

Briefly define/describe each of these phrases

1. Excess volatiles
2. Impact degassing
3. Banded iron formation
4. Stromatolite
5. Faint young sun paradox
6. Negative feedback
7. Positive feedback
8. Blackbody radiation
9. Stefan-Boltzman Law
10. Wilson cycle
11. Subduction
12. Residence time
13. Kerogen
14. Fixed nitrogen
15. Anoxic
16. Denitrification
17. Troposphere
18. Nitrogen fixation
19. Oceanic conveyor belt
20. North Atlantic Deep Water
21. Upwelling
22. Greenhouse gas
23. Radiative forcing
24. Milankovitch cycle
25. Holocene
26. Younger Dryas
27. Dansgaard-Oeschger events
28. Thermal drag
29. IPCC
30. CLAW hypothesis
31. Ozone hole
32. Polar vortex
33. Montreal Protocol
34. Biodiversity

Essay and Calculation Questions

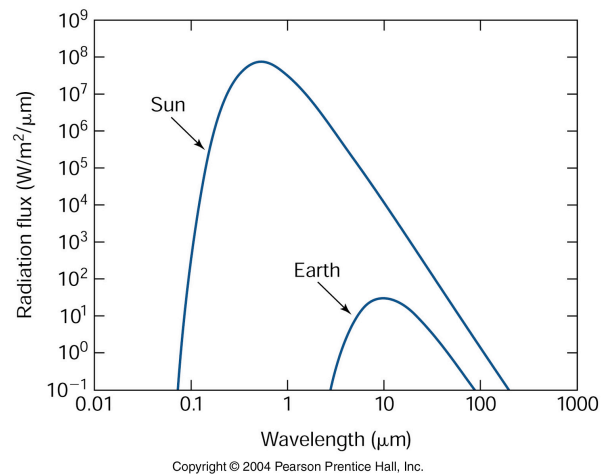
Time Scales and the Systems Approach

1. Describe the difference between positive and negative feedback. In the Daisyworld model, describe how white daisies exhibit negative feedback on planetary temperature. In answering this question remember that the albedo of black daisies (~ 0.2) is less than the albedo of bare ground (~ 0.5), which is less than the albedo of white daisies (~ 0.7).
2. A perturbation that causes a decrease in component A leads to a decrease in component B. Is this coupling between these two components positive or negative?

Global Energy Balance and Greenhouse Effect

1. What is albedo and how does it influence climate?

2. Please explain the reason why the wavelength of maximum emission for the blackbody emission curve of the Earth is shifted relative to the Sun.



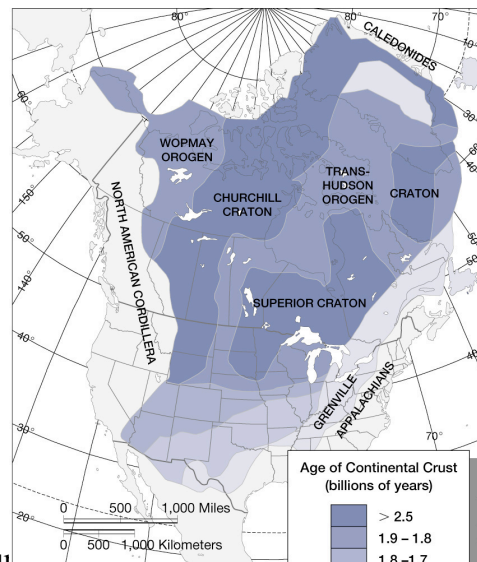
3. Please briefly describe what the greenhouse effect is.
4. In our discussion of planetary energy balances we defined two temperatures, the effective radiating temperature of the planet (T_e) and surface temperature of the planet (T_s).
 - a. On Earth why is $T_s > T_e$, and what controls the magnitude of T_e ?
 - b. We also defined the greenhouse effect ΔT_g as $T_s - T_e$. Please explain why ΔT_g is a function of the atmospheric CO_2 and water vapor concentrations, as well as the atmospheric temperature (essentially T_e).
5.
 - a. On Earth the effective radiating temperature of the planet (T_e) is less than the surface temperature of the planet (T_s). Why is this so? What controls T_e ?
 - b. We also defined the greenhouse effect ΔT_g as $T_s - T_e$. What controls the magnitude of ΔT_g ?

6. In class we discussed a simple model which showed that the presence of a “greenhouse” atmosphere substantially increases the surface temperature of the Earth. Please briefly explain how this occurs.

The Geosphere and Planetary Evolution

1. The age of the earth is estimated to be ~4.6 billion years, yet the oldest crustal rocks (found on the continents) are only ~4 billion years old.
 - a. What types of materials were used to determine the age of the earth?
 - b. Briefly describe why the oldest rocks found on the earth are younger than the age of the earth.
 - c. Why is all oceanic crust significantly younger than the oldest continental crust?
2. How has solar luminosity changed over the past 4.6 billion years? What caused this change?
3. The oldest rocks that have been found on Earth are no older than ~3.8-4.2 billion years, yet we believe the age of the Earth is ~4.6 billion years. How was this age determined? Why is there this difference between the age of the Earth and oldest rocks on Earth? (Note that simply telling me that scientists have not looked hard enough is not an acceptable answer).
4. The age of the Earth is estimated to be ~4.6 billion years, yet the oldest crustal rocks (found on the continents) are only ~3.8-4.2 billion years old.
 - a. Briefly describe why the oldest rocks found on the Earth are younger than the apparent age of the Earth.
 - b. Why are the oldest rocks on Earth found on the continents and not in the oceanic crust?
5.
 - a. At a convergent plate boundary where oceanic and continental crust meet, why does the oceanic crust “sink” back into the Earth (i.e., the mantle)?
 - b. Briefly discuss how this observation relates to the fact that all oceanic crust is generally much younger than most continental crust.
6. A friend tells you that he heard scientists had recently found a piece of oceanic crust (basalt) on the mid-Atlantic ridge that was 2 billion years old. Please tell me why it is highly unlikely that a piece of oceanic crust is that old.

7. Please discuss the reasons why many continents consist of very old cratons surrounded by younger materials (see the figure to the right for example).



8. Describe the processes that are responsible for the destruction of oceanic and continental crust. How do these differences contribute to the fact that the oldest crustal material is found on the continents?

9. a. What is the internal energy source that ultimately drives plate tectonics on the Earth?
b. What are the major differences between the Earth and the moon with regards to this point (i.e., why do we think that the moon no longer has active plate tectonics)?

10. The history of the earth can roughly be defined as comprising two time periods: a period of uni-directional change (4.6 bybp -> 2.5 bybp), and a period of recycling (2.5 bybp -> the present). Please discuss this observation in terms of the evolution of oceans and continental and marine crust.

11. The pockmarked surface of the moon suggest that meteoric impacts have played a major role in defining the surface features on the moon. This contrasts with the Earth, where such surface features are of minor importance. Assuming for now that over geologic time both the Earth and moon have received the same number of impacts per surface area, discuss possible reasons for these differences.

12. a. On the early (pre-biotic) Earth, where was the bulk of the water likely found (e.g., in glaciers, in the oceans, in giant storage tanks, etc)? Why?
a. On the early Earth, what process likely produced small amounts of oxygen?
b. Thinking about the two answers above, please explain why they could lead to the loss of all water on the planet.
c. Since we know that Earth did not lose all of its water during its early history, please discuss what may have occurred that prevented this water loss from occurring.

13. a. What are “excess volatiles”?
b. In the early history of the Earth how did excess volatiles contribute to the evolution of the oceans as a body of water with a high salt content?

14. Define “excess volatiles”. In the early history of the Earth where did the excess volatiles likely come from, and where are they found today in the present Earth system.

14. The residence time (τ) of chloride in the oceans is approx. 7×10^7 yr while that of sulfate is only 8×10^6 yr.

a. Why are these residence times both quite short in comparison to the likely “age” of the oceans (which is on the order of the age of the Earth).

b. These residence times are also quite long in comparison to the average mixing time of the ocean (~500-1000 yrs). What are the implications of these observations in terms of the distribution of the major cations and anions in the oceans?

15. The residence time (τ) of sodium in the oceans is approx. 4.8×10^7 yr while that of calcium is 8.5×10^5 yr.

- What does this tell us about the reactivity of sodium vs. calcium in the oceans?
- Why are these residence times both quite short in comparison to the likely “age” of the oceans (which is on the order of the age of the Earth)?
- These residence times are also quite long in comparison to the average mixing time of the ocean (~500-1000 yrs). What are the implications of these observations in terms of the distribution of the major cations and anions in the oceans?

16. In your textbook, the authors describe a calculation made in 1715 that attempted to determine the age of the Earth. This was done on the basis of estimates of the salt content of the ocean and rate of salt delivery to the ocean. This calculation goes as follows:

- The total amount of salt in the ocean is approx. 5×10^{22} gr,
- The rate at which rivers deliver salt to the ocean is 4×10^{15} gr/yr,
- Therefore the “age” of the Earth is $(5 \times 10^{22}) / (4 \times 10^{15}) = 13 \times 10^6$ yr.

Since we now know that the age of the Earth is approx. 4.6 billion years, this 13 million year age is clearly incorrect.

- What is “wrong” with this calculation as an estimate of the age of the Earth (i.e., what are the flaws in the assumptions made in this calculation)?
- This 13 million year age is, however, a better rough estimate of another quantity of interest to us. What is this?

18. Describe the processes that occurred early in the earth’s history that lead to evolution of the ocean as a body of water with a high salt content. Please be sure to describe the original sources of anions (i.e., Cl^- and SO_4^{2-}) and cations (i.e., Na^+ , Ca^{2+} and Mg^{2+}) to the early ocean.

19. In class I made the emphatic statement that seawater is not simply concentrated river water. Please briefly discuss why this is so and how (in general) this occurs.

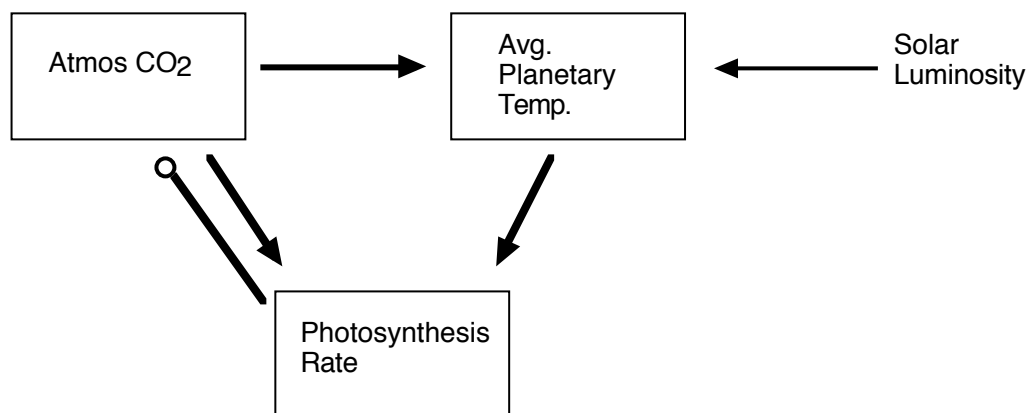
20. In the present-day ocean dissolved iron is extremely low in concentration (much less than $1 \text{ nM} = 10^{-9} \text{ M}$), and predominantly exists as Fe(III). In contrast, when the oceans first formed dissolved iron was found at much higher concentrations and existed as Fe(II). Explain the reasons for this change in concentration and oxidation state of iron in the ocean. Where is most of the iron that was in the early ocean now located?

21. What are banded iron formations, and what does their existence tell us about the evolution of conditions on the Earth’s surface?

22. Assuming a near-constant atmospheric composition over the Earth’s history (similar to that found today) and a near constant albedo, the figure below (Fig. 12-2 from the book) illustrates the faint young Sun paradox. Note that T_e is the effective radiating temperature of the planet and T_s is the Earth’s surface temperature.

- Describe in words what the faint young Sun paradox is and how this graph illustrates this paradox.

- b. What role do changes in the composition of atmosphere over geologic time play here ?
23. During the early history of the Earth the sun was less bright than it is today (i.e., roughly 4 billion years ago solar luminosity was ~75% of its present day level).
- Discuss the significance of this fact, and the fact that the early atmosphere likely had a much higher level of atmospheric CO₂ than it does today, in terms of the evolution of the Earth as a habitable planet.
 - Where is most of the CO₂ from the original atmosphere now found, and what are some of the possible ways that it likely got there?
 - What are the implications of the subsequent decrease in atmospheric CO₂ over geologic time in terms of the maintenance of habitable conditions on the Earth?
24. The early atmosphere was likely dominated by CO₂ (> ~90%). However in the present atmosphere CO₂ is found only at trace quantities. Where is most of this CO₂ now found and how did it get there? What are the implications of this significant decrease in atmospheric CO₂ in terms of the evolution of the earth as a habitable planet and the faint young sun “paradox”?
25. In one of our homework exercises we developed the following systems diagram for the system photosynthetic rate (on Earth)-atmospheric CO₂-average planetary temperature. We also discussed the effect of an external forcing function, namely solar luminosity on this system.
- Explain why atmospheric CO₂ exerts a positive feedback on the photosynthesis rate and why photosynthesis exerts a negative feedback on atmospheric CO₂.
 - In the absence of these feedback loops in this global system how would an increasing solar luminosity affect planetary temperatures?
 - Given the feedback mechanisms described in this systems diagram use this diagram to explain how increasing solar luminosity will likely affect planetary temperatures and atmospheric CO₂ levels.
 - Discuss the significance of these observations in terms of the “faint young sun paradox” and proposed long term changes in atmospheric CO₂ over the entire history of the Earth.



26. Why do we think that methanogenic bacteria are likely to be among the earliest life forms to evolve?

27. a. Describe the major processes that control the concentration of methane in the present-day atmosphere.

b. In light of your answer in part a., discuss why atmospheric methane concentrations may have been higher in the late Archean/early Proterozoic (~3.8-2.3 bybp).

c. In light of both of these answers, discuss the possible relationship between the rise of atmospheric O₂ around 2.3 bybp and the occurrence of the Huronian glaciation at ~2.2-2.5 bybp.

29. Discuss the role that the evolution of oxygenic photosynthesis had on the evolution of oxidizing conditions on the Earth's surface (e.g., on land, in the oceans and in the atmosphere).

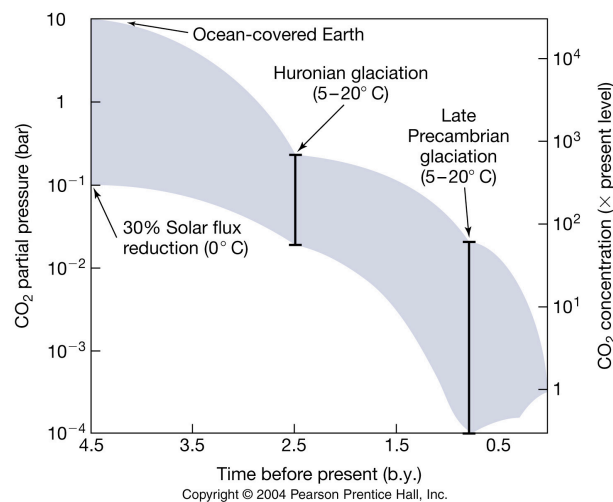
30. Describe the geologic evidence for the rise of atmospheric O₂ around 2.2 bybp. Why is it likely that oxygenic (oxygen-producing) photosynthesis evolved some time before this net accumulation of oxygen in the atmosphere?

31. The figure below shows one estimate of the predicted change in atmospheric CO₂ over geologic time that is needed to compensate for changing solar luminosity. This estimate assumes that CO₂ and H₂O are the only important greenhouse gasses.

a. How and why does solar luminosity change over time?

b. Please explain the reasons for this broad general decrease in CO₂ over the Earth's history as a result of this changing solar luminosity.

c. Recent evidence suggests however, that methane (CH₄) may also have been an important greenhouse gas in the late Archean/early Proterozoic (~3.8-2.3 bybp). Please discuss the evidence that supports this suggestion. What are the implications of this suggestion in terms of the CO₂ curve shown here.

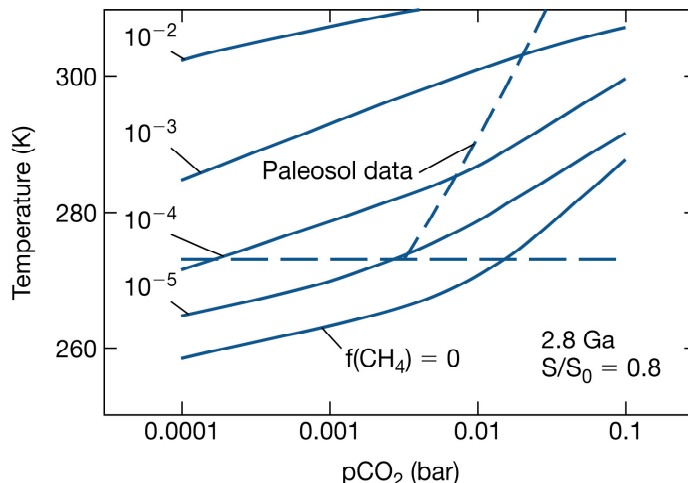


d. In light of the observations in section c, please discuss the possible relationship between the rise of atmospheric O₂ around 2.3 bybp and the occurrence of the Huronian glaciation at ~2.2-2.5 bybp.

32. Look at the figure below and recall that the line labeled “paleosol data” is thought to set the upper limit for the atmospheric CO₂ content in the late Archaen (from say ~3 bybp to ~2.5-2.3 bybp), and the horizontal dashed line is the freezing point of water.

a. Based on this figure, why do we think that methane was likely an important greenhouse gasses in the late Archaen and the CO₂ levels were not as high as previously thought?

b. Why did the oxygen ~2.3 substantial atmospheric



rise in atmospheric bybp likely lead to a decrease in methane.

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33. In his work, James Lovelock argues that the chemical composition of a planet's atmosphere provides strong evidence for the presence of life. Discuss this supposition using the data in the table below.

34. Using the table below and your knowledge about these planets, answer the following questions.

- Why is the temperature on Venus (459 °C) higher than on Earth (13 °C)?
- In class we did a calculation which suggested that without the presence of our present atmosphere, the Earth would have a surface temperature of approx. -18 °C. Why is this temperature lower than the temperature on the present day Earth with an atmosphere (13 °C)?
- The atmosphere on Earth with and without life has a very different CO₂ content. If we assume that atmosphere on Earth without life (listed in this table) is a rough approximation of Earth's original atmosphere, where is the CO₂ from the Earth's early atmosphere now found?

35. The table below compares some of the characteristics of Venus, Earth and Mars. Based on the information in this table, please answer the following questions.

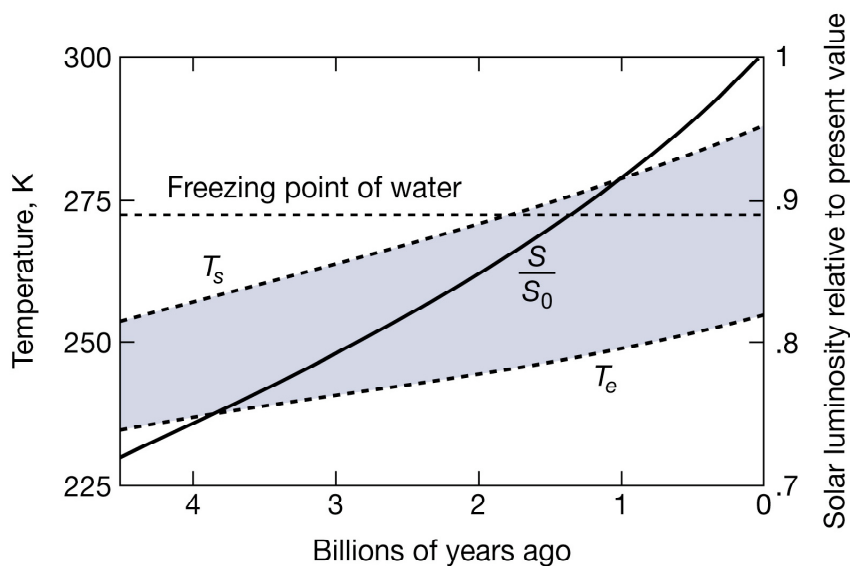
- The solar flux to Venus is much larger than that to Mars, yet their T_e values are very similar. Why is this so?
- What causes the value of ΔT_g on Venus to be so large (please don't simply tell me that it is because T_s >> T_e)?
- On a percentage basis, both Mars and Venus have similar relative amounts of CO₂ yet their albedos and T_s values are very different. Why is this so?

	Venus	Earth	Mars
Distance from the sun (AU)	0.72	1	1.52
Solar flux (W/m^2)	2643	1370	593
Atmos. CO_2 (%)	96.5%	0.03%	95%
Total atmos. pressure (bars)	90	1	0.0064
Planetary albedo	0.8	0.3	0.22
T_e	220°K	255°K	212°K
T_s	730°K	288°K	218°K
ΔT_g	510°C	33°C	6°C

37. a. What is anoxygenic (bacterial) photosynthesis and how does it differ from oxygenic (green plant) photosynthesis?
- b. What is the significance of the evolution of anoxygenic (bacterial) photosynthesis in terms of the evolution of biogeochemical cycles on the Earth?
- c. In class we talked about the co-evolution of the atmosphere and life on the Earth. Discuss this observation in the context of the evolution of oxygenic photosynthesis, the rise in atmospheric O_2 concentrations, and subsequent evolutionary events.

38. Assuming a near-constant atmospheric composition over the Earth's history (similar to that found today) and a near constant albedo, the figure below illustrates the faint young Sun paradox. Note that T_e is the effective radiating temperature of the planet and T_s is the Earth's surface temperature.

- a. Describe in words what the faint young Sun paradox is and how this graph illustrates this paradox.
- b. What role do changes in the composition of the atmosphere over geologic time likely play in resolving this paradox?



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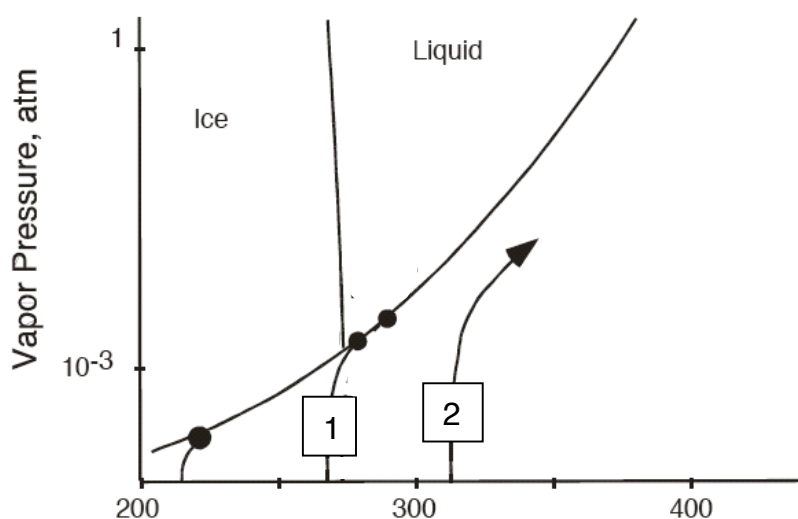
39. Match each of the processes on the left with its time in Earth history on the right. Please put your answers on a separate sheet of paper.

Earliest evidence for life in the geologic record	4.6 bybp
The Younger Dryas event	~4.2 – 4.4 bybp
Evolution of oxygenic photosynthesis	3.8 bybp
Net accumulation of O ₂ in the atmosphere	3.5 – 3.8 bybp
Beginning of the Pleistocene	2.5 bybp
Age of the oldest sedimentary rocks (Ishua formation)	~2.7 bybp
Onset of “modern” plate tectonics	~2.3 bybp
Formation of the Earth	0.54 bybp
Beginning of the Phanerozoic	1.8 mybp
Formation of the Ocean	11,000 ybp

40. a. The trajectory marked 1 will lead to a stable climate (i.e., one in which surface temperature and outgoing IR flux interact in a negative feedback loop). Please explain why this is so.

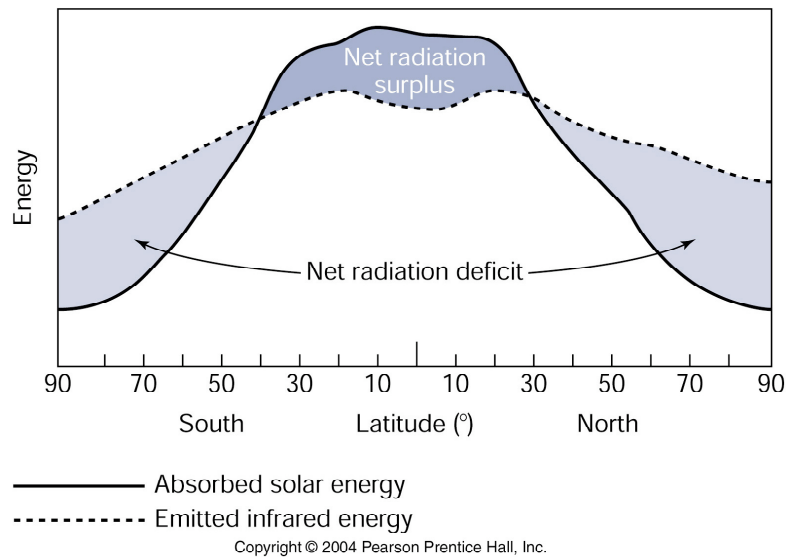
b. In contrast, please explain why trajectory 2 leads to what is referred to as a runaway greenhouse.

c. If trajectory 2 describes the planet Venus, please further explain why Venus is a hot, dry planet with an atmosphere that is thick in CO₂ and sulfuric acid (H₂SO₄).



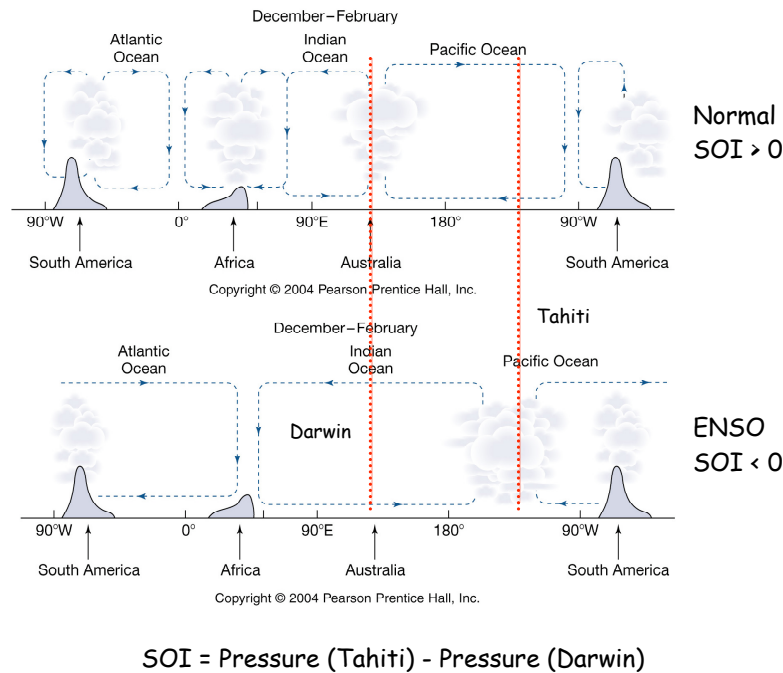
The Atmosphere

1. Why does the temperature of the atmosphere decrease with increasing altitude in the lower atmosphere closest to the earth (the troposphere) but then increase with increasing altitude above the troposphere in the stratosphere?
2. Why are many deserts found between 20-30° N or S of the equator?
3. In the figure below please explain the reason for a net radiation surplus near the equatorial region. What process(es) transport heat away from the equatorial region?



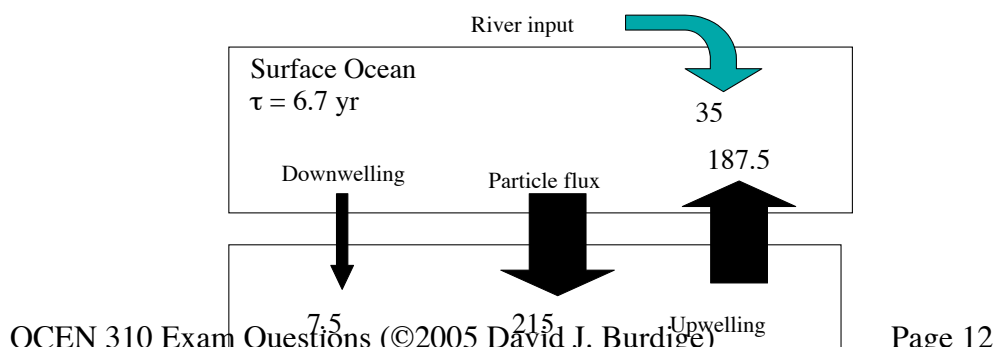
4. ~~Shown here are representations of the east-west atmospheric circulation in the equatorial troposphere during normal and ENSO conditions.~~
 - ~~a. Please explain the reasons for the observed inequalities in SOI under these different conditions.~~

b. How and why does an ENSO event impact ocean circulation near the coast of South America, and what is its effect on the productivity of these waters?



The Hydrosphere

1. Please explain why $\Delta^{14}\text{C}$ values (expressed in ‰ units) are more negative in the bottom waters of the north Pacific than they are in the bottom waters of the north Atlantic?
2. In general, dissolved nutrient concentrations (e.g., nitrate, phosphate or silicate) are higher in the deep ocean than they are in the surface ocean. In contrast, the opposite is true for dissolved oxygen. Please explain why this is so.
3. The 2-box model for phosphate in the ocean shown to the right indicates that $\tau_{\text{sfc ocean}} \ll \tau_{\text{deep ocean}} \ll \tau_{\text{whole ocean}}$, where τ is the residence time. Please explain the reasons for this inequality. Hint: Do not try to calculate these τ values, as I have not given you all the information you need for these calculations. Rather, you should use the information here to simply explain the reasons for these inequalities in residence times.

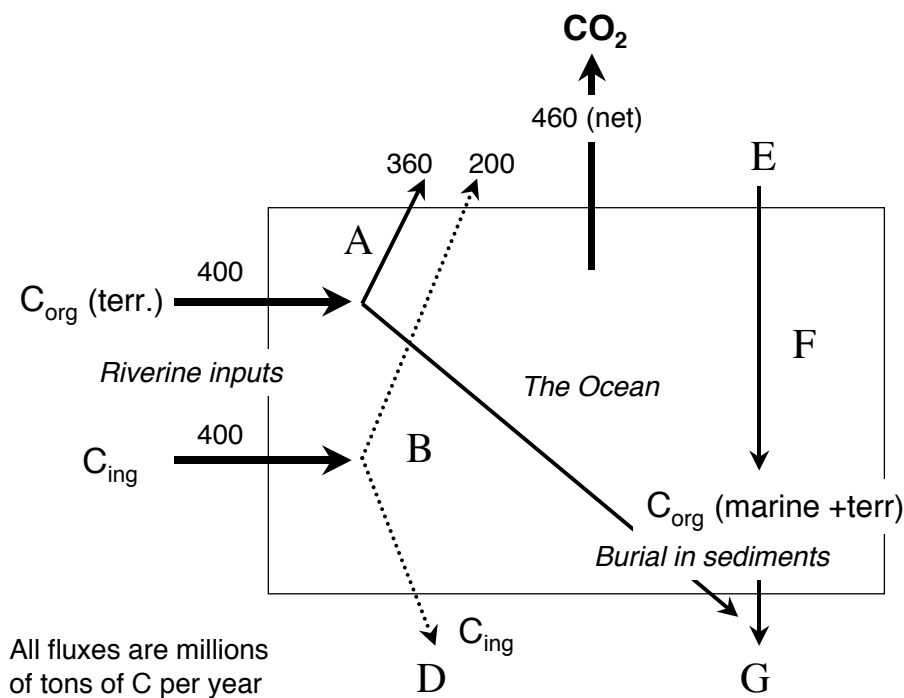


The Biosphere

1. What are the main differences between tropical and temperate soils? How do these differences impact the recovery of these soils to deforestation?

The Carbon Cycle

1. 7. Shown below is a version of the pre-industrial oceanic carbon cycle.
 - a. What processes are responsible for fluxes A, B and F?
 - b. What are the magnitudes of fluxes D, E and G?
 - c. What is the dominant form of inorganic carbon (C_{ing}) in rivers, and how does it get there?
 - d. Based on this figure, what are the amounts of marine and terrestrial organic carbon buried in the sediments?
 - e. How do the processes shown here link components of the overall carbon cycle that operate on different time scales?

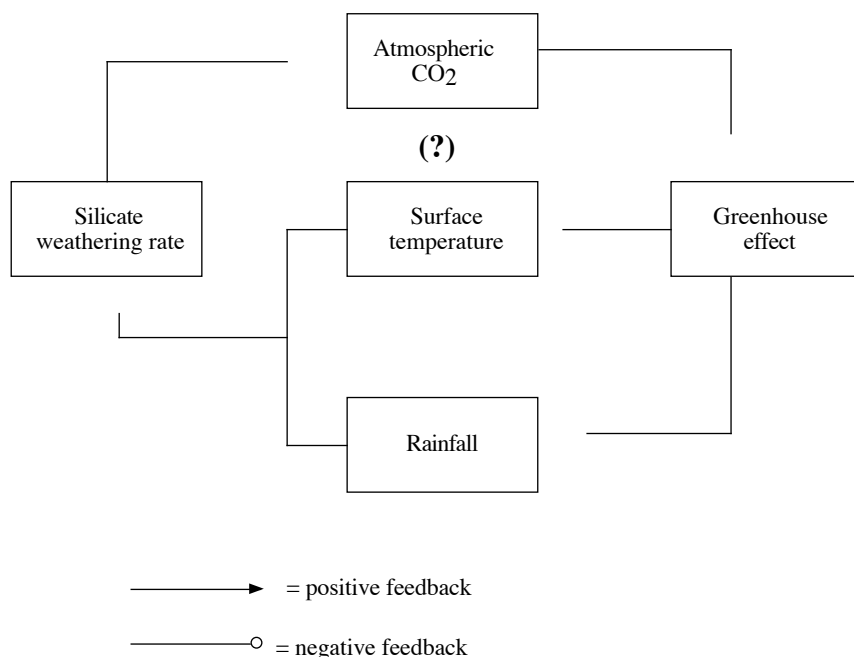


2. On long (geological) time scales, increased rates of seafloor spreading (plate tectonic activity) lead to increased levels of atmospheric CO_2 . Please explain why this is so. What process likely acts to counter this increase in atmospheric CO_2 ?
3. What processes control atmospheric CO_2 concentrations on long (geological) time scales?
4. Which of the following carbon reservoirs has the longest residence time: dissolved inorganic carbon in the ocean, CO_2 in the atmosphere, or sedimentary limestone? Which has the shortest? Please briefly explain the reasons for these observations.
5. In which of the following reservoirs does carbon have the longest residence time: dissolved inorganic carbon in the ocean, carbon in marine phytoplankton, or sedimentary limestone? In which does it have the shortest? Please briefly explain the reasons for your answers.

6. How does the carbonate-silicate cycle illustrated below control atmospheric CO₂ concentrations and climate? As a part of your answer to this question you may want to draw a systems diagram illustrating the pertinent positive and negative feedbacks in the system. Over what time scales do these processes exert controls on CO₂ and climate?

7. The following partial systems diagram illustrates the components of the feedback loop that results from the climate dependence of silicate mineral weathering and its effect on atmospheric CO₂.

- Redraw this figure indicating which of these feedbacks is positive and which is negative.
- What is the overall sign of this feedback loop? (i.e., is the question mark in the center of the figure “+” or “-“). Briefly explain why.
- What are the time scales over which this feedback loop operates? Please be sure to briefly explain/justify your answer.



8. On very long, geological time scales (i.e., 100's of millions of years), how do weathering and tectonic processes control atmospheric CO₂ concentrations? Associated with these processes is a feedback loop that involves the climate dependence of silicate mineral weathering and its effect on atmospheric CO₂. Does this loop (sometimes referred to as the carbonate-silicate cycle) exert a positive or negative feedback on atmospheric CO₂ and, by inference, global temperatures? How does this feedback work?

9. Plants on the Earth today have what is referred to as a “CO₂ compensation point”, which is the atmospheric CO₂ concentration below which they are incapable of carrying out photosynthesis. This compensation point ranges from ~10-150 ppm CO₂ (depending on the type of plant). In light of this observation, discuss how future solar evolution (on several million year to billion year time scales) should affect climate and life on the Earth? [Hint: in the course of

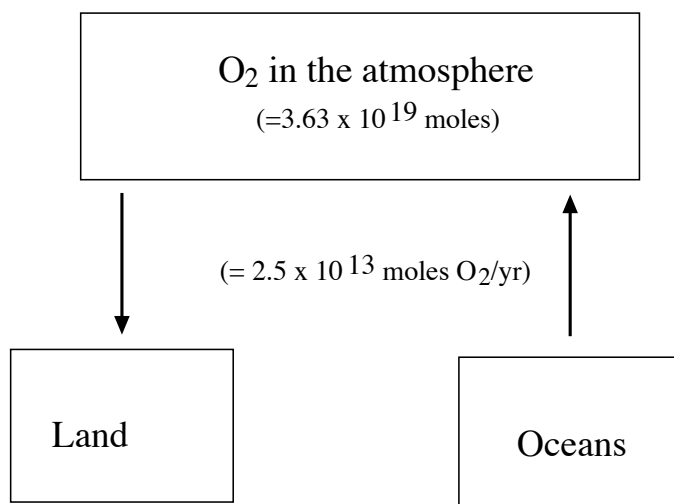
answering this question ignore the relatively “short” (at least on these time scales) increase in atmospheric CO₂ due to fossil fuel burning and deforestation].

10. How does the burial of organic carbon in marine sediments leads to the addition of oxygen to the atmosphere? Since atmospheric O₂ has been relatively constant in recent time, what processes appear to compensate for this addition of oxygen?

11. Shown below is a simplified version of the global oxygen cycle.

a. What are the most important processes that lead to net O₂ production in the oceans (i.e., a flux to the atmosphere) and to net O₂ consumption on land (i.e., a flux from the atmosphere)? Please list only one process for each flux.

b. Assuming these two fluxes are balanced (as is shown below), calculate the residence time of oxygen in the atmosphere.



12. What are the major processes that remove CO₂ from the atmosphere? What are the approximate time scales for these processes to be effective?

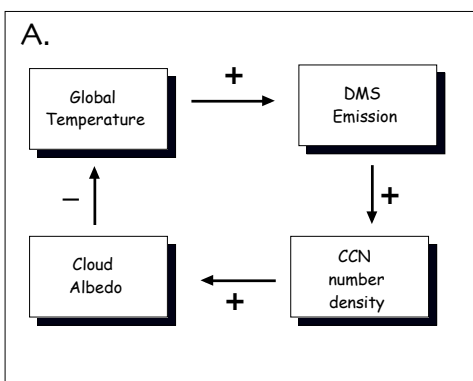
13. What is kerogen and how is it formed? What is the relationship between kerogen cycling (production and consumption) and atmospheric O₂? Over what time scales does this cycling occur?

14.

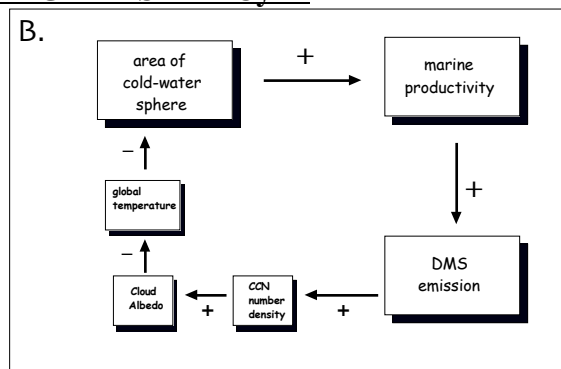
15. If plate tectonics stopped today (i.e., both subduction and mid-ocean spreading) how would CO₂ change over the next few decades? Over the next few million years? Please be sure to explain your answers.

The Nitrogen and Phosphorus Cycles

1. In the simplest sense, we can think of the global nitrogen cycle as a balance between denitrification and biological nitrogen fixation.
 - a. Please explain this observation.
 - b. Please describe how human activities affect this balance.
2.
 - a. Define “reactive nitrogen”.
 - b. Describe three broad anthropogenic processes that add reactive nitrogen to the Earth’s surface.
 - c. As we discussed in class much of this anthropogenic reactive nitrogen is eventually denitrified back to N_2 gas. However, there still appear to be reasons for concern about this anthropogenic nitrogen fixation. Please discuss the reasons for these concerns.
3. Nitrous oxide (N_2O) is a trace gas in the atmosphere with a relatively long atmospheric residence time (100-130 yrs). Recent evidence has shown that its atmospheric concentration is increasing with time in a fashion similar to that for atmospheric CO_2 .
 - a. What are the major sources of N_2O to the atmosphere and why might its concentration be increasing in recent time?
 - b. What role does N_2O play in stratospheric ozone depletion and possible global warming?
4. The figure below shows that riverine fluxes of N and P have roughly doubled as a result of human activities. Based on the data in this figure why might we suggest that these increased nutrient fluxes have their greatest effect in the coastal margins?



The Global Sulfur Cycle



1. In class we discussed the role that phytoplankton production of DMS (dimethylsulfide) might play in affecting global climate. Two possible ways that this might occur are shown below.
 - a. Looking at these figures below please indicate the overall signs of the feedback loops in each part.
 - b. In figure B, why does the area of cold water exert a positive feedback on marine productivity?
 - c. If these components of the Earth system behave as in figure b, describe how this system might play a role in glacial-interglacial climate change?
 - d. If these components of the Earth system behave as in figure b, describe how this system will likely respond to any possible anthropogenic global warming. Will these interactions dampen or amplify any anthropogenic temperature increases?

2. In the CLAW hypothesis it was suggested that phytoplankton production of DMS may exert negative feedback control on global climate. Please explain how this might work.

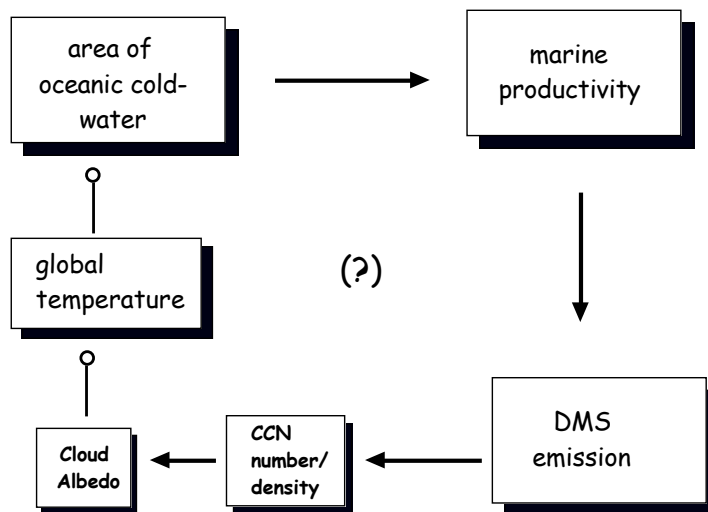
a. Discuss why data from ice cores actually suggests that DMS production may act in a positive feedback mode in affecting global climate.

3. In class we discussed the role that phytoplankton production of DMS (dimethylsulfide) might play in affecting global climate. A modified version of the original CLAW hypothesis is shown here.

a. Looking at this figure please tell me the overall sign of the feedback loop. Briefly explain your answer

b. Why is it thought that the area of cold water exerts a positive feedback on marine productivity?

c. If these components of the Earth system behave as in this figure, describe how this system might play a role in glacial-interglacial climate change?



4. How can volcanic eruptions like that of Mt. Pinatubo affect global climate?

5. Phytoplankton production of DMS and SO₂ production from fossil fuel burning both affect the earth's climate. Please explain how this occurs.

Pleistocene Glaciation

1. Describe the observed relationship between climate, CO₂ and other greenhouse gases on glacial-interglacial time scales. How are these observations relevant to the present-day build-up of greenhouse gases and any possible future global warming?

2. A general global cooling began during the mid-Cenozoic (~20 my bp) that ultimately led to the initiation of Pleistocene glaciation. What role might the formation of the Himalaya Mountains have played in this occurrence?

3. As we discussed in class the Milankovitch theory provides an “explanation” for the causes of glacial-interglacial cycles. As we also discussed, the dominant periodicity of glacial-interglacial cycles is 100,000 years. At the same time though, in the Milankovitch theory eccentricity forcing with a 100,000 year periodicity is the weakest of the three astronomical forcing functions (precession, obliquity and eccentricity). In a general sense, please explain the reason for this apparent discrepancy.

4. In the Milankovitch theory for the ice ages, the eccentricity forcing with a 100,000 year periodicity is the weakest of the three astronomical forcing functions (precession, obliquity and eccentricity). In spite of this, the dominant periodicity of glacial-interglacial cycles is also 100,000 years.

a. Discuss two ways that the Earth’s climate/biogeochemical system may amplify this 100,000 yr eccentricity orbital forcing function, and lead to glacial-interglacial cycles with the same dominant periodicity.

b. What is the significance of these types of amplification (positive feedback) in terms of recent increases in atmospheric CO₂ levels and possible global warming?

5. Explain how changes in the formation of North Atlantic Deep Water (NADW) might have played a role in causing the Younger Dryas event.

6. How does the growth of either sea ice or land-based glaciers amplify cooling of the Earth?

7. Does the growth of sea ice or land-based glaciers amplify or dampen cooling of the Earth? Why is this so? In your answer please be sure to discuss the significance of this in terms of climate change during Glacial cycles, as well as in terms of possible present-day climate change in response to rising atmosphere CO₂.

8. Discuss the processes that are thought to have led to the Younger Dryas event.

9. Explain how processes occurring in and around the North Atlantic might have played a role in causing the Younger Dryas event.

10. What is the significance of the Vostok ice core record in terms of understanding the relationship between global biogeochemical cycle of carbon (e.g., CO₂ and methane) and global climate?

11. Ice core data show that atmospheric methane concentrations were lower during the last glacial period as compared to the pre-industrial Holocene. Please explain why this suggests that glacial times were probably dryer (as well as colder) than they are today?

12. Ice core data show that atmospheric methane concentrations were lower during the last glacial period as compared to the pre-industrial Holocene. Please explain why this suggests that glacial times were probably dryer (as well as colder) than they are today? What role might a dryer global climate also have played in affecting atmospheric CO₂ concentrations during glacial times?

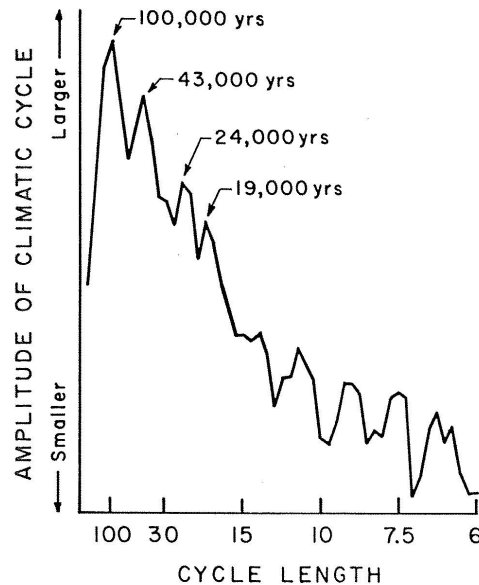
13. Describe possible feedback loops that may cause atmospheric CO₂ to keep pace with glacial climate conditions. Are these positive or negative feedback loops?

14. a. How does the oceanic biological pump affect atmospheric CO₂ concentrations?

b. During glacial times, it has been suggested that this pump may have been more “efficient” than it is today. Describe two ways that this might occur.

c. If this pump was indeed more efficient during glacial times, would it have acted as a positive or negative feedback for changes in atmospheric CO₂ and global climate?

15. This figure comes from an article whose title is “Variations in the Earth’s orbit: pacemaker of the ice ages”. The results shown here are from the spectral analysis of oxygen isotope data in a deep-sea sediment core. Please explain the results in this figure, and their relationship to the title of the article.

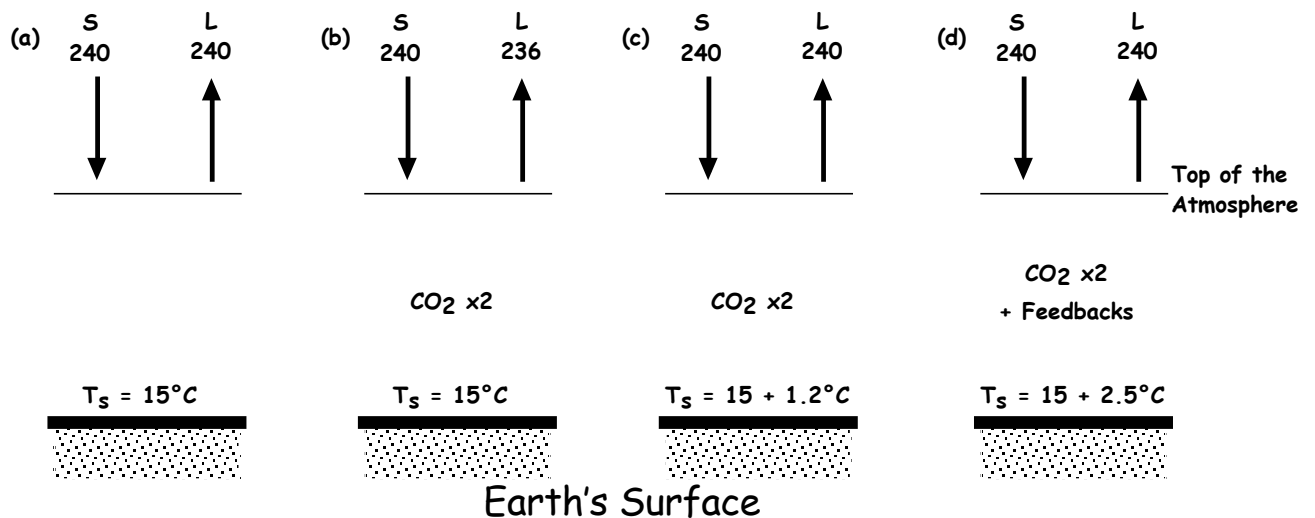


Global Warming and Anthropogenic CO₂

1. Please explain the reasons for sinusoidal variations in atmospheric CO₂ concentrations that are superimposed on the general CO₂ concentration increase (see the figure below). Why are variations in the southern hemisphere (South Pole data) of smaller amplitude and out of phase with those in the northern Hemisphere (Mauna Loa data)? Factoring out these phase differences and looking simply at the general trends in the data, why do the two curves closely follow one another?

2. The residence time of CO₂ in the atmosphere is relatively short (~3-4 yr). However, in our discussion of anthropogenic CO₂ emissions we observed that even if all anthropogenic emissions ceased immediately (i.e., both from fossil fuels and deforestation) that it will take >100 years for atmospheric CO₂ levels to return to pre-industrial levels. Please discuss the reasons for this long response time in spite of this short atmospheric residence time.

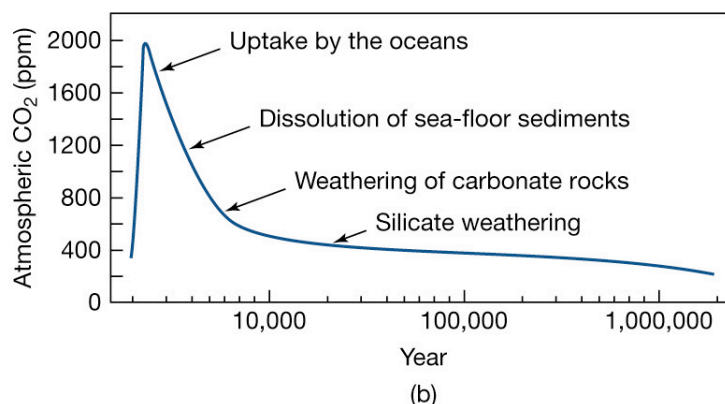
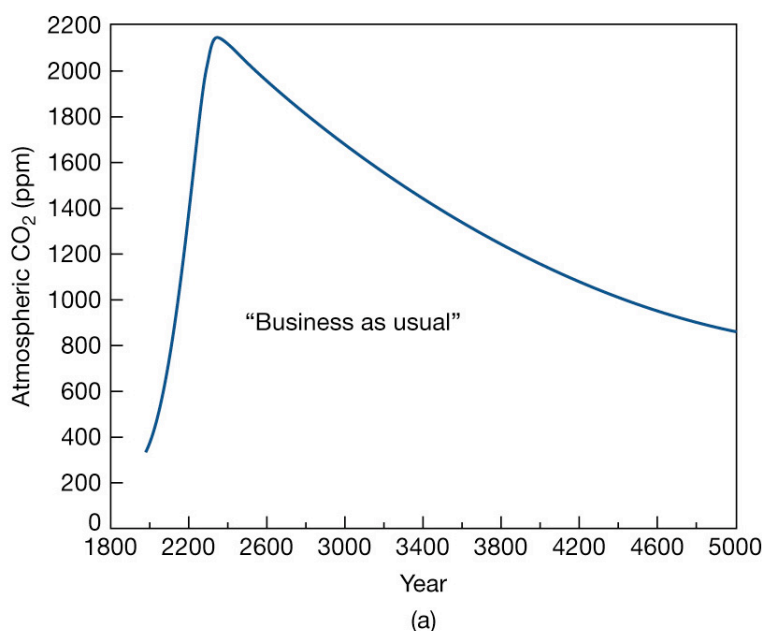
3. The oceans are an important sink for anthropogenic CO₂. However, the oceans are unable to take up CO₂ at a rate equal into its introduction to the atmosphere from fossil fuel burning and land use changes (i.e., deforestation). Please explain why this is so.
4. What factors control the ability of the ocean to take up anthropogenic CO₂ from the atmosphere?
5. Why do the oceans have a limited capacity for atmospheric CO₂ uptake?
6. Describe the factors that limit the ocean's ability to take up anthropogenic CO₂.
7. Why is the ocean only a "temporary" sink for the uptake of anthropogenic CO₂? Hint: be sure to define "temporary" and think about the oceanic processes that add and remove CO₂ from the atmosphere.
8. Simple one-dimensional radiative-convective models predict that a doubling of atmospheric CO₂ will produce a temperature increase of about 1.2°C (i.e., $\Delta T_{2x} = 1.2^\circ\text{C}$). However, more sophisticated three-dimensional general circulation models predict slightly higher values for ΔT_{2x} that range from 1.5-4°C, with 2.5°C being the currently best "accepted" value. Please explain the reasons for these observations.
9. The sequence of events shown below in this thought experiment illustrates the relationship between rising atmospheric CO₂ levels and possible global warming. Recall that S is the net solar radiation coming into the Earth's atmosphere, L is the thermal radiation leaving the top of the Earth's atmosphere, and the units of these fluxes are W/m². Explain why:
 - a. there is a 4 W/m² imbalance in the Earth's radiation budget as one goes from (a) to (b).
 - b. average planetary temperatures increase by 1.2 °C as one goes from (b) to (c).
 - c. average planetary temperatures increase by 2.5 °C as one goes from (c) to (d).



10. Shown below are model estimates for the long-term removal of anthropogenic CO₂ from the atmosphere (upper panel), and the processes that are responsible for this removal (lower panel).

Explain what each of these processes is, how they relate to the global carbon cycle and why each operates over a different uptake time scale.

10a. Shown below is the long-term removal of anthropogenic CO_2 (based on model calculations) and the processes that are responsible for this removal on different time scales. Please explain the reasons for the time scale differences of these removal processes (note that “dissolution of sea-floor sediments” is the dissolution of calcium carbonate on the seafloor).



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11. Please briefly describe what the greenhouse effect is.

12. Increasing levels of atmospheric CO_2 may lead to global warming due to what is known as the “greenhouse effect”. This warming may be amplified (positive feedback) or dampened (negative feedback) by a number of other changes associated with this warming. For each of the

changes described below, please discuss whether it (by itself) will have a positive or negative feedback effect on global warming, and how it will likely occur.

- a. Higher temperatures will increase evaporation from the oceans and increase the water vapor content of the atmosphere. More water vapor in the atmosphere will increase cloudiness.
- b. At higher latitudes higher temperature will melt glaciers. In the north Atlantic, this additional glacial meltwater will decrease the salinity of the surface ocean water and lead to a stratification of the water column; eventually it may also inhibit bottom water formation (i.e., the ocean conveyor belt).
- c. Melting of glaciers or snowpack will replace these high albedo surfaces with lower albedo surfaces (e.g., water vs. land).
- d. Increased temperatures in higher latitudes will release frozen methane (stored as methane clathrates) from soils.
- e. More water vapor in the atmosphere will increase cloudiness.

13. Anthropogenic (or natural) SO_2 emissions have a cooling effect and have the potential to counter some of the possible warming effects due to anthropogenic CO_2 emissions. Why is this so? Assuming fossil fuel consumption was to cease tomorrow, discuss why the potential cooling effects due to SO_2 emissions are not likely to be as long-lived as the potential warming effects due to anthropogenic CO_2 emissions.

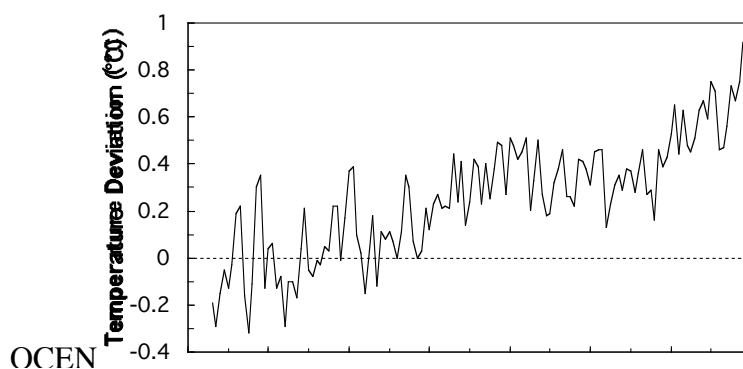
14. Fossil fuel burning emits both CO_2 and SO_2 . On short time scales SO_2 emissions have the possibility to counter any global warming associated with CO_2 emissions. On longer time scales, however, this may not be the case.

- a. How does the short-term cooling effect of SO_2 emissions likely occur?
- b. The atmospheric residence time of SO_2 is on the order of days to weeks, while that for CO_2 is years to decades. Please discuss the reasons for these differences (i.e., what are the differences in the physical and/or chemical processes affecting these gasses in the atmosphere).
- c. Based on your answer above, please discuss why the cooling effect due to SO_2 emissions is not likely to be as long-lived as the warming effect due to CO_2 emissions.

15. Fossil fuel burning emits both CO_2 and SO_2 . On short time scales SO_2 emissions have the potential to counter any global warming associated with CO_2 emissions. On longer time scales, however, this may not be the case.

- a. How do SO_2 emissions have a cooling effect?
- b. Please discuss why the potential cooling effect due to SO_2 emissions is not likely to be as long-lived as the potential warming effect due to CO_2 emissions.

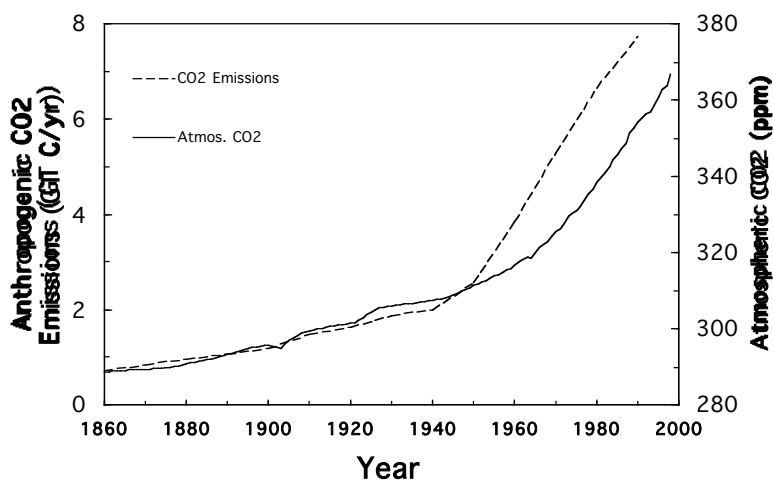
10. Persons who do not believe that increasing CO_2 levels will lead to global warming point to



the fact that global temperature records do not appear to be strongly coupled to anthropogenic CO₂ emissions or atmospheric CO₂ concentrations (compare the two graphs below). In particular they note that during the time period of around 1930 to 1980 when both anthropogenic emissions and atmospheric CO₂ levels increased rapidly, global mean temperatures actually decreased slightly. Please discuss some of the other factors that control global climate that could play a role in explaining these observations even if anthropogenic CO₂ emissions do play a significant role in affecting radiative forcing and global temperatures.

17. Increasing levels of atmospheric CO₂ may lead to global warming due to what is known as the greenhouse effect. The extent of this warming may vary spatially, with high latitudes possibly showing the greatest warming. Increasing temperatures at high latitudes will likely melt glaciers, and in the North Atlantic Ocean the resulting increased glacial meltwater will decrease the salinity of the surface ocean. This will then lead to a stratification of the water column and eventually also inhibit bottom water formation (i.e., the ocean conveyor belt). Please explain how these processes may both dampen (exert negative feedback) regional warming yet also amplify (exert positive feedback) warming on a more global scale.

18. The atmospheric concentration of methane (CH₄) has been increasing during recent times, in ways that show a similar temporal trend to the recent increase in atmospheric CO₂. However the causes of the increase in methane are not as well understood. It may be related to either an increase in net methane production on the earth's surface, or a decrease in the rate of methane



oxidation in the atmosphere.

- What are some of the major sources of methane to the atmosphere, and why might they be increasing in recent time?
- The major sink for methane in the atmosphere is oxidation (in the troposphere) by the hydroxyl radical. Other trace gasses in the troposphere that consume hydroxyl radicals include ozone (O₃), carbon monoxide (CO) and SO₂. Given these observations, please discuss why methane concentrations in the atmosphere could be increasing due to a decrease in the atmospheric methane oxidation rate.

CFCs and Stratospheric Ozone

1. Describe how the emission of chlorofluorocarbons leads to the depletion of stratospheric ozone?
2. Describe the processes leading to excess ozone in the troposphere (the lower atmosphere) and ozone depletion in the stratosphere (the upper atmosphere). Why are these of environmental concern? If there is too much ozone in one part in the atmosphere, yet not enough in another, why do physical processes (e.g., atmospheric mixing) not help to alleviate the problem?
3. Prior to the widespread production and use of CFC's, it was observed that the stratospheric ozone concentration was ~30% lower than that predicted by the Chapman mechanism. Please explain why this was the case. Explain how CFC's lead to the further catalytic destruction of stratospheric ozone.

Biodiversity

1. Using a variation of his Daisyworld model, Lovelock comes to the conclusion that what is important is not biodiversity *per se* but potential biodiversity (which he defines as the capacity of a healthy system to respond through diversification when it is perturbed in some way). Explain how this is consistent with the results in Figs. 6 and 10 below (recall that Fig. 6 is a model in which there are 20 different daisies each with an albedo that ranges from 0.25 to 0.6).