

MIDTERM EXAM SOLUTIONS

1. *Explain the concept of “net radiative forcing” that results when a greenhouse gas is added to the atmosphere. How might feedbacks in the system, particularly those involving water vapor, affect the absorption of solar energy by the climate system? (10 points)*

Net radiative forcing is the change in the energy balance of the climate system. Adding a greenhouse gas increases the absorption of infrared energy, decreasing the amount of energy radiated to space. In response, the surface warms and the emission of infrared increases until a new equilibrium is established.

Feedbacks can amplify or dampen greenhouse warming. Water vapor is generally believed to be a strong positive feedback: warmer temperatures lead to more evaporation and higher H₂O concentrations. But the increased evaporation may also lead to greater cloud cover, increasing albedo and decreasing the absorption of solar energy: a negative feedback.

2. *Does the burning of fuels derived from vegetation contribute to the greenhouse effect? (10 points)*

It depends. Burning vegetation can release even more CO₂ per unit energy produced than oil or coal. But if vegetation is grown at the same rate as it is consumed, then there is no net emission of CO₂. Growing vegetation for fuel could conceivably increase the emission of other greenhouse gases—particularly methane and nitrous oxide—if the vegetation is fertilized or irrigated, but this is less important.

3. *It is sometimes argued that, since temperatures change from day to day, from season to season, and from place to place by many tens of degrees, a 1 or 2 °C change in average global temperature can have little significance. Comment. (10 points)*

Ecosystems generally are adapted to a particular climate, and the regular daily and seasonal variations in temperature. A change of a few degrees in average temperature can, in fact, change the type of ecosystems that can be supported in a particular location. In addition, temperature changes in some locations (e.g., high-latitude forests) are likely to be twice as large as global-average changes. But temperature is by no means the only climate variable. Precipitation and evaporation are generally more important, and these vary exponentially with temperature. Ecosystems also are vulnerable to extreme events—for example, flood and drought—and the incidence of these events can change greatly if average temperature changes by a few degrees. A good point of comparison is the last ice age: the average temperature was only about 5 °C cooler than today, but the world looked dramatically different. There is also the question of the stability of climate.

There is evidence that, in past, changes of several degrees triggered fundamental changes in ocean and atmospheric circulation.

4. *How might climate change affect the Chesapeake Bay? (10 points)*

Sea-level would rise, flooding existing marshes that are the most productive areas of the estuary. Of course, new marshes also might be created, but levees probably would be built to protect towns and farmland. The increased sea level would lead to increased tidal exchange of seawater, generally increasing salinity. Water temperatures generally would be warmer, and increased precipitation might increase runoff into the Bay, and dilute nutrients/pollutants such as nitrates. Alternatively, increased evaporation could decrease runoff and concentrate pollutants; the balance between these effects is difficult to judge for a particular region. Overall, these changes in water temperature, salinity, depth, and nutrient concentrations could affect significantly the ecology of the Bay.

5. *As discussed in class, the global-average equilibrium temperature change is roughly proportional to the change in radiative forcing, ΔF . For carbon dioxide, $\Delta F \cong 6.3 \log_e(C/C_0)$ watts per square meter, where C is the carbon-dioxide concentration and C_0 is its initial concentration. The global-average equilibrium temperature change that would result from a doubling of the carbon-dioxide concentration, ΔT_{2x} , is estimated to be 1.5 to 4.5 °C.*

A. *What temperature increase would result from a quadrupling of the CO₂ concentration? (10 points)*

$$\Delta T = \lambda \Delta F = 6.3 \lambda \ln(C/C_0) \quad \frac{\Delta T_{4x}}{\Delta T_{2x}} = \frac{6.3 \lambda \ln(4)}{6.3 \lambda \ln(2)} = \frac{\ln(4)}{\ln(2)} = 2 \quad \Delta T_{4x} = 2 \Delta T_{2x}$$

$$\Delta T_{4x} = 3 \text{ to } 9 \text{ °C.}$$

B. *Compare this increase to historical changes in temperature (10 pts)*

Average temperature has not varied by more than ± 1 °C during the last 10,000 years. During the last ice age, average temperature was about 5 °C lower than today. The temperature change from a quadrupling of CO₂ would approach or exceed the temperature changes experienced during the last 2 million years.

6. *The preindustrial concentration of methane (CH₄) was about 0.7 parts per million by volume (ppmv). Natural sources of methane are estimated to emit about 160 million tonnes (Mt) of methane per year.*

A. *What was the preindustrial stock of methane in the atmosphere, in Mt? (10 points)*

$$\text{stock} = (\text{concentration by volume}) \cdot (\text{volume}) \cdot (\text{density})$$

$$\left[\frac{0.7 \text{ mole}(\text{CH}_4)}{10^6 \text{ mole}(\text{air})} \right] \left[1.78 \cdot 10^{20} \text{ mole}(\text{air}) \right] \left[\frac{(12 + 4) \text{ g}}{\text{mole}(\text{CH}_4)} \right] \left[\frac{\text{t}}{10^6 \text{ g}} \right] \left[\frac{\text{Mt}}{10^6 \text{ t}} \right] = 2000 \text{ Mt}$$

- B. *If natural sources have remained unchanged since preindustrial times, what was the residence time of methane in the preindustrial atmosphere? (10 points. If you don't have the answer to part A, assume it is 1000 Mt.)*

$$\tau = (\text{stock}) \div (\text{flow})$$

$$\frac{2000 \text{ Mt}}{160 \frac{\text{Mt}}{\text{yr}}} = 12.5 \text{ yr}$$

- C. *It is estimated that human activities currently release an additional 400 Mt/yr of methane into the atmosphere. Assuming this rate stays constant, estimate the steady-state concentration of methane. How long would it take to achieve this concentration? (10 points)*

$$\text{concentration by volume} = \text{stock} \div (\text{volume} \cdot \text{density}); \quad \text{stock} = \tau \cdot (\text{flow})$$

The flow increases from 160 Mt/yr (preindustrial) to (160 + 400) = 560 Mt/yr (today)—a factor of 3.5 increase. If the residence time stays the same, then the stock also increases by a factor of 3.5, to 7000 Mt, and the concentration increases by the same factor, to 2.45 ppmv.

The more-difficult way:

$$\left[\frac{560 \text{ Mt}(\text{CH}_4)}{\text{yr}} \right] \left[12.5 \text{ yr} \right] \left[\frac{10^{12} \text{ g}}{\text{Mt}} \right] \left[\frac{\text{mole}(\text{CH}_4)}{16 \text{ g}} \right] \left[\frac{1}{1.78 \cdot 10^{20} \text{ mole}} \right] \left[\frac{\text{ppmv}}{10^{-6}} \right] = 2.45 \text{ ppmv}$$

7. *At what rate would carbon emissions grow if population grows at 1 percent per year and per-capita emissions grow at 2 percent per year? How long would it take for carbon emissions to double? (10 points)*

$$(\text{total emissions}) = (\text{population}) \cdot (\text{emissions/person}); \quad E = P \cdot C$$

If P is growing at rate r_p and C is growing at rate r_c , then E grows at rate $(r_p + r_c)$

In this case we are given annual (not continuous) growth rates, but because $i \ll 1$, $i \cong r$. So total consumption grows at a rate of about 3 percent per year.

The product of the doubling time, T_{2X} , and the growth rate r in percent per year is $rT_{2X} = 69$. In this case $r = 3$ percent per year, so $T_{2X} = 69/3 = 23$ years.