USESO 2023

Training Camp Exam

Free-response

Instructions:

- Section II consists of 5 multipart questions that further assess geoscience knowledge in the form of mostly free-response questions.
- You have 2 hours and 15 minutes.
- Any type of calculator is allowed.
- Participating in this exam is agreement to our academic integrity policy.

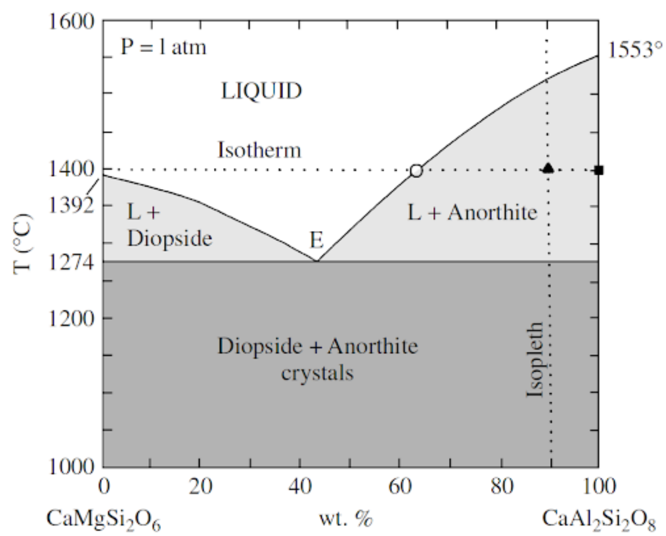
Problem 1

Question	1	2	Total
Points	9	11	20 (20%)

Naturally, Ca- and Mg-containing minerals can undergo carbonation reactions to produce carbonate minerals like calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), or magnesite ($MgCO_3$). There is some interest in artificial carbonation of igneous rocks as a method of carbon sequestration. Here we will explore some of the basic science related to this field.

1. (a) (3 points) Most of the basalt on the Earth's surface are flood basalts. In two or three sentences, briefly explain the origin of continental flood basalts. In your answer, characterize volcanism as either effusive or explosive and briefly describe the mechanism of formation for volcanoes that produce flood basalts.

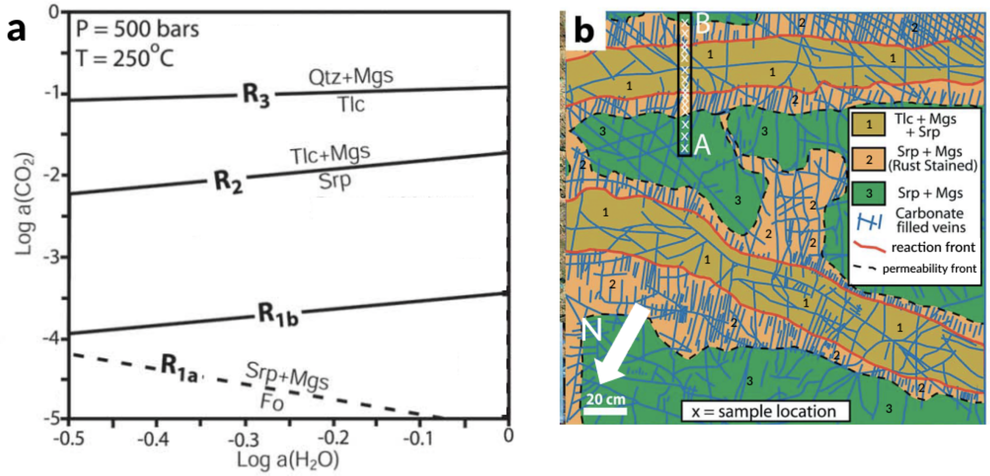
   (b) Diopside ($CaMgSi_2O_6$) and anorthite ($CaAl_2Si_2O_8$) are two relatively common minerals in basalt. Consider the composition-temperature phase diagram of diopside and anorthite:



   i. (4 points) Consider a mixture with bulk composition and temperature plotted by the triangle mark. What are the composition of the solid and liquid phases? Estimate the fraction of solid and liquid phases in the mixture. (*Detailed work is not needed, a description of your calculation is sufficient*)

   ii. (2 points) As that mixture cools, suppose some of the solid crystals no longer remain in chemical equilibrium with the rest of the mixture. Describe briefly what occurs to the bulk composition of the mixture. What igneous differentiation process does this model?

Studies have been done on the natural carbonation of serpentinite, which forms from the hydrothermal alteration of basalt. One such study showed that the carbonation of serpentinite occurs via a pathway of four reactions, labeled here R_{1a}, R_{1b}, R_2, and R_3.



(a) shows the stability of various mineral phases present in serpentinite as a function of the chemical activity of CO_2 and H_2O. For our purposes, consider activity to be a dimensionless quantity that represents an "effective concentration". **(b)** shows a 2 by 2 meter outcrop that has been mapped and labeled with mineral assemblages.

Key for mineral abbreviations

Srp	serpentine group
Mgs	magnesite
Tlc	talc
Qtz	quartz
Fo	forsterite

2. (a) (2 points) Which reaction occurred within the tan conduits (labeled 1) but did not occur in the green matrix (labeled 3) that distinguishes the tan mineral assemblage from that of the green mineral assemblage?

   A. R_{1a}

   B. R_{1b}

   C. R_2

   D. R_3

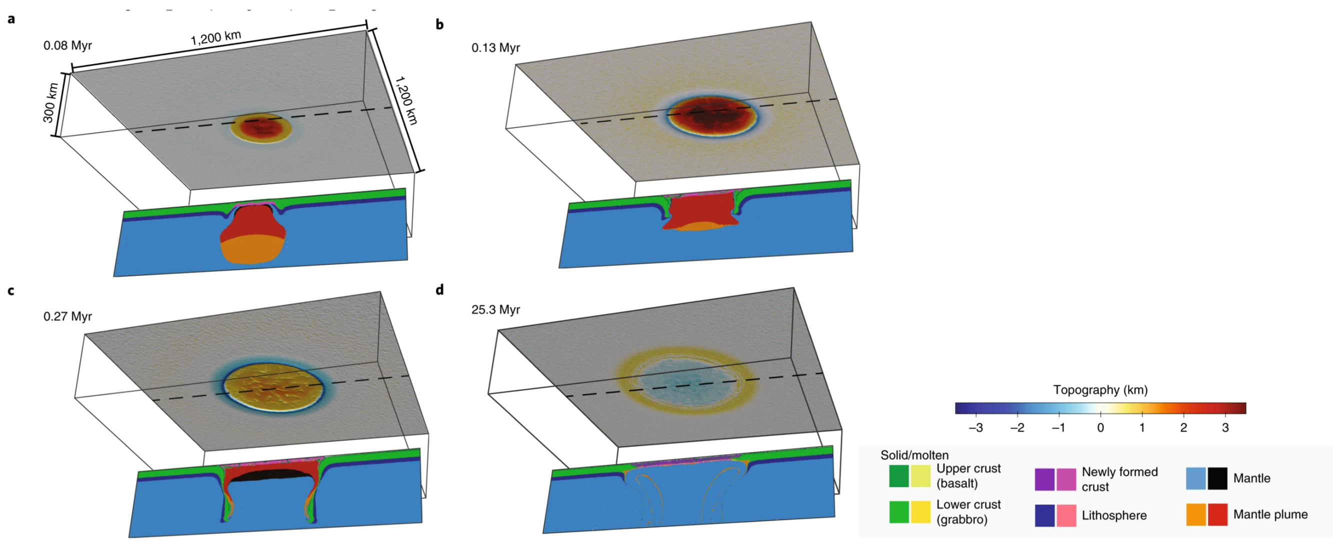
   (b) (6 points) Calculations show that each of the four carbonation reactions proceed with an increase in solid volume. Considering how these reactions *physically* take place (i.e., how is CO_2 transported into rock so that carbonation can actually occur?), explain how this increase in volume can feed back on reaction rates.

   (c) (3 points) In Figure (b), the carbonate-filled veins tend to have a preferred orientation, perpendicular to the conduits where carbonation has taken place. What does this suggest about the mechanical stresses that occurred during carbonation? In your answer, indicate whether the stress was compressive or tensile, and the primary axis of stress (note that north is given by the white arrow in the bottom left).

Problem 2

Question	1	2	3	4	5	Total
Points	4	3	4	2	7	20 (20%)

Venus's surface contains dozens of *coronae*, circular regions of highly deformed and fractured crust. The following figure depicts a proposed method of formation in four steps (chronologically from a to d) in which a mantle plume rises and deforms part of the crust. The image includes both surface topography and a mantle cross-section for each stage.



1. (a) (2 points) The process depicted in stages (a) and (b) is most similar to which of the following tectonic processes on Earth?

   A. Seafloor spreading

   B. Alpine-type mountain building

   C. Fault-block mountain formation

   D. Batholith formation

   (b) (2 points) This process is different on Venus because the Venusian crust is not split into tectonic plates despite its magmatic activity. Explain how one difference between Venus and Earth contributes to Venus's lack of tectonic plates.

2. (3 points) In stage (c), part of the lower crust delaminates from the upper crust and sinks into the mantle. This sinking does not immediately occur because the crust is slightly less dense than the mantle. Briefly explain why the crust eventually becomes dense enough to sink.

3. In stage (d), the crust returns to a stable state after a long time. Notice that the center and rim have inverted since stage (c), with the center sinking and the rim rising.

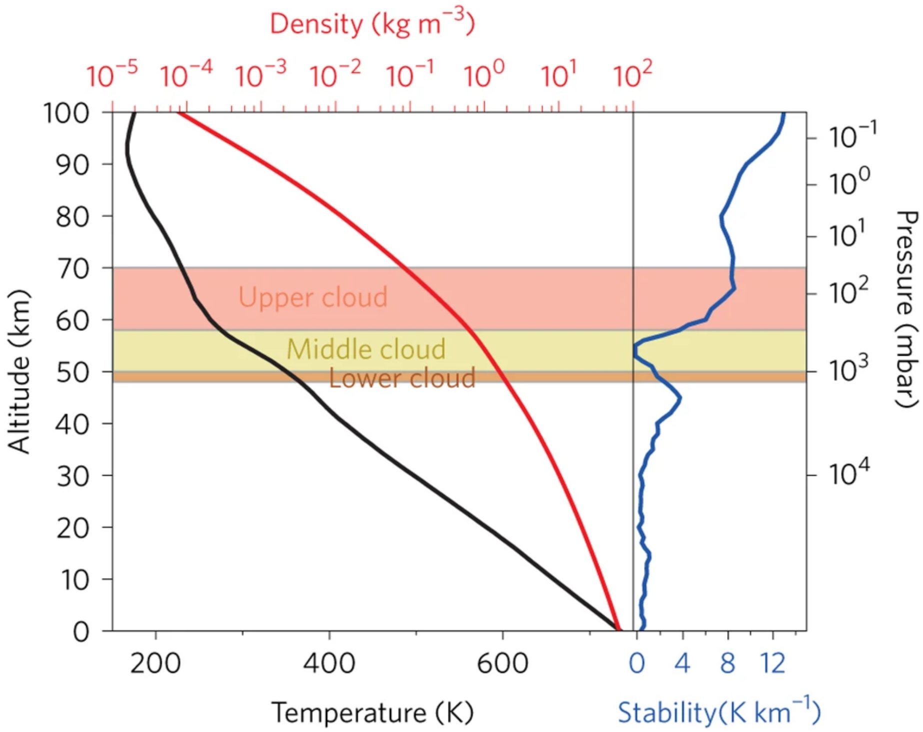
   (a) (2 points) Briefly account for the sinking of the center of the corona.

   (b) (2 points) Briefly account for the rise of the outer rim of the corona.

The following table gives the concentrations of the most common gases in the Venusian atmosphere.

Gas	Concentration
Carbon dioxide	96.5%
Nitrogen	3.5%
Sulfur dioxide	150 ppm

4. (2 points) Tectonic activity at coronae significantly impacts Venus's atmospheric composition. Briefly explain how this tectonic activity contributes to the unusually high concentrations of CO_2 and SO_2 in Venus's atmosphere.



5. Venus has an enormously strong greenhouse effect because of the high concentrations of CO_2 in its atmosphere and the insulating effect of sulfuric acid clouds. These thick clouds trap most outgoing radiation and absorb a small percentage of incoming radiation.

   (a) (4 points) Venus's atmosphere absorbs more energy from the Sun at its equator than at its poles. Most of this energy is absorbed by the upper cloud layer rather than the Venusian surface. How does this differential energy absorption affect the stability of Venus's cloud layer and lower atmosphere at the equator compared to the poles?

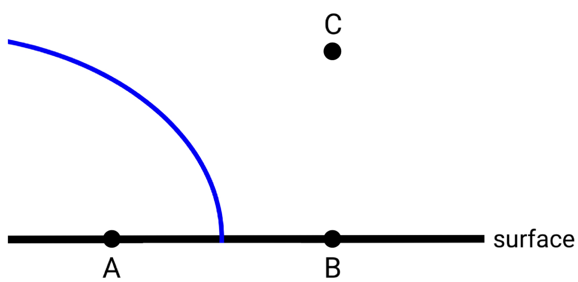
   (b) (3 points) Does this effect strengthen or weaken global Hadley circulation on Venus? Explain.

Problem 3

Question	1	2	3	4	Total
Points	6	6	3	5	20 (20%)

This question explores various aspects of and features associated with mid-latitude cyclones and storms. For this question, assume that all weather systems are in the Northern Hemisphere.

1. The structure of fronts in mid-latitude cyclones can be diagnosed by the *potential temperature* θ, which is defined as the temperature that a parcel would attain if moved dry adiabatically (9.8 K/km) to 1000 hPa (approx same as surface pressure). Consider the following simplified cross-section of a cold front (the boundary is marked blue):



(a) (2 points) Assuming that the environmental lapse rate < 9.8 K/km everywhere, rank the letters in order from lowest to highest *potential* temperature θ. Use $<$ or $=$ between each letter.

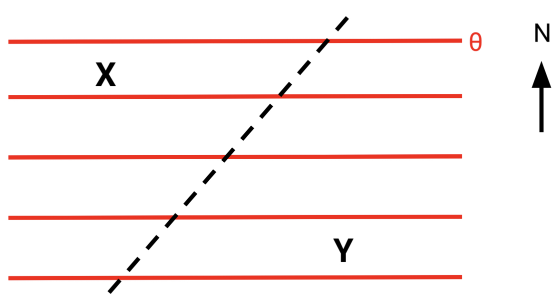
(b) (2 points) The buoyancy frequency N^2 over some small range in height Δz is proportional to (static) stability in the atmosphere, given by the formula

$$N^2 \approx g \frac{\Delta \ln \theta}{\Delta z}$$

where g is the gravitational acceleration and z is height.

Based on the relative stability of air masses, on which side of the cold front in the diagram (A or B) is the vertical gradient of θ greater?

(c) (2 points) Frontogenesis occurs when the potential temperature gradient becomes tighter with time. Consider the following horizontal map view of surface potential temperature (red contours), the position of a future front (dashed line), and the location of two pressure systems X and Y:



Identify each pressure system X and Y that most typically leads to frontogenesis.

A. X - low, Y - low

B. X - low, Y - high

C. X - high, Y - high

D. X - high, Y - low

2. Although mid-latitude flows are usually close to geostrophic balance, it is not always a valid assumption throughout the atmosphere.

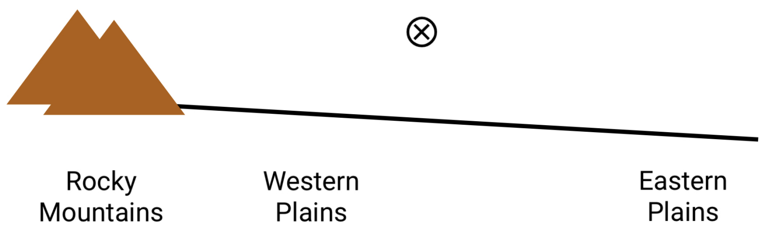
   (a) (4 points) Identify the **two** cases below for which geostrophic balance does **not** approximate the flow. Briefly justify your answer for each choice. *Merely stating the forces behind geostrophic balance is **not** sufficient justification; consider which forces can/can't be neglected.*

   - Flow near the equator
   - Flow near the poles
   - Flow within the planetary boundary layer (PBL)
   - Slow flow aloft outside of jet streams

   (b) (2 points) Geostrophic balance also does not hold for aloft flows around closed lows, which are detached from the jet stream and are nearly symmetric. Identify the dominant force causing air aloft to accelerate around closed lows.

3. (3 points) Severe thunderstorms are relatively common in the Central Plains of the United States.

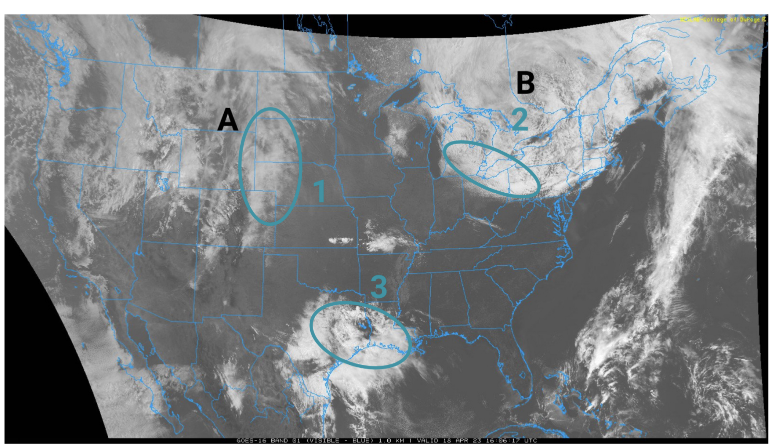
   The nocturnal (nighttime) low-level jet (LLJ), which advects moist air via southerly winds, can sustain thunderstorms at night over the Central Plains. The Rocky Mountains and western Plains are at higher elevations than the eastern Plains, as shown in the figure below.



The circled cross indicates the LLJ is blowing into the page.

   Explain how a west-to-east moisture gradient contributes to the development of the LLJ. In your answer, identify the direction in which the moisture gradient must point. *(Hint: consider how temperature is affected.)*

4. Mid-latitude cyclones can also be a cause of severe thunderstorms. Shown below is a visible satellite image on April 18, 2023. A and B refer to different cyclones, and circled regions 1 to 3 correspond to different cloud regions.



(Image courtesy of Iowa State/NOAA)

(a) (3 points) Indicate whether each of the following statements is true or false.

i. A has a higher surface pressure than B.
ii. A is expected to weaken sooner than B.
iii. Of all the cloud regions, the clouds in Region 2 are most likely to be formed by frontal lifting.

(b) (2 points) A day later, tornadic supercell thunderstorms affected parts of the Central Plains, including Oklahoma, with strong wind shear observed. Briefly describe one reason that wind shear helped to support supercell thunderstorms.

Problem 4

Question	1	2	Total
Points	10	10	20 (20 %)

The fact that Earth's surface temperature and pressure allows liquid water at its surface is one of the defining features of our planet that allows it to support life. In this question, we will explore various factors that influence Earth's surface temperature and apply it in the TRAPPIST-1 planetary system.

1. The energy radiated by an object can be modeled by the Stefan-Boltzmann law:

$$P = A\varepsilon\sigma T^4$$

where P is the power output, A is the surface area of the object, ε is a dimensionless number called emissivity, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant, and T is the absolute temperature.

(a) (1 point) We will assume the Sun is a perfect blackbody with a radius of 6.96×10^8 m and surface temperature of 5772 K. Find the power output of the Sun in W. You may use $P = 5.00 \times 10^{26}$ W for following parts if you do not obtain an answer to this part.

(b) A planet's effective temperature is the temperature that it would have if it were a blackbody radiating away all incident energy absorbed from its parent star.

i. (2 points) Let P denote the power outputted by the Sun. First, write an algebraic expression for the radiant flux density ρ (defined as radiant power per unit area) at a distance r from the Sun.

ii. (2 points) Write an algebraic expression for the incident power P_{inci} (how much power Earth absorbs) in terms of P, r, the radius of the Earth R, and Earth's albedo α.

iii. (2 points) Solve algebraically for the effective temperature T_{eff} of the Earth by equating the incoming and outgoing power. Use $\varepsilon_{\text{Earth}}$ to denote the emissivity of Earth.

iv. (1 point) If you used the emissivity of the Earth's atmosphere, estimated to be around $\varepsilon_{\text{Earth}} = 0.96$, the temperature you would calculate would be far lower than the average surface temperature of the Earth (288 K, or 15°C). This is, of course, because we didn't account for the greenhouse effect. As a surrogate for this omission, we can let ε instead be an *effective* emissivity ε_{eff} to artificially parameterize the greenhouse effect. Give a physical explanation for why $\varepsilon_{\text{eff}} < \varepsilon_{\text{Earth}}$.

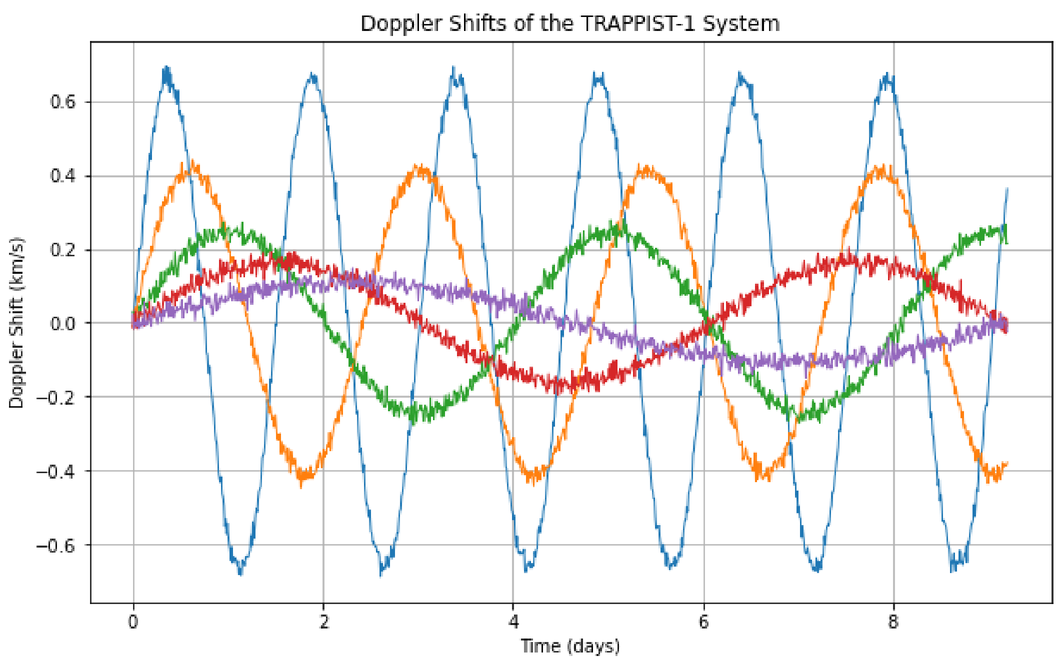
v. (2 points) Calculate the value for ε_{eff} needed to raise Earth's effective temperature T_{eff} to its current average surface temperature of 288 K. Use $\alpha = 0.3$, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, and $r = 1.50 \times 10^{11}$ m = 1 AU.

2. Applying these calculations to the TRAPPIST-1 system allows us to estimate a very rough estimate for its habitable zone.

   (a) (3 points) The star TRAPPIST-1 has a luminosity (radiant power output) of about 5.5×10^{-4} solar luminosities. Assuming that the habitable zone is defined by distances from the star where liquid water can exist on a planet's surface, calculate the inner and outer radii of TRAPPIST-1's habitable zone, in AU. Use ε_{eff} that you calculated in 1b(v) to emulate a greenhouse effect, and use $\alpha = 0.3$ for an Earth-like surface. (Note: $0°\text{C} \approx 273$ K)

   (b) (3 points) What are two facts you had to assume about the exoplanets' atmospheres in order to calculate (a)? (*Hint: consider how we defined the habitable zone*)

   (c) (2 points) The following image shows the Doppler shift data of the planets in the system. Unfortunately, you forgot to label the plot! However, you know that the order of the planets from innermost to outermost is TRAPPIST-1b through TRAPPIST-1f. What planet corresponds to each of the lines? (Name the planet and the color of the line it corresponds to.)



   (d) (2 points) Which of the planets in the TRAPPIST-1 system exhibit 2:3 resonance with TRAPPIST-1f?

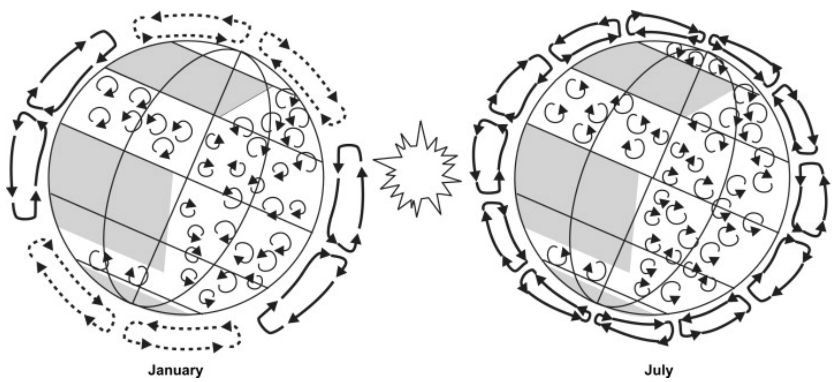
Problem 5

Question	1	2	3	4	Total
Points	3	6	3	8	20 (20 %)

The Cretaceous period (145 to 66 million years ago) had elevated temperatures and a different arrangement of continents that led to a greenhouse state dramatically unlike our modern climate.

1. (3 points) The elevated temperatures occurred both in equatorial and even more so in polar regions. If the average global meridional (north/south) temperature difference was lower, how would you expect average wind strength to compare to the present? Briefly explain why.

2. Some models suggest that during the Cretaceous, the polar pressure seasonally alternated between high and low. Below is a diagram of atmospheric circulation cells (drawn as cross sections) during two parts of the year (January on left, July on right). Shaded areas represent land, and unshaded areas represent open water.



   (a) (1 point) Of the months January and July, which month do the poles have a surface high-pressure zone? Low-pressure?

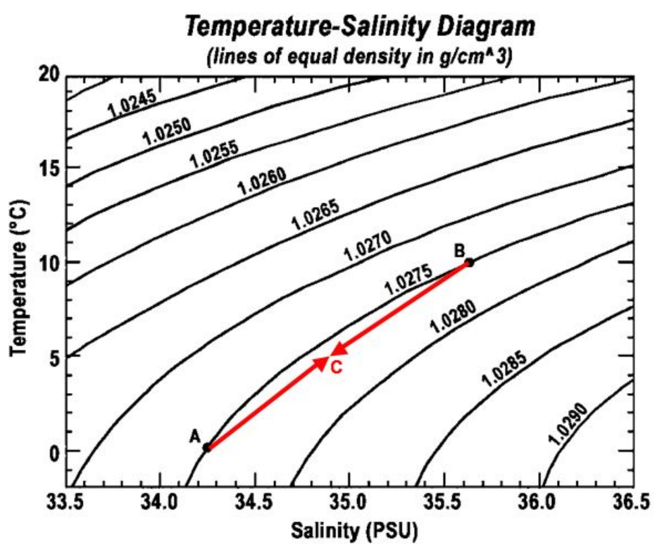
   (b) (3 points) The model is based on the assumption the Cretaceous is ice-free. Let's bring our attention to the Arctic (upper pole), then an open-water region surrounded by land. Explain why the Cretaceous Arctic was a high or low pressure zone in winter, and a high or low pressure zone in summer.

   (c) (2 points) What characteristic of ice currently allows the Arctic to maintain the polar high in the winter?

3. (3 points) The small curled arrows in the previous figure represent small eddies that may have governed ocean circulation instead of the highly structured circulation we observe in modern oceans. Using your answer to question 1, explain why structured circulation was less likely to form during the Cretaceous. (*Hint: consider the implications of the changing pressure systems on zonal, or east-west winds.*)

4. Global sea level was higher than present day through most of the Cretaceous. Within what we now know as North America was the Western Interior Seaway, the inland sea pictured above.

   (a) (1 point) When sea level further rose, the cooler, fresher water mass from the north mixed with the warmer, saline water mass from the south. Assume for simplicity that our scenario is illustrated by the figure below.



   When the water masses mix, the new parcel:

   A. Upwells

   B. Downwells

   C. Neither upwells nor downwells

   (b) (3 points) Based on your previous answer, are instances of sea level rise in the Western Interior Seaway associated with instances of relatively oxic or anoxic conditions at the sea floor? Describe your reasoning.

   (c) (4 points) Imagine a bed of shale is deposited in the seaway as sea level lowers. Why might you expect the shale to be dark in color? Synthesize conclusions from both parts (a) and (b) in your answer to (c).