

## MIDTERM EXAM SOLUTIONS

1. *What changes in climate are expected as a result of greenhouse-gas emissions? What changes in climate have been observed? (15 points)*

Expected changes. An increase in global mean surface temperature, and in the temperature of the troposphere and the surface layer of the ocean. The temperature change should be greater near the poles, and greater in the nighttime than in the daytime (due to the compensating effect of aerosols).

An increase in cloudiness, in global mean precipitation, and in storminess. Also, an increase in global mean evapotranspiration. Because the increase in evaporation may be greater than the increase in precipitation, some areas will become dryer.

A decrease in sea ice and an increase in sea levels.

Observed changes. An increase in global mean surface, troposphere, and ocean temperatures of about 0.5 °C over the last century. The increase is larger near the poles and in the nighttime.

Cloudiness has increased, at least since 1950. Precipitation has increased over the century in areas with good records. The percentage of precipitation falling in high-precipitation events has also increased.

Sea ice coverage is decreasing by about 3 percent per decade, and sea level has increased by 10 to 25 cm.

2. *Discuss the uncertainties in some of the key climate predictions and observations noted in question 1. (9 points)*

The expected change in temperature is uncertain primarily because of uncertainties in the radiative forcing due to aerosols, and uncertainties in the climate sensitivity. The uncertainty in the latter is due primarily to uncertainties in cloud feedbacks, and, to a lesser extent, ocean current and biospheric feedbacks.

The measured temperature increase is uncertain because temperature records extend only to 1850, and because the geographical coverage of measurements has changed dramatically over that time. Additional uncertainties are caused by changes in measuring instruments and techniques, and changes in the environment surrounding measuring stations (the urban heat island effect).

The global mean change in precipitation is due mostly to uncertainties about changes in temperature. Changes in regional precipitation, however, are highly uncertain, because they depend on the relative increase in precipitation and evaporation in a particular place. Climate models are not yet able to make reliable predictions of evaporation.

Like temperature, historical changes in precipitation are uncertain because of the short time record of precipitation measurements, particularly over the oceans and in the southern hemisphere.

Uncertainties in sea ice and sea-level rise are highly uncertain, due partly to uncertainties in temperature change, which are magnified at the poles. Measurement also are highly uncertain.

3. *Briefly enumerate all of the environmental impacts associated with the application of fertilizer. (8 points)*

Fertilizers stimulate plant growth. Fertilizers, together with other anthropogenic sources of nitrogen and sulfur, may be increasing the stock of biomass in natural forests, particularly in the northern hemisphere. If so, this will slow the rate of increase of CO<sub>2</sub> in the atmosphere, and thereby reducing greenhouse warming.

This fertilization effect upsets certain ecosystems. For example, in the Chesapeake Bay fertilizer runoff has resulted in increased algae growth, decreasing the penetration of sunlight into the water. The subsequent decay of algae decreases the concentration of dissolved oxygen in the water, reducing its ability to support animal life. Similar effects have occurred in lakes from fertilizers containing phosphorus. Fertilizer runoff can also result in outbreaks of disease, such as phisteria.

The application of nitrogen fertilizer also increases production of nitrous oxide. Nitrous oxide is a powerful greenhouse gas. It is also a ozone depleting substance.

Ammonia fertilizer neutralizes acids, both in the air and on the ground. Excess application of fertilizer can decrease soil fertility, and runoff can be a health hazard. While nitrates themselves are not particularly harmful, they are converted into nitrites, which cause methemoglobinemia, and nitrosamines, which cause cancer.

4. A. *Roughly how many new passenger vehicles (cars, minivans, SUVs, light trucks) will be sold in the United States this year? (5 points)*

You must estimate the stock and average residence time. In class, we noted that there are roughly 200 million passenger vehicles in the United States. I would guess that the average car taken to the junk yard has 150,000 to 200,000 miles on it; at 12,000 mi/yr, this is roughly 15 years. In equilibrium:

$$F = M/\tau = (200 \text{ million vehicles})/(15 \text{ years}) = 13 \text{ million/yr}$$

The actual figure is about 15 million/yr; anything from 10–20 million/yr is fine.

- B. *Average fuel economy of passenger vehicles is about 20 miles per gallon. If this were doubled over the next 10 years, as was proposed by the Bryan Bill, by roughly how much would U.S. carbon emissions be reduced? Gasoline is 30 percent less dense than water, and its chemical composition is roughly CH<sub>1.5</sub>. (15 points)*

Estimate current emissions of carbon from cars; if fuel economy is doubled, then carbon emissions would be cut in half.

$$\left[ 200 \cdot 10^6 \text{ cars} \right] \left[ \frac{10^4 \text{ mi}}{\text{car} \cdot \text{yr}} \right] \left[ \frac{\text{gal}}{20 \text{ mi}} \right] \left[ \frac{3.8 \text{ L}}{\text{gal}} \right] \left[ \frac{0.7 \text{ kg}}{\text{L}} \right] \left[ \frac{12 \text{ kgC}}{13.5 \text{ kg}} \right] \left[ \frac{\text{MtC}}{10^9 \text{ kgC}} \right] = 230 \text{ MtC}$$

So doubling fuel economy would reduce U.S. carbon emissions by about 120 MtC, if the number of vehicle-miles did not increase. If past trends hold, however, the number of vehicle-miles will grow by 30 to 40 percent over the next 10 years.

5. A. *The Greenland ice sheet contains 3 million km<sup>3</sup> of grounded ice (ice resting on land). If climate change caused 10 percent of this ice to melt, by about how many feet would mean sea level rise? (7 points)*

$$\left[ 0.3 \cdot 10^6 \text{ km}^3 \right] \left[ \frac{1}{0.7 (5.1 \cdot 10^{14} \text{ m}^2)} \right] \left[ \frac{10^9 \text{ m}^3}{\text{km}^3} \right] \left[ \frac{3.3 \text{ ft}}{\text{m}} \right] = 2.8 \text{ ft} \approx 3 \text{ ft}$$

- B. *The North Pole ice pack, which is a series of floating ice slabs, contains on average about 20,000 km<sup>3</sup> of ice. If this ice melts, how much will sea level rise? (3 points)*

It won't rise at all. Floating ice (or anything else that floats) displaces a volume of water equal to its mass.

6. A. *The preindustrial concentration of CO<sub>2</sub> was 280 ppmv. What was the mass of CO<sub>2</sub> in the preindustrial atmosphere, in gigatons of carbon (GtC)? (7 points)*

$$\left[ \frac{280 \cdot 10^{-6} \text{ mole}_{\text{CO}_2}}{\text{mole}_{\text{air}}} \right] \left[ 1.78 \cdot 10^{20} \text{ mole}_{\text{air}} \right] \left[ \frac{\text{mole}_{\text{C}}}{\text{mole}_{\text{CO}_2}} \right] \left[ \frac{12 \text{ g}_\text{C}}{\text{mole}_{\text{C}}} \right] \left[ \frac{\text{Gt}}{10^{15} \text{ g}} \right] = 600 \text{ GtC}$$

- B. *If CO<sub>2</sub> concentration is stabilized at twice the preindustrial value, and the added CO<sub>2</sub> (from fossil-fuel burning and deforestation) has an average residence time of 150 years, what would be the steady-state flow of carbon into the atmosphere, in GtC/yr? (7 points)*

$$F = M/\tau; \text{ if } M = 600 \text{ GtC, and } \tau = 150 \text{ yr, then } F = (600 \text{ GtC})/(150 \text{ yr}) = 4 \text{ GtC/yr}$$

- C. *The current rate of anthropogenic emission is 25 billion metric tons of CO<sub>2</sub> per year. Suppose that parties to the Framework Convention on Climate Change agreed to stabilize global emissions by 2050 at the level calculated in part B. At what average rate would emissions have to decline over the intervening 50-year period? (7 points)*

$$F = \left[ \frac{25 \text{ Gt}_{\text{CO}_2}}{\text{yr}} \right] \left[ \frac{12 \text{ GtC}}{44 \text{ Gt}_{\text{CO}_2}} \right] = 6.8 \frac{\text{GtC}}{\text{yr}}$$

$$r = \frac{\log_e \left( \frac{F}{F_0} \right)}{t} = \frac{\log_e \left( \frac{4}{6.8} \right)}{50} = -1.1\% / \text{yr}$$

$$i = \left( \frac{F}{F_0} \right)^{\frac{1}{t}} - 1 = \left( \frac{4}{6.8} \right)^{\frac{1}{50}} - 1 = -1.1\% / \text{yr}$$

D. Total emissions are the product of population, per-capita GDP, and emissions per unit of GDP. Over the next 50 years, population is expected to grow from 6 to 9 billion, and per-capita GDP is expected to grow at an average rate of 1.5 percent per year.

If global emissions are to be stabilized as described in part C, at what average rate must emissions of carbon per dollar of GDP decline? How does this compare to the average rate of decline over the last 50 years of about 1.2 percent per year? (7 points).

Carbon emission (I) equals the product of population (P), per-capita GDP (A), and emissions of carbon per dollar of GDP (T), so the growth rates are additive.

$$r_P = \frac{\log_e \left( \frac{9}{6} \right)}{50} = 0.0081 = 0.81\% / \text{yr}$$

$$r_I = r_P + r_A + r_T \qquad r_T = r_I - r_P - r_A = -1.07 - 0.81 - 1.5 = -3.4\% / \text{yr}$$

Thus, the required rate of improvement over the next 50 years is nearly three times the rate over the 50 years.

7. As discussed in class, the carbon dioxide concentration has measured each month at a station in Hawaii since 1958.

A. (5 points) In what month of the year is the concentration:

Low? late summer/early fall                      High? late winter/early spring

Why? photosynthesis and respiration/decay: CO<sub>2</sub> concentrations are lowest when the amount of stored biomass is highest, and vice-versa.

B. The difference between the annual high and low concentrations has been increasing steadily since 1958. What does this indicate? (5 pts)

It means that the amount of carbon stored in the biosphere is growing, because the amount of carbon absorbed from the atmosphere in the spring and summer is increasing, and the amount of carbon released by decay in the fall and winter is increasing.