PUAF 741

Global Environmental Problems

FINAL EXAM

15 December 1994, 4:00–7:00 p.m., room 1107 VMH

Please enter your student number here: ______________________________

This exam contains 100 points. Allocate your time accordingly (i.e., about 1.5 minutes per point).

This is a closed-book exam, except for one sheet of notes. The last page of the exam contains useful information (equations, constants, conversion factors, data, etc.). You may wish to separate that sheet from the exam to make its use more convenient.

Enter all answers and do your work directly on this exam in the space provided. Partial credit for incorrect answers can be given only if you show your work. If you need more space, use a blue book. Circle or underline final answers. If you need a number you can't find or derive, define a symbol for it and continue, or take a guess as to its value. If you don't have time to complete a problem but think you know how to do it, describe the steps.

Qualitative questions should be answered as precisely and succinctly as possible. Use the space provided; use a blue book if you need more space. *Make sure your handwriting is legible.* It is your responsibility, not mine, to ensure that I can read and understand your answer. Demonstrate a solid understanding of fundamental concepts; grammar is unimportant here.

When you are finished, turn in the exam along with any blue books that contain information you wish to be considered. Remember to write your student number, *not your name,* on everything you turn in.

Exam scores and course grades will be posted near my office door, rm. 4103 VMH, probably on Monday, 19 September. Good luck!

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1. According to ***World Resources***, energy consumption in China increased by 66 percent from 1971 to 1991, from 16.5 to 27.4 exajoules per year.

   A. What was the average annual rate of increase in energy consumption during this period, in percent per year? (4 points)

   $(1.66)^{1/20} = 1.0257 =$ ***2.6%/yr***; or $r = \log_e(1.66) \div 20 = 0.0253 = 2.5\%/yr$

   B. If this trend continues, how long will it take for China's energy consumption to double? (3 points)

   $rT = 69$; $T = 69/r = 69/2.5 = 28$ *years*; or

   $(C/C_o) = e^{rT}$; $T = \log_e(C/C_o) \div r = \log_e(2) \div 0.0253 = 27.4 =$ ***27 years***

   C. U.S. energy consumption is 80.8 exajoules. Assuming that China's energy consumption continues to grow at the 1971–91 rate, how long will it take for China to consume as much as the U.S. does today? (4)

   $(C/C_o) = e^{rT}$; $T = \log_e(C/C_o) \div r = \ln(80.8/27.4) \div 0.0253 =$ ***43 years***; or

   (80.8/27.4) = 2.9, or about 1.5 doublings; (1.5) x (28 yr) = 42 years

   D. Population growth in China averaged 1.5 percent per year during the 1971–91 period. At what rate did *per-capita* consumption increase? (4)

   rates are additive: $r_{(energy\ consumption)} = r_{(population\ growth)} + r_{(per\text{-}capita\ consumption)}$

   $r_{(per\text{-}capita\ consumption)} = 2.5 - 1.5 =$ ***1.0%/yr***.

2. You are working as a legislative aid for Senator Wackpood. The Senator would like you to explain why the Clean Air Act's provisions for limiting sulfur dioxide emissions will have only a minimal effect on the acid rain problem. The Senator has one minute to hear your case. (10)

   The CAA amendment requires a 50% reduction in SO_2 emissions; this limit will be reached by 2000 by creating a market in a limited number pollution permits. If SO_2 was the only source of acid rain, this reduction would increase the pH of rainfall by only 0.3 units (e.g., from 4.0 to 4.3). But it isn't the only source: NO_2 is an important contributor as well, which the CAA reduces by only 10%. Also, protection of forests in sensitive soils, aquatic life, and even limestone buildings requires that the pH of rainfall be closer to its preindustrial value—in the low 5's.

Technology is available and in widespread use in western Europe and Japan to reduce emissions by 90%; if they can do it, why can't we?

3. Mexico City contains 15 million people and 2.5 million automobiles. The automobiles use leaded gasoline containing 0.6 grams of lead per liter. The average fuel efficiency of Mexican automobiles is 20 miles per gallon. In addition, let's assume that the average automobile is driven 20,000 kilometers per year.

   A. Estimate the rate at which lead flows into the Mexico City atmosphere from automobile emissions, in tonnes of lead per year. (5 points)

$$2.5 \cdot 10^6 \text{ cars} \cdot \frac{20{,}000 \text{ km}}{\text{car} \cdot \text{yr}} \cdot \frac{\text{gal}}{20 \text{ mi}} \cdot \frac{3.75 \text{ L}}{\text{gal}} \cdot \frac{\text{mi}}{1.6 \text{ km}} \cdot \frac{0.6 \text{ g(Pb)}}{\text{L}} \cdot \frac{\text{te}}{10^6 \text{ g}} = \mathbf{3{,}500 \text{ te/yr}}$$

   B. The residence time of air in a city is roughly the time it takes for air, carried by the wind, to cross the city. The area of Mexico City is 522 square miles; the average wind speed is 6 miles per hour. What is the average residence time of air in Mexico City? (5 points)

Assume that Mexico City is a square; each side would then be $(522)^{1/2}$ = 23 mi. A lead particle would, on average, only travel half this distance, since some would be emitted on the windward side and some would be emitted on the leeward side of the city. (You can show, with integral calculus, that the residence time doesn't depend on the shape of the city or the orientation of the wind.) Thus, the residence time τ = (11.4 mi) ÷ (6 mi/hr) ≈ ***2 hr.***

   C. Using your answer to (B), calculate the average stock of lead in the Mexico City atmosphere, in kilograms. (5 points)

$$S = F \cdot \tau = \frac{3{,}500 \text{ te(Pb)}}{\text{yr}} \cdot \frac{1000 \text{ kg}}{\text{te}} \cdot \frac{\text{yr}}{365 \text{ d}} \cdot \frac{\text{d}}{24 \text{ hr}} \cdot 2 \text{ hr} = \mathbf{800 \text{ kg(Pb)}}$$

   D. In order to calculate the *concentration* of lead, one must know not only the stock of lead but also the volume of air into which it is mixed. Mexico City suffers from frequent atmospheric inversions, during which pollution is trapped within 100 meters of the surface. Estimate the concentration of lead in Mexico City air in micrograms per cubic meter under these conditions. (HINT: your answer should be several times greater than the EPA standard of 1.5 μg/m^3.) (5 points)

$$V = 522 \text{ mi}^2 \cdot (1602 \text{ m/mi})^2 \cdot 100 \text{ m} = 1.34 \cdot 10^{11} \text{ m}^3$$

$$C = S/V = (800 \cdot 10^3\ g) \div (1.34 \cdot 10^{11}\ m^3) = 6 \cdot 10^{-6}\ g/m^3 = \mathbf{6\ \mu g/m^3}$$

E. The average five-year-old weighs 18 kg, contains 1.5 liters of blood, and breathes 10 cubic meters of air per day. Like adults, 48 percent of inhaled lead is absorbed directly from the lung into the bloodstream, where it remains with a residence time of 17 days. Another 15 percent is swallowed; 20 percent of this is absorbed from the GI tract into the bloodstream. Using your answer from (D), estimate the concentration of lead in the bloodstream of the average five-year-old, in micrograms per 100 milliliters. How does this compare with the levels which have been shown to cause various health effects in children? (5 points)

$$\frac{6\ \mu g}{m^3} \cdot \frac{10\ m^3}{d} \cdot [0.48 + 0.15 \cdot (0.2)] \cdot \frac{17\ d}{1.5\ L} = 350\ \mu g/L = \mathbf{35\ \mu g/100\ mL}$$

This is above the level known to cause IQ deficiencies in children, and only slightly below the level known to cause anemia in children.

4. The Intergovernmental Panel on Climate Change has concluded that, if the concentration of atmospheric carbon dioxide doubles, the average surface temperature of the Earth will rise by 1.5 to 5 °C, with a “most likely” increase of 2.5 °C. (10 points each)

A. What is the main source of uncertainty in the expected temperature increase? Explain briefly. Can we expect this uncertainty to be substantially reduced in the coming years by additional scientific study?

The main source of uncertainty is feedback—the response of the climate system to the additional carbon-dioxide heating. The most uncertain of these is cloud feedback. Clouds both cool the atmosphere (by reflecting incoming solar radiation) and heat it (by absorbing out-going infrared radiation). In today’s climate, clouds are net cooling agents; an increase in the amount of such clouds would result in a negative feedback. But the very nature of clouds—their latitudinal distribution, altitude, albedo, and infrared absorption—will change as a result of global warming. Most climate models predict a strong positive feedback from clouds, but this is highly uncertain because the models don’t use the fundamental physics of cloud formation. The controversy surrounding the role of clouds is unlikely to be resolved for many years, because such models would require computers billions of times faster than today’s machines to do the basic physics. A combination of satellite observations of the Earth warms, together with calculations of individual cloud “microphysics,” might give us better insight, however.

B. “Gee,” says Senator Bale Dumpers (D–AK), “two or three degrees doesn’t seem like a big deal to me. I’m from an agricultural state, and we might even benefit from a longer growing season and milder winters. And some scientist feller told me that carbon dioxide was good for crops. Why should I be so worried about global warming?”

First off, the effect you describe—carbon-dioxide fertilization—has only been seen in greenhouses, where the plants have all the water and other nutrients they want. Scientists think that the effect may largely go away under realistic growing conditions. On the whole, global warming is likely to have serious negative effects on U.S. agriculture. Higher temperatures mean greater water loss and dryer soils; scientists predict a decrease in rainfall in the midwest; plants are much more sensitive to soil moisture than they are to temperature.

Two or three degrees might not seem like a lot, but it is. This is a global average temperature increase—the increase will be greater here, and much greater—two or three times greater—at the poles. Why, during the last ice age the Earth was only five degrees cooler *than today, and look at what that meant for the U.S.—the whole northern part of the country was covered by glaciers! To make things worse, we’re changing the temperature of the Earth must faster than it has changed on its own in the past. It will be hard for people, let alone forests and wildlife, to keep up with the movement of climate.*

Finally, two or three degrees is only the average *estimate for a* doubling *of carbon dioxide. Some models predict temperature increases twice as high for a doubling. And if we don’t do something about carbon emissions, carbon dioxide will much more than double. We could be looking at temperature increases of as much as ten degrees over the long run!*

5. (15 points) In many developing countries, a significant fraction of energy use is in the form of biomass fuels (wood, crop waste, and dung) burned for cooking and heating. These biomass fuels contain both sulfur and nitrogen, and they are burned without emission controls. Investigate to what extent these practices could contribute to an acid rain problem in India, using the following assumptions:

- biomass fuel use rate ≈ 1 te/yr per person for 600 million rural people;
- biomass fuel composition = 4.7% N, 1.2% S by weight;
- 100% of S in fuel is emitted as SO_2; 25% of SO_2 oxidized to sulfate and deposited in rain;
- 10% of N in fuel is emitted as NO_2; 50% of NO_2 deposited in rain;
- each mole of S in rain leads to 2 moles of H^+ in rain;
- each mole of N in rain leads to 1 mole of H^+ in rain;
- all other sources of acid can be ignored;
- precipitation = 1 meter per year over land area of 3 million km^2;

- pre-industrial pH of regional rain = 6.

$$\frac{1\ te(bm)}{person \cdot yr} \cdot \frac{10^6\ g}{te} \cdot \frac{0.012\ g(S)}{g(biomass)} \cdot \frac{mole(S)}{32\ g(S)} \cdot (600 \cdot 10^6\ people) = 2.2 \cdot 10^{11}\ mole\ (S)$$

$$\frac{1\ te(bm)}{person \cdot yr} \cdot \frac{10^6\ g}{te} \cdot \frac{0.047\ g(N)}{g(biomass)} \cdot \frac{mole(N)}{14\ g(N)} \cdot (600 \cdot 10^6\ people) = 2.0 \cdot 10^{12}\ mole\ (N)$$

$$2.2 \cdot 10^{11}\ mole(S) \cdot \frac{1.0 \cdot (0.25)\ mole(SO_4)}{mole(S)} \cdot \frac{2\ mole(H^+)}{mole(SO_4)} +$$

$$2.0 \cdot 10^{12}\ mole(N) \cdot \frac{0.1 \cdot (0.5)\ mole(NO_2)}{mole(N)} \cdot \frac{1\ mole(H^+)}{mole(NO_2)} = 2.1 \cdot 10^{11}\ mole(H^+)$$

volume of precipitation = $(3 \cdot 10^6\ km^2) \cdot (1000\ m/km)^2 \cdot (1\ m)(1000\ L/m^3) = 3 \cdot 10^{15}\ L$

$[H+] = (2.1 \cdot 10^{11}\ mole) \div (3 \cdot 10^{15}\ L) = 7.1 \cdot 10^{-5}\ mole/L$

$pH = -log_{10}[H^+] = -log_{10}(7.1 \cdot 10^{-5}) =$ **–4.2**

6. Write a very short paper, in the form of "talking points" for a congressperson, describing the stratospheric ozone problem. (15 points)

   - *The stratospheric ozone layer shields the Earth's surface from harmful ultraviolet radiation. Life could not exist with it. A 10% decrease in ozone will result in a 20% increase in skin cancer—almost all in the U.S. and western Europe.*

   - *Possible problem identified in early-1970s in connection with SST exhaust products; SST canceled in U.S.*

   - *Later, scientists discover that CFCs can destroy ozone. Because CFCs are highly stable, they eventually find their way into the stratosphere. There ultraviolet light breaks the CFCs down, releasing chlorine. Each chlorine atom can destroy 100,000 ozone molecules.*

   - *Spray cans with CFC propellants banned in late 1970s, but releases of CFCs used as refrigerants and in various industrial processes (as solvents, to blow foams, etc.) continued. Talks over limiting CFCs continued at slow pace.*

   - *Ozone hole was discovered over Antarctic in mid-1980s; scientists shocked at depth, extent. Scientists linked hole to chlorine from CFCs. Montreal Protocol signed in 1987; subsequent amendments will phase out CFCs completely by 2000. Hole will worsen until that time, then gradually recover by middle of next century.*