PUAF 741 **GLOBAL ENVIRONMENTAL PROBLEMS** SPRING 2004

FINAL EXAM SOLUTIONS

1. True or false (10 points total):

   A. If the rate of consumption is growing exponentially, consumption in next doubling period equals all previous consumption. **True** False

   B. Carbon dioxide is the chief greenhouse gas in the atmosphere.

   Water vapor is by far the most important GHG; CO2 is the most important human perturbation. True **False**

   C. In general, low clouds warm and high clouds cool the atmosphere. True **False**

   D. Uncertainty in climate models has steadily decreased with time.

   The range of climate sensitivities has remained remarkably constant, at 1.5 to 4.5 C, despite enormous improvements in the sophistication of the models. True **False**

   E. Sea level has risen from melting of sea ice in the Arctic Ocean.

   Sea ice floats; its melting has absolutely no effect on sea level. The melting of grounded ice—mountain glaciers and the vast ice sheets in Greenland and possibly Antarctica contributes to sea level rise, as does thermal expansion of ocean water. True **False**

   F. It is estimated that 90% of all species are found in the tropics.

   The estimate presented in class was 50-70%. True **False**

   G. As a result of Title IV of the 1990 amendments to the Clean Air Act, emissions of nitrates decreased about 50 percent.

   Emissions of SO2 were reduced by about 50 percent; emissions of NOx were reduced by only about 20 percent. True **False**

   H. All elements heavier than lithium were created in stars. **True** False

   I. All else equal, ecosystems with greater diversity are generally more productive and more stable to environmental change. **True** False

   J. In species-area relationships, the exponent z gives the change in the number of species for a 1 percent change in ecosystem area.

   The exponent gives the percentage change in the number of species for a 1 percent change in area. True **False**

2. Circle the correct numbers, words, or phrases (10 points total):

   A. The current concentration of CO_2 is about (275, 325, **375**, 450) ppmv.

   B. The population of the US is about (250, **300**, 350, 400) million.

   C. If $\Delta T = 2.5$ °C from a doubling of CO_2, then ΔT from a quadrupling of CO_2 would be roughly (2.5, **5**, 7.5, 10) °C.

   D. If we stabilize emissions of CO_2, the atmospheric concentration of CO_2 will (fall; remain constant; rise for a while then stabilize; **keep rising forever**).

      Remember: about 15% of the emitted CO2 stays in the atmosphere forever.

   E. The pH of pristine rainfall is about (5.0, **5.5**, 6.0, 6.5, 7.0).

   F. The principle source of acidity in natural rainfall is (OH^-, SO_2, **CO_2**, SO_4^{2-}).

      Sorry—I should have said "pristine" rainfall.

   G. In $pH = -\log_{10}[H^+]$, $[H^+]$ is in units of (g/g, g/mole, g/L, mole/g, mole/mole, **mole/L**)

   H. Approximately (**2**, 5, 10, 14, 30, 100) million species have been identified.

   I. In countries with stable populations the birth rate is approximately (4, 7, 10, **13**) per thousand people per year.

      $b = d = S/\tau$ = (1000 people)/75 y = 13 births per thousand people per year.

   J. World population estimates for 2050 have fallen steadily over the last 20 years has result of unexpected (**decreases in fertility**, increases in death rate).

3. The latest IPCC report concludes that climate is warming, and that this warming is due at least in part to human emissions of greenhouse gases. This conclusion is based not simply on the observed increase in global average temperature, but on the observed pattern of this warming.

   A. What pattern of warming would you expect to result from an increase in greenhouse gas concentrations? (5 points)

      If warming is due to greenhouse gases, there should be:

      - **more warming at higher latitudes than at the equator;**
      - **more warming in winter than during the summer;**
      - **more warming at night than during the day;**
      - **more warming over land than over the ocean;**
      - **more warming with time, beginning in late 1800s and increasing as GHG concentrations increase**

B. What observations, other than temperature, are consistent with greenhouse-gas-induced climate change? (5 points)

- **rising sea level due to thermal expansion of oceans and melting of ice;**
- **decrease in extent and thickness of Arctic sea ice and glaciers;**
- **smaller number of frost days;**
- **lakes and rivers freeze later and thaw earlier;**
- **weakening of the thermohaline circulation;**
- **more precipitation and a greater fraction of precipitation in storms;**
- **changes in animal behavior and migration of species toward poles.**

4. According to BP, total energy consumption in China increased from 441 million tons of oil equivalent (TOE) in 1982 to 998 million TOE in 2002. (10 points)

A. What was the average growth rate, in percent per year, over this 20-year period? (4 points)

ln[(998/441)]/20 = 0.0408 = 4.1%/y (continuous growth rate)

$(998/441)^{1/20} - 1 = 0.0417 = 4.2\%/y$ (annual yield)

B. During this period the population of China grew at an average rate of 1.0 percent per year, from 1050 to 1280 million. What was the average growth rate of per-capita energy consumption? (2 points)

4.1 – 1.0 = 3.1%/y

C. If per-capita consumption in China continued to grow at the average 1982-2002 rate, in what year would it reach the current U.S. level of 8 TOE/y? (4 points)

(998 million TOE/y)/(1280 million people) = 0.78 TOE/y per person

$8 = 0.78\ e^{0.031t}$ $t = [\ln(8/0.78)]/0.031 = 75\ y + 2002 \approx 2080$

$8 = 0.78\ (1.032)^{t}$ $t = [\ln(8/0.78)]/\ln(1.032) = 75\ y$

5. The preindustrial atmospheric concentration of methane (CH_4) was stable for thousands of years at about 700 parts per billion. The residence time of methane in the atmosphere is about 12 years.

A. What is the natural (i.e., preindustrial) flow of methane into the atmosphere, in millions of metric tons of CH_4 per year? (5 points)

$F = S/\tau = cV/\tau = (700 \cdot 10^{-9})(1.8 \cdot 10^{20})/12\ y = 1.05 \cdot 10^{13}$ mole/y

$(1.05 \cdot 1013$ mole/y)(16 g/mole)$(10^{-6}$ t/g)$(10^{-6}$ Mt/t) = 170 Mt/y

B. Anthropogenic emissions of methane are currently estimated at 400 million tons of CH_4 per year. If emissions were stabilized at this level, what would be the steady-state concentration of methane? (5 points)

If τ is constant, $c/c_0 = S/S_0 = F/F_0 = (170+400)/170 = 570/170 = 3.35$

$c = c_0\,(F/F_0) = (700\ \text{ppbv})(3.35) = 2350\ \text{ppbv} \approx 2400\ \text{ppbv}$

6. Today, the cost of producing electricity in a new nuclear reactor is estimated to be about \$0.065/kWh, compared to \$0.045/kWh for a new coal plant. What carbon tax (in dollars per metric ton of carbon) would be required to make nuclear economically competitive with coal? Assume coal is 75% carbon by weight, has a heat energy content of 29 MJ/kg, and that this heat can be converted to electricity with an efficiency of 40 percent in a new plant. (15 pts)

$$\left[\frac{\$0.02}{\text{kWh}}\right]\left[\frac{\text{kW}\cdot\text{s}}{\text{kJ}_e}\right]\left[\frac{\text{h}}{3600\ \text{s}}\right]\left[\frac{0.4\ \text{kJ}_e}{\text{kJ}_t}\right]\left[\frac{29\cdot10^3\ \text{kJ}_t}{\text{kg}_{coal}}\right]\left[\frac{\text{kg}_{coal}}{0.75\ \text{kg}_C}\right]\left[\frac{10^3\ \text{kg}_C}{\text{t}_C}\right] = \frac{\$86}{\text{t}_C} \approx \frac{\$90}{\text{t}_C}$$

7. In the early 1970s, NASA examined the effect of supersonic transports (SSTs) on the ozone layer. They considered a fleet of 500 SSTs, each making four transatlantic flights per day. The SST would spend about two hours in the stratosphere during each flight, burning fuel at a rate of 20 tons per hour. They estimated that 15 grams of nitric oxide (NO) would be produced per kilogram of fuel burned. Nitric oxide is a potent catalyst for ozone destruction; each NO molecule would, on average, catalyze the destruction of roughly 10,000 ozone molecules.

A. Estimate the steady-state rate of ozone destruction, in gigatons per year, resulting from the operation of the fleet of SSTs. (10 pts)

$$[500\ \text{SST}]\left[\frac{8\ \text{h}}{\text{d}}\right]\left[\frac{365\ \text{d}}{\text{y}}\right]\left[\frac{20{,}000\ \text{kg}_{fuel}}{\text{h}}\right]\left[\frac{15\ \text{g}_{NO}}{\text{kg}_{fuel}}\right]$$

$$\left[\frac{\text{mole}_{NO}}{30\ \text{g}_{NO}}\right]\left[\frac{10^4\ \text{mole}_{O_3}}{\text{mole}_{NO}}\right]\left[\frac{48\ \text{g}_{O_3}}{\text{mole}_{O_3}}\right]\left[\frac{\text{t}}{10^6\ \text{g}}\right]\left[\frac{\text{Gt}}{10^9\ \text{t}}\right] = 7.0\ \frac{\text{Gt}_{O_3}}{\text{y}}$$

B. Estimate, very roughly, the corresponding percentage decrease in the stratospheric ozone concentration, assuming that the rate of natural production (and natural destruction) remains constant at 160 Gt/y. (5 pts)

$\Delta c/c_0 \approx \Delta F/F_0 = -7/160 = -0.044 \approx -4\%$

8. The United States led the international community in a successful effort to rapidly phase out emissions of ozone depleting substances. In contrast, efforts to limit emissions of greenhouse gases have been much less successful, with the United States generally opposing reduction requirements. Discuss the possible reasons for the difference in policy outcomes, and offer your personal opinion. (10 pts)

Various reasons have been advanced, including:

- **ODCs were far less economically important than fossil fuels**
- **Substitutes were more readily available for ODCs than fossil fuels**
- **The same companies that produced ODCs stood to profit from substitutes, which is not true for industries that produce fossil fuels**
- **Ozone depletion poses a direct threat to human health—skin cancer—whereas the link between climate change and human health is much less clear.**
- **The risk from ozone depletion is predominately to light-skinned people in developed countries, while people in developing countries are usually considered to be at greater risk from climate change**
- **The international community was "shocked" into action by the unexpected appearance of the ozone hole over the Antarctic, which was unambiguously attributed to emissions of ODCs; we so far have had no such event related to climate change**

9. Some people claim that industry and economists greatly overestimate the costs of reducing emissions of pollutants and improving environmental quality. Do you agree? Cite specific examples. (10 pts)

The two examples discussed in class related to the estimated cost of reducing ODCs and SO_2.

In 1982, industry estimated that a 33% reduction in CFCs could be achieved for an average cost of $30/kg, and that 35% of production could not be eliminated to *any* cost. In 1988, after the Montreal Protocol was signed, the estimated cost of the required 50% reduction only $3.50/kg. By 1992, the complete elimination of CFCs was possible for an average cost of only $2.50/kg.

Similarly, in the early 1980s, economists estimated that the marginal cost (the permit price in a free market) of reducing SO_2 emissions by 50% would be $1000 to $3000 per ton of SO_2. After the 1990 amendments to the Clean Air Act were passed, the estimated permit price was $360 to $1200/t, with industry estimates at the high end. The actual permit price as fluctuated between $70 and $210/t, with an average of roughly $150/t.

In both cases, early estimates of mitigation costs were roughly ten times greater than actual costs. These experiences are often used to discount the traditional, very high estimates of CO_2 mitigation costs.