_2\text{O}}}=\mathbf{300\ ppb}$$

   C. Exxon paid $2.5 billion for clean-up, $300 million in claims, and $5 billion in punitive damages. If this is charged to the total amount of oil that has been pumped through the Alaskan pipeline (about 11 billion barrels), roughly how much would this increase the price of gasoline made from this oil? (5 points)

$$\frac{\left[\$(2.5+0.3+5)\cdot 10^{9}\right]}{\left[11\cdot 10^{9}\ \text{bbl}\right]\left[\frac{42\ \text{gal}_{\text{oil}}}{\text{bbl}}\right]\left[\frac{\approx 1\ \text{gal}_{\text{gas}}}{\text{gal}_{\text{oil}}}\right]}=\frac{\$0.017}{\text{gal}}$$

7. When considering the energy balance of the Earth, we assumed that the rate at which infrared energy is radiated to space is equal to the rate at which solar energy is absorbed.

   A. What is this average rate of energy absorption/radiation, in W/m^2? (5 points)

$$P_{\text{solar in}} = P_{\text{IR out}}$$

$$(1-\alpha)\Omega\,\pi R^2 = 4\pi R^2\,\sigma T^4$$

$$\sigma T^4 = \frac{(1-\alpha)\Omega}{4} = \frac{(1-0.3)}{4}\left(1370\frac{W}{m^2}\right) = 240\frac{W}{m^2}$$

   B. The basic assumption (infrared out = solar absorbed) ignores the production of energy by humans from fossil and nuclear fuels. Virtually all this energy, regardless of its use, is converted into heat. Would including this factor tend to increase or decrease the average surface temperature? Justify your answer. (3 points)

   It should be intuitively obvious that the conversion of stored energy into heat would make the Earth warmer. To prove it, let W = the rate of heat output by humans:

$$P_{\text{solar in}} + P_{\text{heat}} = P_{\text{IR out}}$$

$$(1-\alpha)\Omega\,\pi R^2 + 4\pi R^2\,W = 4\pi R^2\,\sigma T^4$$

$$\sigma T^4 = \frac{(1-\alpha)\Omega}{4} + W$$

   So W adds to the average solar flux, making the Earth warmer.

   C. I did not include the production of energy from biomass, wind, solar, or hydropower in question B. Why not? (3 points)

   Because all of these are derived from the average solar flux. Therefore, no additional heat is generated when these are harnessed for human energy purposes. There are a few minor caveats: the use of these energy sources must alter not the climate system in ways that change the net amount of

solar energy absorbed. For example, it is conceivable that solar cells or hydropower reservoirs would change the Earth's albedo.

Of course, fossil fuels are derived from biomass, so you might wonder why fossil fuels are included but biomass is not. That's because biomass fuels, to be sustainable, must be grown at about the same rate as they are used. Thus, there is no net change in the total amount of heat released (absent changes in albedo). But fossil fuels are, in effect, solar energy that has been stored for hundreds of millions of years, that can be converted into heat in as little as one millionth that period of time.

D. The current rate of fossil and nuclear energy production is about 400 EJ/yr. Compare this rate, in W/m^2, to the change in the energy balance expected from a doubling of the CO_2 concentration. What do you conclude? (5 points)

Doubling of CO_2: $\Delta F_{2xCO2} = 6.3 \log_e(2) = 4.4\ W/m^2$.

$$\frac{\left[\frac{400\ EJ}{yr}\right]\left[\frac{10^{18}\ J}{EJ}\right]\left[\frac{W\cdot s}{J}\right]\left[\frac{yr}{3.15\cdot 10^{7}\ s}\right]}{\left[5.1\cdot 10^{14}\ m^2\right]} = 0.025\ \frac{W}{m^2}$$

So the change in the energy balance due to a doubling of CO_2 is nearly 200 times greater than the rate of human energy production.

E. Over the last century, energy consumption has grown at an average rate of about 3.5 percent per year. If it continued to grow at this rate for the next century, what would the rate of human energy use be in W/m^2? Would the resulting heat, if derived largely from fossil, nuclear, or geothermal sources, then be of climate concern? Do you consider this scenario likely? (5 pts)

$$\left[\frac{0.025\ W}{m^2}\right][1.035]^{100} \cong \left[\frac{0.025\ W}{m^2}\right]e^{0.035(100)} = 0.8\frac{W}{m^2}$$

While not insignificant, this is less than the radiative forcing from the increase in greenhouse gas concentrations that has already occurred. Although it should be included in calculations, it would not be of "concern," at least in the same way that increasing concentrations of CO_2 is of concern.

Whether this scenario is likely is debatable. Most scenarios show global energy use increasing over the next century by far less than the factor of 30 increase implied by continued growth at 3.5 percent per year. This is partly because population growth is expected to decrease, partly because economic growth may decrease as economies mature, and partly because technological advances and structural changes in economies will lead to less energy use per unit GDP.

8. As noted in class, there are natural as well as anthropogenic sources of acidity. Nitrification—the conversion of ammonium (from decay) to nitrate (the more usable nutrient form)—is one such source of acidity:

$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + 2H^+ + H_2O$$

The rate of nitrification in freshwater lakes typically is about 10^{-4} moles of nitrogen per liter per year. Consider a lake with an area of 1 km^2 and an average depth of 100 m, with a stream outflow of 550,000 m^3/d.

A. Considering only the above reaction (i.e., nitrification is the only source of H^+ and there are no neutralizing bases), what would the equilibrium pH of the lake be? (10 points)

$$\tau = \frac{S}{F} = \frac{\left[1\,km^2\right]\left[100\ m\right]\left[\frac{10^6\ m^2}{km^2}\right]}{\left[\frac{550{,}000\ m^3}{d}\right]\left[\frac{365\ d}{yr}\right]} = \frac{10^8\ m^3}{2\cdot 10^8\ \frac{m^3}{yr}} = 0.5\ yr$$

$$[H^+] = \left[\frac{10^{-4}\ mole(N)}{L\cdot yr}\right]\left[\frac{2\ mole(H^+)}{mole(N)}\right]\left[0.5\ yr\right] = 10^{-4}\ \frac{mole}{L}$$

$$pH = -\log_{10}[H^+] = -\log_{10}\left[10^{-4}\right] = 4$$

B. The solution in part A indicates that nitrification is a substantial source of acidity—more significant than acid rain. There is, however, a good reason not to be concerned about acidification from nitrification. What is that reason? (3 points)

Nitrification is not a concern because it normally is balanced by other denitrification reactions that recycle the nitrogen, which convert the NO_3^- into N_2 or N_2O plus OH^- (which then neutralizes the H^+) or which convert the NO_3^- and H^+ back into NH_4^+. For example:

$$NO_3^- + 2H^+ + H_2O \longrightarrow NH_4^+ + 2O_2$$

$$4NO_3^- + 2H_2O \longrightarrow 2N_2 + 5O_2 + 4OH^-$$

$$C_6H_{12}O_6 + 6NO_3^- \longrightarrow 6CO_2 + 3H_2O + 6OH^- + 3N_2O$$