Study Questions and Answers

Questions

Chemistry

1. The most simple chemical expression for the production of organic matter in plants is

\[ \text{CO}_2 + \text{H}_2\text{O} = \text{CH}_2\text{O} + \text{O}_2 \]

The chemical compound \( \text{CH}_2\text{O} \) is organic matter; \( \text{CO}_2 \) is carbon dioxide gas; \( \text{O}_2 \) is diatomic oxygen; and \( \text{H}_2\text{O} \) is water. The atomic weights of the elements C, H, and O are, respectively, 12, 1, and 16.

A. What are the gram molecular weights of the compounds of \( \text{CH}_2\text{O} \), \( \text{CO}_2 \), \( \text{O}_2 \), and \( \text{H}_2\text{O} \)?

B. What is the weight of one mole of each of these compounds?

C. If 10 moles of plant matter have been produced, how many moles of \( \text{CO}_2 \) did it take to produce the plant matter? How many grams of \( \text{CO}_2 \)?

D. If the C:N ratio of the plant material in moles is 106:16 (that of marine phytoplankton), how many moles of nitrogen were needed to produce the plant matter?

E. If the source of the nitrogen were nitrate \( (\text{NO}_3^-) \) in the euphotic zone of the ocean, how many grams of nitrate were consumed in the process?

2. Write a balanced chemical reaction for the weathering of the mineral orthoclase feldspar \( (\text{KAlSi}_3\text{O}_8) \) by water containing dissolved \( \text{CO}_2 \). The products that are formed in this weathering reaction are: kaolinite \( ((\text{Al}_2\text{Si}_2\text{O}_10(\text{OH})_4)) \), bicarbonate \( (\text{HCO}_3^-) \), monomeric silicic acid \( (\text{H}_4\text{SiO}_4{\text{O}}) \), and dissolved potassium ion \( (\text{K}^+) \). (Hint: to begin, balance the reaction on aluminum.)

3. The concentration of dissolved potassium \( (\text{K}^+) \) in the ocean is 390 mg/kg. The atomic weight of potassium is 39. The average density of seawater is 1.027 g/cm\(^3\).

A. What is the concentration of \( \text{K}^+ \) in seawater in moles/kg?

B. What is its concentration in parts per million by volume of seawater?

4. The average molecular weight of the gases in the atmosphere is 29 and the mass of the atmosphere is \( 52 \times 10^{20} \) grams.

A. What is the total number of moles of gases in the atmosphere?

B. Carbon dioxide gas makes up 0.036 % of the atmosphere in moles. How many moles of \( \text{CO}_2 \) are there in the atmosphere? How many grams?
5. Water vapor in the atmosphere averages about 0.2% of the atmosphere in weight.
   A. What is the total mass of water vapor in the atmosphere?
   B. How many moles of H$_2$O vapor are there in the atmosphere?

The Oceans, Atmosphere, Sediments, and Rocks

1. The average depth of the ocean is 3.8 kilometers and the average upwelling rate of deep water into the surface open ocean and into coastal environments is 4 m/yr. The area of the ocean is $3.6 \times 10^{18}$ cm$^2$.
   A. About how long would it take to upwell the entire volume of the ocean?
   B. The average nitrogen content of deep water is about $40 \times 10^{-6}$ moles per liter (L). What is the annual rate of addition of nitrogen to the surface water due to upwelling?
   C. At a molar ratio of C:N of 106:16, what is the productivity in the global surface ocean in grams (g) C/m$^2$/yr sustained by the upwelling of nitrogen?

2. One source of the deep water of the world’s oceans is in the Norwegian Sea. Here water is sufficiently dense to sink to the bottom. This water mainly forms from the cooling by evaporation of water carried northward by the Gulf Stream. The Gulf Stream carries heat to the high latitudes of the North Atlantic Ocean which helps to moderate the climate of Europe. There is considerable interest in the rate of formation of North Atlantic deep water (NADW) because of the role it plays in climate. Possible changes in the rate of its formation have been cited as the cause of rapid climate change in the past. Any global warming could modify the rate of deep water formation.
   A. How would you expect the residence time of the deep water to change from the Atlantic Ocean to the Pacific Ocean?
   B. How does the deep water return to the surface?
   C. If the continental glaciers were to begin melting because of a global warming, what would you expect might happen to the rate of deep water formation and the climate of Europe?

3. The winds of the earth tend to blow along latitudinal lines around the planet. The major wind belts are the Polar Easterlies, Westerlies, Trade Winds, and Equatorial Easterlies in both the Northern and Southern Hemispheres. The winds drive the surface currents of the ocean. Cool air that has descended at midlatitudes moves toward the equator as the Northeast and Southeast Trade Winds in the Northern and Southern Hemispheres, respectively. These winds exert a force on the sea surface, and currents are generated that flow toward the equator. Both the winds of the atmosphere and the surface currents of the ocean converge near the equator. The warm equatorial air rises and moves north and south toward the poles. The converging ocean currents generate westward-flowing equatorial currents.
   A. Based on the above, would you expect a pollutant gas like carbon monoxide with major anthropogenic sources in the Northern Hemisphere and a short atmospheric residence time to be evenly distributed in the troposphere?
   B. Is there an equatorial barrier to the dispersal of floating tar balls produced when petroleum tankers spill oil in the shipping lanes of the North Atlantic?
   C. Does such a barrier exist for the deep waters of the ocean?
4. The very finest particles of airborne dust carried by winds off the Sahara Desert travel in the troposphere for long distances westward across the Atlantic Ocean. These particles are deposited on the ocean surface and settle out at a rate of 500 cm/yr. How long would it take such particles to reach the bottom of the Atlantic Ocean at 4 km?

5. The global atmosphere in 1996 contained about 360 ppmv of CO₂. This concentration is equivalent to a partial pressure of CO₂ (PCO₂) of 10⁻³.₄₅ atmosphere (atm).
   A. What is the concentration of dissolved CO₂ in the surface ocean in equilibrium with atmospheric CO₂ at a temperature of 25°C?
   B. In the year 1700, when atmospheric CO₂ was at a concentration level of 280 ppmv (PCO₂ = 10⁻³.₅₅ atm), what was the concentration of CO₂ in the surface ocean?
   C. What was the percentage change in atmospheric CO₂ concentration between 1700 and 1996?

6. The primary energy sources for the earth are:
   • solar radiation, 0.5 cal/cm²/min (about 343 W/m²)
   • heat flow from the interior of the earth, 0.9 x 10⁻⁴ cal/cm²/min
   • tidal energy, 0.9 x 10⁻⁵ cal/cm²/min.

   About 49% of the solar radiation is absorbed by earth’s surface and reradiated to space as longwave, infrared radiation.
   A. What percentage of the total comes from the combination of heat from the interior of the earth and tidal energy?
   B. In units of W/m², how much solar radiation reaches the earth’s surface and is absorbed there? What does this energy do?
   C. Of the 388 W/m² of longwave radiation emitted to space by the earth’s surface, 326 W/m² are absorbed by water vapor, CO₂, and other greenhouse gases in the atmosphere and reradiated back to the earth. What happens to this energy, and what effect does it have on the earth?

7. The area of land today is 150 x 10¹² m², and the mean elevation of the continents is 0.84 km. The continents are being eroded at a rate of 200 x 10¹⁴ g/yr. The average density of rock is 2.7 g/cm³.
   A. At the current rate of erosion, how long would it take to wear the continents down to sea level?
   B. Your answer to question 7A was a period of time much less than the age of the earth of 4.6 billion years. In that case, why are there any continents?

8. The total mass of sedimentary rock younger than 600 x 10⁶ years is 1.8 x 10¹⁸ metric tons. Its mean residence time is 400 x 10⁶ years.
   A. In an unchanging system, what is the flux of sediment in and out of the sedimentary rock reservoir?
   B. How does sediment get into the sedimentary rock reservoir and how does it get out?
9. What chemical species of nitrogen, sulfur, and carbon might you expect to find in a water-logged (anoxic) soil? In a well-aerated soil?

10. What does the weathering of silicate minerals subtract from or add to the atmosphere?

**Ecology**

1. Tropical rain forests have a total area of $17 \times 10^{12}$ m$^2$, and estuaries have an area of $1.4 \times 10^{12}$ m$^2$. Their mean net primary production is $2,000$ g dry plant matter/m$^2$/yr and $1,800$ g dry plant matter/m$^2$/yr, respectively. Their mean plant biomasses in kg C/m$^2$ are 20 and 0.45, respectively. Forty-five percent of dry plant matter is carbon.

   A. What is the total net primary production of tropical rain forests and estuaries in metric tons of dry plant matter and carbon per year?

   B. What is the total plant mass of these ecosystems in metric tons of dry plant matter and carbon?

   C. The tropical rain forests of the world lost 9% of their area due to cutting in the 1980s. How much dry plant matter does this cutting represent? How much carbon?

   D. If all of the carbon in the cut trees of question 1C were emitted to the atmosphere by burning and slow oxidation, how many grams of CO$_2$ would this represent? What fraction of the atmospheric CO$_2$ reservoir is this (see Figure 11)?

   E. Estuaries receive $1.5 \times 10^{12}$ g of pollutant dissolved phosphorus annually (see Figure 18). This amount of P could support how much additional plant productivity as dry matter and as C/m$^2$ per year?

   F. If all the additional plant matter in 1A were buried in the sediments of the estuaries, would this flux qualify as a biological feedback to the accumulation of CO$_2$ in the atmosphere? Explain. What percentage of the atmospheric flux of $6 \times 10^{15}$ g C from fossil fuel burning in 1995 does the additional total plant production in estuaries represent?

2. The net primary production of the earth’s surface is 0.37 kg dry matter/m$^2$/yr.

   A. With a total area of $510 \times 10^{12}$ m$^2$, what is the total production of dry matter?

   B. How much carbon does the production in 2A represent?

   C. Total production on land exceeds that in the ocean by perhaps as much as two times. What is the annual total production on land and in the ocean?

3. What is the difference between autotrophy and heterotrophy?

4. What are three biogeochemical processes performed by the prokaryotes?

5. What is cultural eutrophication? Why may this phenomenon qualify as a negative feedback to the accumulation of CO$_2$ in the atmosphere?
Biogeochemical Cycles

1. Construct a diagram showing the reservoirs and fluxes in the global biogeochemical cycle of water. Use the information in Figure 21 and Table 3, and the reservoirs of atmosphere, land, and ocean.

   A. What is the residence time of water in the ocean with respect to the flux of water via the rivers to the ocean?
   
   B. If the concentration of dissolved calcium is 400 ppm in the ocean and 15 ppm in average river water, what is the residence time of calcium in the ocean?

2. A nearly rectangular-shaped lake is 5 km long, 2 km wide, and 100 m deep and contains 0.001 mg/L of dissolved mercury. A river discharges $2 \times 10^{12}$ L/yr of water with a concentration of mercury of 0.0005 mg/L into the lake.

   A. What is the water volume in the lake (in liters)?
   
   B. What is the total mass of mercury in the lake?
   
   C. What is the residence time of mercury in the lake?
   
   D. An industrial plant near the mouth of the river accidentally discharges mercury into the lake. How long will it take for most (95%) of the mercury contamination to work its way out of the lake?

3. The terrestrial living biomass contains 600 x $10^9$ tons of carbon. It is argued that during the decade of the 1980s, about 135 x $10^{12}$ moles of anthropogenic CO$_2$ were taken up annually by the terrestrial biomass.

   A. What would be the average annual percentage increase in the mass of carbon in the terrestrial biosphere?
   
   B. Do you believe such an increase would be detectable by doing field studies to determine the increase in biomass?

4. The mixed layer of the ocean is the vertical layer that is well stirred by winds blowing across the surface of the sea. Chemical and physical characteristics of the water column are rather uniform over the depth of the mixed layer. The average thickness of the mixed layer throughout the world’s oceans is about 100 meters but varies from 50 to 300 meters. The average total dissolved inorganic carbon (DIC, HCO$_3^-$ + CO$_3^{2-}$ + CO$_2$) content of the mixed layer is 2.2 micromoles (mmol) per kg.

   A. What is the total mass (reservoir) of DIC in the mixed layer of the ocean in moles of carbon? (The area of the ocean is $360 \times 10^{12}$ m$^2$.)
   
   B. The ocean takes up about 2 billion tons of carbon annually from the human activities of fossil fuel combustion, cement manufacturing, and deforestation. What is the annual increase in dissolved carbon in the mixed layer of the ocean in mmol/kg due to this absorption of anthropogenic CO$_2$?
   
   C. Use the annual increase you derived from 4B and assume the DIC content of the mixed layer was 2.2 mmol/kg in 1975. What would be the percentage increase in the DIC content of the mixed layer from 1975 to 1996?
5. Total evaporation is $496 \times 10^3$ km$^3$ H$_2$O/yr over the earth's surface.
   A. What is the residence time of water in the atmosphere?
   B. If a pollutant is susceptible to being rained out (washed out) of the atmosphere, would you expect it to mix evenly throughout the troposphere?

6. What are the three major processes controlling atmospheric CO$_2$ concentration levels on a long time scale? Write a balanced set of chemical equations demonstrating these processes.

7. What is the connection between organic matter and atmospheric O$_2$?

8. What is the major difference between the biogeochemical cycle of phosphorus and those of carbon, nitrogen, and sulfur?

9. What is the major difference in the reactivity of DMS and OCS in the atmosphere?

10. The mean atmospheric lifetime (residence time) of NH$_3$ is 14 days; that of CO is 60 days. How do the rates of destruction of these gases in the atmosphere by OH$^*$ compare qualitatively?

11. Referring to Figures 9–11, what is the major reaction in the atmosphere that couples the biogeochemical cycles of CH$_4$, CO, and CO$_2$? What percentage of the enhanced greenhouse forcing on climate is due to CO$_2$? To CH$_4$? What are the sources of emissions of CH$_4$ to the atmosphere from human activities? Of CO$_2$ and CO? If the concentration of CO$_2$ in the atmosphere were doubled, what would be the potential increase in temperature? How much more effective is CH$_4$ than CO$_2$ as a greenhouse gas?

12. Referring to Figure 12, what is the ratio of anthropogenic N fluxes on land involving fixation of atmospheric N to natural biological fixation? What is the minimum percentage of the N fixed by human activities that is discharged to the ocean by rivers? What is the important environmental problem related to this additional N flux to the ocean?

13. Referring to Figure 13, what is the ratio of these two fluxes: the upwelling flux of N to the coastal zone and the dissolved N flux to the ocean via rivers? Which flux would you expect to change during the next century?

14. Referring to Figure 14, based on the summation of the high and low estimates of fluxes of N$_2$O from earth’s surface to the atmosphere, what is the range in residence time estimates for N$_2$O in the atmosphere? What percentage of the enhanced greenhouse forcing of climate is due to N$_2$O?

15. Referring to Figure 16, of the total flux of NO$_x$ to the atmosphere, what percentage is from human activities? What is the principal type of reaction that destroys NO$_x$ in the atmosphere? Write the reaction for the destruction of NO$_2$ and its subsequent removal as HNO$_3$.

16. Referring to Figure 18, the total mass of P in land plants is 1,800 million tons and that in marine plankton is 73 million tons. What is the ratio of the internal recycling flux in the ocean to that on land? What is the residence time of P in the land biota relative to the recycling flux? In the marine plankton?
**Answers**

**Chemistry**

1. This question is designed to enable the student to review basic knowledge of the meaning of a chemical equation. Many biogeochemical processes are simply described by chemical reactions. In this reaction, there are four pure substances that can be decomposed by a chemical change, that is, four chemical compounds: \( \text{CO}_2(\text{gas}) \), \( \text{H}_2\text{O}(\text{liquid}) \), \( \text{CH}_2\text{O}(\text{solid}) \), and \( \text{O}_2(\text{gas}) \). The atoms in these compounds may separate from one another and rearrange themselves during a chemical reaction. In this case, in the presence of light and available nutrients, plant material has formed from \( \text{CO}_2 \) and \( \text{H}_2\text{O} \), and the carbon atom in \( \text{CO}_2 \) has been rearranged into the carbon atom of \( \text{CH}_2\text{O} \). This reaction further shows that all chemical equations must balance. The total number of atoms of an element on the left-hand side of an equation must equal the total number of atoms of that element on the right-hand side of the equation.

A. The atomic weights of the elements in these compounds are \( C = 12 \), \( H = 1 \), \( O = 16 \). Thus, the summation of these weights, or the gram molecular weight, for \( \text{CH}_2\text{O} \) is \( 12 + (2 \times 1) + 16 = 30 \text{ g} \); for \( \text{O}_2 \), \( 2 \times 16 = 32 \text{ g} \); for \( \text{CO}_2 \), \( 12 + (2 \times 16) = 44 \text{ g} \); and for \( \text{H}_2\text{O} \), \( (2 \times 1) + 16 = 18 \text{ g} \).

B. The weight of one mole of these compounds is \( \text{CH}_2\text{O} = 30 \text{ g} \); \( \text{O}_2 = 32 \text{ g} \); \( \text{CO}_2 = 44 \text{ g} \); and \( \text{H}_2\text{O} = 18 \text{ g} \).

C. The relationships between the compounds as shown in the equation must always be preserved; thus one unit—that is, one mole of the reactant compound \( \text{CO}_2 \)—must react with an equivalent number of moles of the reactant compound \( \text{H}_2\text{O} \) to give you a ratio of product compounds of \( \text{CH}_2\text{O}:\text{O}_2 = 1:1 \). Thus, the formation of 10 moles of plant material requires 10 moles, or 10 moles \( x 44 \text{ g/mole} = 440 \text{ g} \) of \( \text{CO}_2 \).

D. At a molar ratio (that is, a ratio of moles) of \( \text{C}:\text{N} = 106:16 \), the moles of nitrogen are \( 16/106 \times 10 \text{ moles} = 1.51 \text{ moles} \).

E. The atomic weight of \( N \) is 14. The reaction required 1.51 moles of \( N \) or 1.51 moles of \( \text{NO}_3^- \). (There is 1 mole of \( N \) in 1 mole of \( \text{NO}_3^- \).) The molecular weight of \( \text{NO}_3^- \) is \( 14 + (3 \times 16) = 62 \text{ g} \). Thus, the grams of nitrate consumed were \( 1.51 \text{ moles} \times 62 \text{ g} \times \text{moles} = 93.6 \text{ g} \) \( \text{NO}_3^- \).

2. This question again deals with chemical reactions. The equation to be balanced represents the weathering of a common mineral found at the surface of the earth. The student not only learns to balance a reaction on the basis of atoms but also on the basis of charge. The reason for starting the balance on aluminum is that solids containing aluminum are very insoluble at the temperature and pressure of weathering. Thus, it is assumed that all the aluminum from the weathering of orthoclase feldspar is simply transferred to the solid weathering product kaolinite. Of course, this is not true, but it is a reasonable approximation.

\[
2\text{KAlSi}_3\text{O}_8 + 2\text{CO}_2 + 11\text{H}_2\text{O} = \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{K}^+ + 2\text{HCO}_3^- + 4\text{H}_4\text{SiO}_4^0
\]

3. Dissolved potassium is the sixth most important dissolved constituent in seawater. Its concentration is important to biological processes, although it is a minor essential element for phytoplankton productivity.

A. The concentration of \( \text{K}^+ \) in the ocean in moles/kg = \( 390 \times 10^{-3} \text{ g/kg seawater} \div 39 \text{ g/mole} = 10 \times 10^{-3} \text{ moles/kg seawater} \) or 10 millimoles.
B. The average density of seawater is 1.027 g/cm³. Thus, 1 kg of seawater is equivalent to 1,000 g of seawater ÷ 1.027 g/cm³ = 973.7 cm³ of seawater. The concentration in parts per million by volume of seawater is 390 x 10⁻³ g/kg seawater x 1.027 x 10⁻³ kg/cm³ x 1,000 cm³/L seawater = 400.5 x 10⁻³ g/L = 400.5 mg/L = 400.5 ppmv of seawater.

4. The atmosphere is an important reservoir that exchanges materials with the earth’s surface. Its composition has changed on a geological time scale and on the human scale of generations because of the activities of human society. This problem illustrates the fact that although atmospheric CO₂ accounts for 60% of the enhanced greenhouse effect, it represents a relatively small part of the total atmospheric mass.

A. The mass of the atmosphere can be obtained from the weight of air above 1 cm² of the earth’s surface and the total area of the earth: 1,031 g/cm² x 5.1 x 10¹⁸ cm² = 5.2 x 10²⁰ g. The total number of moles of gases in the atmosphere is 5.2 x 10²⁰ g ÷ 29 g/mole = 1.8 x 10²⁰ moles.

B. The number of moles of CO₂ is 0.00036 x 1.8 x 10²⁰ moles = 64.8 x 10¹⁵ moles. The mass of CO₂ in grams is 64.8 x 10¹⁵ moles x 44 g/mole = 2,850 x 10⁹ metric tons = 2,850 gigatons x (12 ÷ 44) = 777 gigatons of C ÷ 12 g/mole = 64.8 x 10¹⁵ moles C.

5. Water vapor is the most important greenhouse gas, yet as the following calculation shows, it is a small portion of the mass of the atmosphere.

A. The total mass of water vapor in the atmosphere is 0.002 x 5.2 x 10²⁰ g = 10.4 x 10¹⁸ g.

B. There are 10.4 x 10¹⁸ g ÷ 18 g/mole = 57.8 x 10¹⁶ moles of water vapor.

The Oceans, Atmosphere, Sediments, and Rocks

1. Upwelling is an important process in the ocean. It involves the upward movement of water and dissolved constituents from depth in the ocean to the surface. Upwelling occurs in the coastal regions of offshore Peru, California, Namibia, Mauritania, and Somalia, and in open ocean equatorial regions and the high latitudes of the Southern Hemisphere.

A. To upwell the volume of the ocean with an average depth of 3,800 m at the mean upwelling rate of 4 m/yr would take 3,800 m ÷ 4 m/yr = 950 years.

B. 400 cm of water rises 1 cm²/yr. With an ocean area of 3.6 x 10¹⁸ cm², this is equivalent to a volume of water of 1.44 x 10¹⁸ cm³/yr or 1.44 x 10¹⁵ L/yr x 40 x 10⁻⁶ moles N/L = 57.6 x 10¹² moles N/yr x 14 g/mole = 806 x 10¹² g N/yr.

C. 806 x 10¹² g N/yr ÷ 14 g/mole = 57.6 x 10¹² moles of N/yr. At a C:N ratio of 106:16 = 382 x 10¹² moles C/yr x 12 g/mole = 4.6 x 10¹⁵ g C/yr ÷ 360 x 10¹² m² = 13 g C/m²/yr. This productivity is only about 10% of global marine net primary productivity (Figure 11). This calculation illustrates the fact that much of the nitrogen used in biological productivity in the euphotic zone of the ocean comes from recycling of the N within this zone.

2. The formation of the deep water of the ocean is part of the conveyor belt circulation pattern of the world oceans. This pattern is not well known from observations; our understanding of it is based mainly on theoretical models. The North Atlantic deep water (NADW) flows southward at depth from its source in the high latitudes of the North Atlantic Ocean and meets a northward-flowing current (the Antarctic Bottom Water, ABW) whose water originated by sinking in the Weddell Sea near Antarctica. The currents merge and part of the water flows into the deep Indian Ocean and Pacific
Ocean. Water upwells to the surface in all basins of the ocean. In addition, warm water returns from the Pacific and Indian Oceans into the Atlantic Ocean at about the depth of the thermocline. We believe these return flows to the Atlantic Ocean occur through the Drake Passage between Antarctica and South America and through the Bering Sea into the Arctic Ocean and thence to the Atlantic Ocean. The return flows in the high latitudes of the North Atlantic sink as the NADW.

A. Because of this pattern of circulation, the deep water of the world’s oceans generally gets older from the Atlantic Ocean to the Indian Ocean to the Pacific Ocean. The time the water stays out of contact with the atmosphere, that is, its residence time, increases toward the Pacific Ocean. The residence time of the bottom waters of the Atlantic Ocean is 200–500 years; that of the Pacific Ocean is 1,000–2,000 years.

B. By upwelling as described above.

C. This is a difficult question and one that is asked by a number of scientists today. The answer is of concern to the world’s people because of the link to climate. It is likely that any substantial melting of sea ice and the continental glacier of Greenland would add fresh water to the surface of the ocean in the high latitudes of the North Atlantic for some period of time. This would affect the rate of deep water formation because of the change in the salt content of surface ocean water. In turn, the pattern of the conveyor belt circulation of the ocean could be altered. One suggestion is that there would be a less intense flow of warm water northward by the Gulf Stream, and the climate of Europe would cool.

3. A. Because of the short residence time of CO in the atmosphere (about 70 days) and the fact that the upwelling of air near the equator effectively separates air exchange in the troposphere between the two hemispheres, the gas would not be evenly distributed. Higher concentrations would be found in the Northern Hemisphere troposphere than in the Southern Hemisphere. In fact, observations show a strong gradient in the concentration of CO between the two hemispheres, with higher concentrations in the North.

B. The barrier is the convergence of the North Equatorial Current and the South Equatorial Current near the equator and their westward flows. This converging pattern inhibits exchange of surface waters between the Northern Hemisphere and the Southern Hemisphere. Floating tar balls in the North Atlantic would be caught in the North Equatorial Current and transported westward to the northward-moving Gulf Stream.

C. No, the NADW moves southward at depth in the North Atlantic Ocean into the South Atlantic Ocean. The ABW moves north at depth. Neither current is involved with surface ocean currents.

4. The fine dust particles would take \( 4 \text{ km} \times 10^5 \text{ cm/km} = 4 \times 10^5 \text{ cm} / 500 \text{ cm/yr} = 800 \text{ years} \). In actual fact, they settle much faster because they are encapsulated in the fecal pellets of animal plankton (zooplankton) in the ocean. During feeding the zooplankton inadvertently pass them through their guts and excrete them contained in bigger mucilaginous fecal particles that sink at rates of 350 m/day.

5. To answer this question requires an understanding of some basic chemistry. The equilibrium between a gas and a solution is normally given by Henry’s Law, which states that the concentration of the gas in the solution equals a constant (known as the Henry’s Law constant) times the partial pressure of the gas. For \( \text{CO}_2 \), the expression is

\[
[\text{CO}_2] = K_{\text{H}} P_{\text{CO}_2}
\]
The brackets around CO₂ denote its concentration in moles/L. The partial pressure of CO₂ (PCO₂) is in atmospheres. The value of KH varies with the composition of the solution and the temperature. For seawater at 25°C, KH equals 10⁻¹·⁵⁴.

A. Carbon dioxide dissolves in seawater to an extent determined by the CO₂ concentration in the atmosphere and the reactions that occur in the seawater. At 25°C and with an atmospheric CO₂ concentration of PCO₂ = 10⁻³·₄₅ atm, the relationship is

\[ [\text{CO}_2] = 10^{-1.54} \times 10^{-3.45} = 10^{-4.99} \text{ mole/L} \]

B. In 1700 for a PCO₂ = 10⁻³·₅₅ atm, we have

\[ [\text{CO}_2] = 10^{-1.54} \times 10^{-3.55} = 10^{-5.09} \text{ mole/L} \]

C. The percentage change is \( \left( \frac{10^{-4.99} \text{ mole/L} - 10^{-5.09} \text{ mole/L}}{10^{-5.09} \text{ mole/L}} \right) \times 100 = 26\% \). Thus, the dissolved CO₂ concentration in the surface ocean has changed by this percentage over the past 300 years because of fossil fuel combustion and biomass burning.

6. A. The percentage is \( \left( \frac{0.9 \times 10^{-4} \text{ cal/cm}^2/\text{min} + 0.9 \times 10^{-5} \text{ cal/cm}^2/\text{min} + 0.9 \times 10^{-4} \text{ cal/cm}^2/\text{min} + 0.9 \times 10^{-5} \text{ cal/cm}^2/\text{min}}{0.5 \text{ cal/cm}^2/\text{min} + 0.9 \times 10^{-4} \text{ cal/cm}^2/\text{min} + 0.9 \times 10^{-5} \text{ cal/cm}^2/\text{min}} \right) \times 100 = 0.02\% \).

B. The amount of energy reaching the earth’s surface and absorbed is 343 W/m² x 0.49 = 168 W/m². This energy is used to heat the atmosphere and surface of the earth; to evaporate water; to generate rising air masses (thermals); to drive wind, waves, and currents; and for photosynthesis.

C. The energy is reabsorbed, keeping the earth warm.

7. A. Provided there were no processes restoring the continents, they would be reduced to sea level by erosion in 150 x 10¹² m² x 840 m = 126 x 10¹⁵ m³ x 10⁶ cm³/m³ = 126 x 10²¹ cm³ x 2.7 g/cm³ = 340 x 10²¹ g ÷ 200 x 10¹⁴ g/yr = 17 x 10⁶ years.

B. This is a question that has plagued geologists for two centuries. There must be processes that add mass to the continents to keep them above sea level. Certainly lavas originating in the interior of the earth add material to the continents. In subduction zones, not all the rock of the oceanic crust is transported down toward the interior of the earth. Some of it is added to the continents and increases their area and thickness. Finally, continents often collide during their movement about the earth’s surface. In the collisions, the continents act as a great vise, squeezing sediments originally derived from their erosion and other sources into high mountain ranges. This action adds volume back to the continents. The collision of India with Asia followed by the formation of the Himalayan Mountains is an example of such an event. Thus, there is a great rock cycle at work in which the continents are eroded and their materials deposited in the ocean. The sediments of the oceans are buried to great depths or transported to subduction zones. In either case, the sedimentary material is eventually returned to the continents to be uplifted to their surfaces and eroded, completing the cycle.

8. A. This question simply uses the concept of residence time, where \( \lambda = \text{mass} ÷ \text{flux} \); therefore, \( \text{flux} = \text{mass} ÷ \lambda = 1.8 \times 10^{18} \text{ metric tons} ÷ 600 x 10^6 \text{ yr} = 3 x 10^9 \text{ metric tons/yr} = 30 x 10^{14} \text{ g/yr}. \)

Interestingly, this flux is much less than that of erosion and thus deposition in the oceans today. This implies that today is somewhat unusual in terms of geologic history. We know that to be the case from other geological information.
B. Sediment (clay, mud, silt, sand, gravel, and skeletal and organic materials) enters the sedimentary rock reservoir by erosion of rocks, transportation of the eroded debris, and subsequent deposition on the seafloor, followed by burial in some cases to depths of 12 km. The sediment “gets out” by uplift due to plate tectonic movements and re-erosion of the sedimentary mass.

9. The chemical species in anoxic soils are chiefly reduced forms of the compounds CH₄, CO, NH₃, and H₂S (see Figures 9, 10, 15, and 19). CO₂ occurs as well, although it is a relatively oxidized form of carbon. In a well-aerated soil, we might expect O₂, CO₂, N₂, and SO₂.

10. Your answer to Question 2 in the Chemistry section shows that the weathering of silicate minerals subtracts CO₂ from the atmosphere. This subtraction must be balanced by an addition of CO₂ from other processes or the atmosphere would run out of CO₂ in about 6,000 years. Those processes involve hydrothermal reactions at midocean ridges and the subduction and/or burial of carbonate minerals to realms of higher pressure and temperature, where carbonates are converted to silicates, and CO₂ is released back to the atmosphere by volcanism and other processes.

Ecology

1. This question is designed to give the student a feeling for some of the characteristics of two important ecosystems that are being severely impacted by human activities. These activities are the deforestation of tropical rain forests and their conversion to pasture and urban areas and the eutrophication of coastal marine environments.

A. The total net primary production of tropical rain forests and estuaries is:

Rain forests: 17 x 10¹² m² x 2,000 g dry matter/m²/yr = 34 x 10¹⁵ g dry matter x 0.45 = 15.3 x 10¹⁵ g C. Dividing by 10⁶ g/metric ton, we get 34 x 10⁹ metric tons dry matter and 15.3 x 10⁹ metric tons C.

Estuaries: 1.4 x 10¹² m² x 1,800 g dry matter/m²/yr = 2.52 x 10¹⁵ g dry matter x 0.45 = 1.13 x 10¹⁵ g C. Dividing by 10⁶ g/metric ton, we get 2.52 x 10⁹ metric tons dry matter and 1.13 x 10⁹ metric tons C. Notice that although the NPP of tropical rain forests and estuaries is similar, the smaller area of estuaries leads to more than an order of magnitude difference between the total net primary production of the two ecosystems.

B. The total plant mass (biomass) of these ecosystems is:

Rain forests: 17 x 10¹² m² x 20 kg C/m² = 340 x 10¹² kg C ÷ 0.45 = 755 x 10⁹ metric tons dry matter.

Estuaries: 1.4 x 10¹² m² x 0.45 kg C/m² = 630 x 10⁹ kg C ÷ 0.45 = 1.4 x 10⁹ metric tons dry matter. Notice the orders-of-magnitude difference between the biomass of tropical rain forests and estuaries.

C. In ten years, 9% of the area of rain forests was lost; this represents 755 x 10⁹ metric tons dry matter x 0.09 = 68 x 10⁹ metric tons dry matter x 0.45 = 30.6 x 10⁹ metric tons C.

D. The grams of CO₂ emitted to the atmosphere in this ten-year period would be 30.6 x 10⁹ metric tons C x 10⁶ g/metric ton = 30.6 x 10¹⁵ g C x (44 ÷ 12) = 112 x 10¹⁵ g CO₂. This flux represents (Figure 11) the size of the atmospheric CO₂ reservoir of 744 x 10¹⁵ g C x (44 ÷ 12) = 2,730 x 10¹⁵ g CO₂. 112 x 10¹⁵ g CO₂ ÷ 2,730 x 10¹⁵ g CO₂ = 0.041, or 4% of the atmospheric reservoir.
The flux would represent about $3 \times 10^{15}$ g C/yr for the decade of the 1980s. The magnitude of the flux is too high, meaning that all the woody plant material was not burned to CO$_2$. Some remains on the ground as waste from the cutting, and some has gone into lumber. The flux of CO$_2$ to the atmosphere from all land-use activities in tropical rain forests for the 1980s was on the order of 1–1.6 $\times 10^{15}$ g C/yr.

E. At a C:P ratio of 106:1, the additional plant productivity supported by the pollutant P would be $1.5 \times 10^{12}$ g P/yr $\div$ 31 g/mole = $48.4 \times 10^9$ moles P/yr $\times (106 \div 1) = 5.13 \times 10^{12}$ moles C/yr.

Divided by the estuary area of $1.4 \times 10^{12}$ m$^2$ = 3.7 moles C/m$^2$/yr = 44 g C/m$^2$/yr $\div$ 0.45 = 98 g dry matter/m$^2$/yr, or about a 5% increase in the productivity of the world’s estuaries.

F. In fact, because the pollutant P will be used more than once in plant productivity in estuaries, the total organic carbon that could be buried in the sediments of estuaries amounts to $140 \times 10^{12}$ g C/yr (Figure 18). This flux does qualify as a negative biological feedback because the additional P has been added to the earth’s surface by the human activities of fertilizer application to croplands and sewage discharge. Some of this P makes its way to lakes and coastal marine environments and increases the productivity of such aquatic systems. The flux represents $(140 \times 10^{12}$ g C/yr $\div 6 \times 10^{15}$ g C/yr) $\times 100 = 2\%$ of the fossil fuel flux in 1995. Not much!

2. A. The total production of dry matter is $510 \times 10^{12}$ m$^2 \times 0.37$ kg dry matter/m$^2$/yr = 188.7 $\times 10^{12}$ kg dry matter/yr.

B. 188.7 $\times 10^{12}$ kg dry matter/yr $\times 0.45 = 84.9 \times 10^{12}$ kg C/yr.

C. Let total production in the ocean = X; then production on land = 2X. Thus X + 2X = 188.7 $\times 10^{12}$ kg dry matter/yr, i.e., 3X = 188.7 $\times 10^{12}$ kg dry matter/yr; X = ocean production = 62.9 $\times 10^{12}$ kg dry matter/yr and 2X = land production = 125.8 $\times 10^{12}$ kg dry matter/yr.

3. Autotrophy is the biochemical pathway by which an organism uses CO$_2$ as a source of carbon and simple inorganic nutrient compounds of N and P for synthesis of organic matter. In heterotrophy, more complex organic materials are used as the source of carbon for metabolic processes.

4. Prokaryotes—the Kingdom Monera, including the bacteria and cyanobacteria—take part in a variety of biogeochemical processes (see Table 1). We often forget the fact that the bacteria are responsible for the decay of organic matter both on land and in the ocean. In other words, it is their metabolic activity that returns CO$_2$ and other gases and nutrients back to the environment. The cyanobacteria are photoautotrophic and produce oxygen as a metabolic byproduct. These organisms were responsible for the initial growth of oxygen in the earth’s atmosphere. The processes include CO$_2$ fixation, nitrogen fixation, and oxidation of sulfur as examples.

5. Eutrophication is the set of processes leading to the overnourishment of a lake, river, or marine environment; consequent rapid plant growth and death; and oxygen deficiency of the system. This is a natural set of processes in certain environments. When it occurs because the excess nutrients come from fertilizers, sewage, detergents, etc., it is called cultural eutrophication. This term distinguishes the natural situation from that produced by the activities of people.
Biogeochemical Cycles

1. See Figure 22.
   A. The residence time = \( \lambda = \text{mass of water in the ocean divided by the flux of water to the ocean by rivers:} \)
   \[ 1,370 \times 10^6 \text{ km}^3 ÷ 40 \times 10^3 \text{ km}^3/\text{yr} = 34,250 \text{ years}. \]
   B. \( \lambda \) of Ca in the ocean is \( (1,370 \times 10^6 \text{ km}^3 \times 10^{12} \text{ L/km}^3 \times 400 \text{ mg/L}) ÷ (40 \times 10^3 \text{ km}^3/\text{yr} \times 10^{12} \text{ L/km}^3 \times 15 \text{ mg/L}) = 913,000 \text{ years}. \)

2. Here we apply the concept of residence time in the context of how long it takes for a lake to recover from a single input of a chemical into it. This is an environmental problem often encountered in developing, as well as developed, countries.
   A. The volume of the lake is \( 5 \text{ km} \times 2 \text{ km} \times 0.1 \text{ km} = 1 \text{ km}^3 \times 10^{12} \text{ L/km}^3 = 1 \times 10^{12} \text{ L}. \)
   B. The mass of mercury (Hg) is \( 1 \times 10^{12} \text{ L} \times 1 \times 10^{-6} \text{ g Hg/L} = 1 \times 10^6 \text{ g Hg}. \)
   C. The flux of mercury by the river to the lake is \( 2 \times 10^{12} \text{ L/yr} \times 5 \times 10^{-7} \text{ g Hg/L} = 1 \times 10^6 \text{ g Hg/yr}; \)
   thus the residence time of Hg (\( \lambda_{\text{Hg}} \)) in the lake is \( 1 \times 10^6 \text{ g Hg} ÷ 1 \times 10^6 \text{ g Hg/yr} = 1 \text{ year}. \)
   D. The time to reach a new equilibrium—that is, for the Hg input to work its way through the lake—is \( 3 \times \lambda_{\text{Hg}} = 3 \times 1 \text{ yr} = 3 \text{ yrs}. \) In this period of time, 95% of the Hg input would be gone.

3. This question provides the student with a feeling for the problem of “looking for a needle in a haystack” that scientists have when observing the change in the size of the terrestrial living biomass due to uptake and storage of anthropogenic CO₂.
   A. \( 600 \times 10^9 \text{ tons C} \times 10^6 \text{ g/ton} = 600 \times 10^{15} \text{ g C}. \) \( 135 \times 10^{12} \text{ moles C/yr ÷ 12 g/mole} = 16.2 \times 10^{14} \text{ g C/yr}. \) The annual % change would be \( (16.2 \times 10^{14} \text{ g C/yr ÷ 600} \times 10^{15} \text{ g C}) \times 100 = 0.27\% \text{ per year}. \)
   B. Most unlikely. For the decade of the 1980s, this would be only a 2.7% change in the mass of living biomass globally. This amount of change would be difficult to measure by field studies, even if they were aimed at seeing a change in the amount of organic carbon stored in terrestrial vegetation. However, if the storage continues, such measurements could provide information in a few years.

4. A. The total DIC in the mixed layer is \( 360 \times 10^{12} \text{ m}^2 \times 10^2 \text{ m} = 360 \times 10^{14} \text{ m}^3 \times 10^6 \text{ cm}^3/\text{m}^3 = 360 \times 10^{20} \text{ cm}^3 \times 1.027 \text{ g/cm}^3 = 37 \times 10^2 \text{ g/kg} = 37 \times 10^{18} \text{ kg seawater} \times 2.2 \times 10^{-3} \text{ moles C/kg seawater} \times 81.4 \times 10^{15} \text{ moles C}. \)
   B. \( 2 \times 10^9 \text{ tons C/yr ÷ 12 g/mole} = 166.7 \times 10^{12} \text{ moles C/yr ÷ 37} \times 10^{18} \text{ kg seawater} = 4.5 \times 10^6 \text{ moles C/kg seawater/yr} = 4.5 \text{ micromoles C/kg seawater/yr}. \) Actual measurements of the change in the DIC content of seawater over time show an increase of about 1 micromole per year. The difference is due to the fact that the anthropogenic carbon taken up by the ocean mixes deeper in the ocean than the average depth of the mixed layer used in the problem, on average about 300–400 meters.
C. Using 1 micromole per year as the average carbon uptake since 1975, we get $1 \times 10^{-6}$ mole C/kg/yr \times 21 \text{ yr} = 21 \times 10^{-6} \text{ moles C/kg} \div 2.2 \times 10^{-3} \text{ moles C/kg} \times 100 = 0.95\%$. It was not until the late 1980s that scientists were able to measure these small changes in seawater DIC accurately and precisely.

5. Referring to Table 3, the total amount of water in the atmosphere as water vapor is $0.013 \times 10^6 \text{ km}^3$; thus the residence time of water vapor in the atmosphere calculated with respect to total evaporation (must equal precipitation) is $0.013 \times 10^6 \text{ km}^3 \text{ H}_2\text{O} \div 496 \times 10^3 \text{ km}^3 \text{ H}_2\text{O/yr} = 0.026 \text{ yr} \times 365 \text{ days/yr} = 9.6 \text{ days}$.

B. No, the pollutant would not mix evenly throughout the troposphere because of water’s very short residence time in the atmosphere. In general, the dust and aerosol content of the troposphere exhibits a regional pattern and is most concentrated near sources, downwind from sources, and in regions of relatively dry climate. However, the dust plume in the troposphere derived from the Sahara and Sahel areas of Africa can be seen in satellite images extending all the way across the Atlantic Ocean.

6. The three major processes are (1) inputs of volcanic CO$_2$ derived from the metamorphism of CaCO$_3$ to CaSiO$_3$, (2) weathering of silicate minerals like CaSiO$_3$ and then deposition of calcium carbonate and silica in the ocean, and (3) the evolution of plants and their effect on weathering. The reactions are

1. $\text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{CaSiO}_3 + \text{CO}_2$

2. $\text{CaSiO}_3 + 2\text{CO}_2 + 3\text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- + \text{H}_4\text{SiO}_4^0$, and then $\text{Ca}^{2+} + 2\text{HCO}_3^- + \text{H}_4\text{SiO}_4^0 \rightarrow \text{CaCO}_3 + \text{SiO}_2 + 3\text{H}_2\text{O} + \text{CO}_2$

3. $\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{CH}_2\text{O} + \text{O}_2$

7. The connection is simply the fact that when organic matter is buried in sediments of the ocean, oxygen not used to oxidize the organic matter is left in the atmosphere. With the continuous burial of organic matter on the seafloor, the oxygen content would increase in a few millions of years to levels that would lead to burning of forests and grasslands. This does not happen because the buried organic matter is returned to the earth’s surface through uplift by plate tectonic processes. On exposure to the atmosphere, the organic matter is oxidized, and the oxygen is removed from the atmosphere.

8. The major difference is that there is not a major gas of phosphorus that resides in the atmosphere or is transported through it (see Figure 18). This statement is not true of carbon, nitrogen, and sulfur. All of these elements have important gaseous compounds in the atmosphere that exchange with the earth’s surface. (See the text sections on the cycles of C, N, and S.)

9. DMS in the troposphere reacts fairly rapidly with hydroxyl radical in the presence of light, water, and oxygen to make sulfate aerosol. On the contrary, OCS is inert in the troposphere but is converted in the stratosphere to sulfate aerosol (see Figure 19).

10. The difference in residence time implies that ammonia reacts more rapidly than carbon monoxide in the atmosphere (see Figures 10 and 16). This is simply a consequence of the fact that the shorter the residence time (lifetime) of a chemical compound in a reservoir, the more reactive the substance.
11. This question and the following five questions relate to relationships depicted in the figures of the biogenic trace gases. They are designed to help the student to study the figures and interpret them.

The major reaction in the atmosphere coupling the biogeochemical cycles of CH\(_4\), CO, and CO\(_2\) is the oxidation of the reduced carbon gas CH\(_4\) to CO and then on to CO\(_2\) by OH\(^*\). About 60% of the enhanced greenhouse forcing is due to CO\(_2\), and about 20% is due to CH\(_4\). The major anthropogenic sources of emissions of CH\(_4\) to the atmosphere are fossil fuel burning and leakage from gas transmission pipelines, biomass burning, landfills, rice paddies, and enteric fermentation in domesticated animals. CO emissions come from fossil fuel and biomass burning. Land-use activities and fossil fuel burning are the major anthropogenic sources of CO\(_2\) to the atmosphere. A doubling of atmospheric CO\(_2\) concentration could lead to a 2.5°C increase in mean global temperature. Molecule for molecule, CH\(_4\) is about 20 times more effective as a greenhouse gas than CO\(_2\). (Compare the amount of temperature change per ppbv for the two gases.)

12. The ratio is \((42 + 20 + 78) \times 10^6 \text{ metric tons N/yr} ÷ 126 \times 10^6 \text{ metric tons N/yr} = 1.1:1.\) The anthropogenic nitrogen fluxes on land slightly exceed the natural biological fixation flux! The minimum percentage is \(21 \times 10^6 \text{ metric tons N/yr} ÷ 140 \times 10^6 \text{ metric tons N/yr} \times 100 = 15\%\). The additional nitrogen flux to the ocean is a cause of eutrophication of coastal marine environments.

13. The ratio is \(206 \times 10^6 \text{ metric tons N/yr} ÷ 62 \times 10^6 \text{ metric tons N/yr} = 3.3:1.\) This is a difficult question to answer. On the time scale of a century, it is very likely that the flux of N to the ocean from rivers and groundwaters will increase because of continuous use of industrial fertilizers, atmospheric deposition of anthropogenic nitrogen, and disposal of sewage. If there is climatic change on this time scale, it is uncertain whether the upwelling rate of the world’s oceans will change. However, a warming of the global surface layer of the ocean would most likely lead to a slowing of upwelling and thus delivery of nutrients to the surface ocean.

14. The range is 143 to 339 years. \(73 \times 10^6 \text{ tons N} ÷ (2.9 + 0.1 + 0.02 + 0.01 + 1.4) \times 10^6 \text{ tons N/yr} = 339 \text{ years.}\) \(1,500 \times 10^6 \text{ tons N} ÷ (5.2 + 0.3 + 0.2 + 2.2 + 2.6) = 143 \text{ years.}\) N\(_2\)O accounts for about 9% of the enhanced greenhouse effect.

15. The percentage from human activities is \([21 + 3) \times 10^6 \text{ tons N/yr} ÷ (21 + 3 + 20) \times 10^6 \text{ tons N/yr}] \times 100 = 54.5\%.\) Human activities substantially interfere with the fluxes of NO\(_x\). Environmental problems associated with the anthropogenic fluxes are acid deposition, photochemical smog, and increased tropospheric ozone, a greenhouse gas. The principal reaction leading to destruction of NO\(_x\) in the atmosphere is photochemical. The products of the reaction are nitric acid, peroxylacetyl nitrate, and organic nitrates. The reaction is \(\text{NO}_2 + \text{OH}^* + \text{light} \Rightarrow \text{HNO}_3.\)

16. The ratio is \(1,085 \times 10^6 \text{ tons P/yr} ÷ 186 \times 10^6 \text{ tons P/yr} = 5.8:1.\)

The residence time of P in the marine biota relative to the recycling flux is \(73 \times 10^6 \text{ tons P} ÷ 1,085 \times 10^6 \text{ tons P/yr} = 0.07 \text{ years.}\) That for P in the land biota is \(1,800 \times 10^6 \text{ tons P} ÷ 186 \times 10^6 \text{ tons P/yr} = 9.6 \text{ years.}\) The phytoplankton of the ocean “turn over” much more rapidly than do terrestrial plants. There are more generations of death and birth for marine plankton than for most plants growing on land.