FINAL EXAM SOLUTIONS

1. Short answer (2 points each, 20 point total):

   A. What is the primary source of U.S. SO_2 emissions?

   Coal-fired electricity generation

   B. What is the primary source of U.S. NO_x emissions?

   Transportation (automobiles)

   C. Name two things that happen when acid rain falls onto soils.

   Carbonate buffering; nutrient leaching; mobilization of metals

   D. What does “ANC” stand for? What is another common term for it?

   Acid-neutralizing capacity; alkalinity or buffering capacity

   E. The population growth rate in Ukraine is –0.8 percent per year. If the growth rate remains constant, how long will it take for the population to be cut in half?

   $\mathbf{T_{1/2} = \ln(0.5)/r = -0.69/-0.008 = 87 \approx 90}$ **years**

   F. If a population doubles in 23 years, what is the average annual growth rate?

   $\mathbf{r = \ln(2)/T_{2X} = 0.69/23 = 0.030 = 3}$ **percent per year**

   G. What is the pH of water with a hydrogen ion concentration of $5 \cdot 10^{-5}$ moles per liter?

   $\mathbf{pH = -\log_{10}[H^+] = -\log_{10}(5 \cdot 10^{-5}) = 4.3}$

   H. What are two ways sulfate particles in the troposphere can cool climate?

   Reflection and scattering of sunlight; increased cloudiness

   I. Give an example of a positive climate-change feedback involving the biosphere.

   CO_2 → temperature (+) → decay/respiration (+) → CO_2 (+)

   CO_2 → climate change (+) → forest die-back and decay (+) → CO_2 (+)

   J. Give an example of a negative climate-change feedback involving the biosphere.

   CO_2 → NPP, carbon storage (+) → CO_2 (–)

   Forcing → climate change (+) → forest die-back → albedo (+) transp (–) → forcing (–)

2. Short answer (3 points each, 15 points total):

   A. What is the hydrogen ion concentration in pristine rainfall?

      $[H^+] = 10^{-pH} = 10^{-5.6} = 2.5 \cdot 10^{-6}$ moles/liter

   B. Why is climate change a global problem, while acid rain is a regional problem?

      The greenhouse gases of concern (CO_2, CH_4, N_2O, etc.) have residence times of decades to centuries and therefore become uniformly mixed throughout the atmosphere; a ton of CO_2 released in Australia has the same effect on climate as a ton released in the United States.

      Acids and acid precursors have residence times of days and therefore mainly affect areas immediately downwind from the source.

   C. Sulfates and CO_2 are released when coal is burned. The estimated cooling effect of the sulfate aerosols roughly offset the estimated warming effect of the CO_2. Why, then, are we worried about the effects of coal burning on climate?

      First, as noted above, the effect of aerosols is regional while the effect of CO_2 is global. Thus, even if the global-average warming and cooling effects were offsetting, there still would be regional changes in climate.

      Second, the offsetting effect of aerosols can be maintained only if sulfate emissions continue to increase along with increased coal burning. This would have large environmental impacts, particularly in Asia.

      Third, reductions in coal burning or sulfate emissions produce immediate reductions in aerosol concentrations, but no reduction in CO_2.

   D. List three ways albedo might change as a result of climate change.

      Melting of snow and ice; increased snowfall; forest die-back or desertification; changes in cloud type and amount.

   E. Explain the differences between UV-A, UV-B, and UV-C light.

      UV-A is light with wavelengths between 320 nm and visible light; it is not absorbed by O_2 or O_3 but cannot break DNA molecules and cause cancer

      UV-C is light with wavelengths between 280 nm and x-rays; it is lethal to DNA or proteins but is absorbed entirely by O_2

      UV-B is light with wavelengths between 280 and 320 nm; it is largely absorbed by O_3 but breaks DNA molecules and is a major cause of cancer

3. Short answer (5 points each, 10 points total):

   A. Why does a hole in the ozone layer appear over the Antarctic each October? Why isn't there a hole over the Arctic?

      The ozone hole formed over Antarctica due to the unique conditions that exist during the Antarctic winter. An intense circumpolar vortex forms, confining and isolating the air above Antarctica from the rest of the atmosphere. The natural production of ozone stops during winter, since the pole receives no sunshine. Temperature becomes extremely low, leading to the formation of ice crystals even in this extremely dry air. The chlorine becomes adsorbed onto the surfaces of these crystals in the form of a weakly-bound molecule. In the spring (October), sunshine liberates the chlorine, which rapidly destroys ozone in a catalytic reaction. In comparison, the thinning of the ozone layer over the Arctic is much smaller, mostly because the Arctic is not cold enough to permit the formation of the same ice crystals.

   B. Comment on the following statement: "Tree planting is a lousy way to solve the problem of increasing atmospheric CO_2 because all the trees we plant today will just die and rot some day, thereby foisting off on our descendants the problem of having to deal with the CO_2 from all the decaying trees we planted."

      Future generations have the option of maintaining the forest by letting the mature trees produce new ones, just as in natural forests. While there will be no additional stored carbon after an equilibrium is achieved, when the rotting of dead trees is in balance with the net productivity of new trees, there won't be a net release of carbon to the atmosphere.

      If our descendants destroy the forest (to convert it to agricultural production) or if it dies as a result of climate change, then the carbon stored in the forest would be released into the atmosphere. Will the overall situation be better or worse than if we had not planted the trees in the first place? If we hadn't planted the trees, climate would change faster during the period from today until the forest is destroyed, and our descendents would have to deal the consequences of those larger changes in climate. But some of the carbon we would have released will have disappeared from the atmosphere due to ocean and perhaps terrestrial vegetation uptake, and the overall concentration of CO_2 in the atmosphere will be higher than if we didn't plant trees that later died. A rapid increase in CO_2 concentrations, as a result of forest die-back, might also trigger larger changes in climate than the same increase over a longer period of time. There is also the question of opportunity cost—if the effort that had gone into tree planting had been invested in other measures that reduced CO_2 emissions, such a biofuel production, the future CO_2 concentration might be significantly lower.

4. According to BP, total energy consumption in India increased from 222 million tons of oil equivalent (TOE) in 1993 to 345 million TOE in 2003.

   A. What was the average growth rate, in percent per year, over this period? (4 pts)

   ln[(345/222)]/10 = 0.0441 = 4.4%/y (continuous growth rate)

   $(345/222)^{1/10} - 1 = 0.0451 = 4.5\%/y$ (annual yield)

   B. In mid-1993, India's population was 900 million. Since then, the growth rate has averaged 1.7 percent per year. What is the population of India today? (2 points)

   $(900)\ e^{0.017(2005\text{-}1993)} = (900)\ e^{0.017(12)} = 1100$ million

   $(900)\cdot(1.017)^{12} = 1100$ million

   C. What was the average growth rate of per-capita energy consumption? (2 points)

   4.4 – 1.7 = 2.7 %/y

   D. If per-capita consumption in India continues at the average rate calculated in part C, in what year would it reach the current U.S. level of 8 TOE/y? (4 points)

   (222 million TOE/y)/(900 million people) = 0.247 TOE/y per person

   $8 = 0.247\ e^{0.027t}$ t = [ln(8/0.25)]/0.027 = 129 y + 1993 ≈ 2120

   $8 = 0.247\ (1.027)^t$ t = [ln(8/0.25)]/ln(1.027) = 130 y

5. Hoover Dam on the Colorado River was built in 1936, creating Lake Mead. Sediment carried by the Colorado River settles out of the water when it reaches Lake Mead. About long will it take for Lake Mead to be completely filled with sediment? The volume of Lake Mead is 35 billion cubic meters; the average flow rate of the Colorado River is 17 million acre-feet per year; the average concentration of sediment in water when it reaches Lake Mead is 14 grams per liter. Assume that the density of sediment is about twice that of water. (8 points)

   Note: density of water = 1000 kg/m^3; 1 g/L = 1 kg/m^3:

$$\left[\frac{y}{17\cdot 10^6\ \text{acre}\cdot\text{ft}}\right]\left[\frac{\text{acre}\cdot\text{ft}}{1234\ m^3_{H_2O}}\right]\left[\frac{m^3_{H_2O}}{14\ kg_s}\right]\left[\frac{2000\ kg_s}{m^3_s}\right]\left[35\cdot 10^9\ m^3_s\right] = 240 \text{ years}$$

   1936 + 238 = 2174 ≈ about the year 2175

6. According to a recent article in Science,* increases greenhouse gas and aerosol concentrations and other changes from 1880 to 2003 produced a total radiative forcing of about 1.8 watts per square meter. Over this same time period, global-average surface temperature rose by about 0.65 °C. Measurements and model results indicate that the Earth is radiating to space less energy than it is receiving from the Sun; the difference was about 0.9 watts per square meter in 2003.

   *James Hansen, et al., "Earth's Energy Imbalance: Confirmation and Implications," 2 May 2005.

   A. If the Earth has warmed, why is it radiating less energy to space than it is receiving from the Sun? (2 points)

      The climate system has not yet come entirely into equilibrium with the increased forcing. The observed warming has increased the rate at which the Earth radiates energy to space, but by an amount equal to the total forcing (1.8 W/m^2) minus the remaining the energy imbalance (0.9 W/m^2). The Earth will continue to warm until there is no energy imbalance.

   B. If greenhouse gas and aerosol concentrations were frozen at today's level, what would happen to global-average surface temperature in the future? (3 points)

      Because the observed temperature increase of 0.65 °C has compensated for half of the total forcing, we would expect the long-term temperature increase resulting from today's total forcing to be 1.3 °C.

   C. A doubling of the CO_2 concentration corresponds to a radiative forcing of 3.7 W/m^2. Based on the information given above, what would be the total change in global-average surface temperature from a doubling of CO_2? (3 points)

      Assuming the temperature increase is proportional to forcing, the change in temperature would be (1.3 °C)(3.7 W/m^2)/(1.8 W/m^2) = 2.7 °C.

   D. How does your answer to part C compare to the range of values given by the IPCC? (2 points)

      Very consistent: the IPCC range is 1.5 to 4.5 , with a best estimate of 2.5 C.

7. Dioxin is believed to be one of the most potent toxic and carcinogenic compounds created by humans. Primary sources of dioxin in the human diet are meat and milk. About 70 percent of ingested dioxin is absorbed and retained in the body, entirely in fatty tissues, with a residence time of 10 years.

   A. Typical dioxin levels are 1 pptw (parts per trillion by weight) in meat and about 10 picograms (pg) per gram of milk fat (whole milk is 4 percent fat). The average U.S. adult eats 8 ounces of meat and 8 ounces of milk per day. Estimate the dioxin intake of the average U.S. adult in pg per day, and confirm it is roughly consistent with the EPA estimate of 4 pg/d per kilogram of body weight. (6 pts)

   Note: 1 pptw = 10^{-12} g/g = pg/g

$$\left[\frac{8\ \text{oz}_{\text{mt}}}{\text{d}}\right]\left[\frac{454\ \text{g}_{\text{mt}}}{16\ \text{oz}}\right]\left[\frac{1\,\text{pg}}{\text{g}_{\text{mt}}}\right]+\left[\frac{8\ \text{oz}_{\text{mk}}}{\text{d}}\right]\left[\frac{454\ \text{g}}{16\ \text{oz}}\right]\left[\frac{0.04\ \text{g}_{\text{fat}}}{\text{g}_{\text{mk}}}\right]\left[\frac{10\ \text{pg}}{\text{g}_{\text{fat}}}\right]=320\,\frac{\text{pg}}{\text{d}}$$

   For a 70-kg male, this is 320/70 = 4.5 pg/d per kg. This assumes whole milk; skim milk eliminates the fat and reduces the total to 230 pg/d or about 3.2 pg/d per kg.

   B. The average person is 15 percent fat by weight. Estimate the concentration of dioxin in fatty tissues at the end of the average person, in pg per gram of body fat, assuming a dioxin intake of 4 pg/d per kilogram. Compare this concentration to the estimated threshold for toxic effects in humans of 100 pg/g. (6 points)

$$c=\frac{S}{M_{\text{fat}}}=\frac{\tau F}{M_{\text{fat}}}=\frac{(10\ \text{y})\left(\frac{4\ \text{pg}}{\text{d}\cdot\text{kg}}\right)\left(\frac{365\ \text{d}}{\text{y}}\right)(0.7)}{\left(\frac{0.15\ \text{kg}_{\text{fat}}}{\text{kg}}\right)\left(\frac{10^3\ \text{g}}{\text{kg}}\right)}=70\,\frac{\text{pg}}{\text{g}_{\text{fat}}}$$

   Yikes—we've reached the threshold for toxic effects!

   C. What key assumption did you make in part B? Is the assumption is valid? (3 pts)

   The key assumption is that intake and outflow are in equilibrium. Because the lifetime of the average male (75 y) is many times greater than the residence time of dioxin (10 y), this is approximately valid.

8. A lake has a surface area of 500,000 m^2 and receives 1 m/y of rainfall with average pH = 4. The local government is considering neutralizing the acidity in the rainfall by adding lime ($CaCO_3$) to the lake.

   A. At what rate must lime be added, in tons per year? Consider only the following simplified reaction: $CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$. (8 points)

   $[H^+] = 10^{-pH} = 10^{-4}$ moles/L

$$\left[\frac{10^{-4}\ \text{mole}_{H^+}}{L}\right]\left[\frac{\text{mole}_{CaCO_3}}{2\ \text{mole}_{H^+}}\right]\left[\frac{100\ g}{\text{mole}_{CaCO_3}}\right]\left[\frac{t}{10^6\ g}\right]\left[\frac{10^3\ L}{m^3}\right]\left[500{,}000\ m^2\right]\left[\frac{1\,m}{y}\right]$$

$$= 2.5\frac{t}{y}$$

   B. The actual reactions are more complicated. The addition of lime establishes a new equilibrium between the concentrations of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and H^+ in the lake water. Taking this into account qualitatively, the calculation in part A is (circle one: **too low**, too high, about right). (2 points)

$$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^-$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

$$HCO_3^- + H^+ \leftrightarrow H_2O + CO_2$$