USESO 2023

# Open Exam

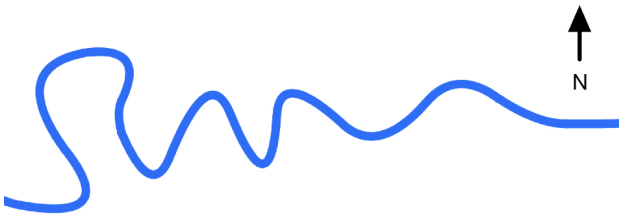
## Section I - **KEY**

---

**Instructions:**

- Section I consists of 30 multiple choice questions. Each question is worth 2 points.
- Questions are **not** ordered by difficulty.
- Print your name on the ZipGrade answer sheet and the cover of this test.
- Bubble your answers clearly on the ZipGrade answer sheet. **Ignore the Student ID field**; the answer bubbles start below this section.
- You have **2 hours** to complete both sections in any order, and you may flip back and forth between sections.

1. Consider the following map of the main channel of a graded stream segment. Tributaries are hidden and the width of the stream on the map is **not** proportional to its discharge. The top of the map is north.




It can be inferred that the stream gradient is higher near the _____ end of the stream segment, and the discharge is higher near the _____ end of the segment.

A. Western, western B. Western, eastern C. Eastern, eastern **D. Eastern,western**

**Solution:** The western end of the stream segment has a higher sinuosity, or has more pronounced meanders, than the eastern end. Sinuous, meandering channels are often found in areas with low gradients, such as a floodplain, whereas streams with steeper gradients tend to be straighter. As streams typically proceed downstream with a decreasing gradient, the flow direction is towards the west. The discharge of the main channel increases downstream as more tributaries feed into it, so increasing discharge is expected towards the western end.

2. A sediment core is taken from the abyssal plain and layers of different sediments are marked. From top to bottom, in what order would you expect to find the following three layers?

I) Coarse-grained sandstone

II) Well-sorted sandstone

III) Laminated mudstone

A. I, II, III B. I, III, II **C. III, II, I** D. II, III, I E. I, III, II

**Solution:** Abyssal sediments commonly display graded bedding, where sediments are deposited according to their grain size. The coarsest sandstone will always be deposited first, as these sediments require the most energy to remain suspended in water and will deposit while smaller sediments remain in the water. This is followed by more well-sorted sandstone, deposited once the water has settled and only a single size of sediment will be deposited, with the smallest mudstone grains added on top.

3. Which of the following conditions would most favor cloud formation?

**A. An increase in humidity and a decrease in temperature**

B. An increase in both humidity and temperature

C. A decrease in humidity and an increase in saturation vapor pressure

D. A decrease in both humidity and saturation vapor pressure

**Solution:** Conceptually, higher vapor pressure corresponds to adding moisture to the air, which is necessary for clouds. Lowering the temperature decreases the evaporation rate; lowering the temperature enough would cause saturation and net condensation to occur.

Alternatively, cloud formation is most favored under high relative humidity conditions, which is given by $\text{RH} = 100\dfrac{e}{e_s}$, where $e$ is the vapor pressure and $e_s$ is the saturation vapor pressure. We want to find the choice that gives the greatest increase in RH. Of the given options, an increase in $e$ and a decrease in $e_s$ would most certainly increase the RH. Since $e_s$ increases as temperature increases, a decrease in temperature would decrease $e_s$.

4. The Bonneville Salt Flats are an extremely flat plain in northern Utah with extensive evaporite deposits. Considering the formation of salt flats, which of the following is likely **not** true of the location's geology?

A. Terraces can be found surrounding the area

**B. The bedrock has relatively high permeability**

C. The flats are at a lower elevation than the surrounding area

D. The flats are thinner during the wet season

**Solution:** Salt flats are typically remnants of lakes that have evaporated, leaving behind large deposits of salts. During the wet season, a thin layer of water forms and dissolves some of the salt in the area, thinning the flats until the same salt is re-deposited during the dry season. Terraces are indeed found around the area, formed by wave erosion when the original lake was present. However, this lake can only form if evaporation is the main way water exits the lake; this means there are likely no outflows, so it must be surrounded by land with a higher elevation, and water cannot infiltrate to become groundwater, so the bedrock must have relatively low permeability.

5. The coast of Antarctica is notable for producing the Antarctic Bottom Water, a dense water mass that rapidly sinks to the bottom of the ocean. Which of the following changes in the coastal ocean would most likely **inhibit** the formation of this water mass?

A. Increase in ice formation rate around Antarctica

**B. Rainfall over open water surrounding Antarctica**

C. Strengthening of warm equatorial currents moving towards Antarctica

D. Strengthening of cold winds blowing away from Antarctica

**Solution:** AABW formation requires a highly cold and salty water mass to form off of Antarctica. An increase in ice formation rate would promote AABW formation, as brine rejection adds more salt to the seawater. A strengthening of Antarctic winds would promote sea ice formation and cause the same effect, as it moves ice away from the location where it forms and exposes new water that can now form ice. A strengthening of warm equatorial currents would not significantly affect AABW formation, since these are typically blocked by the Antarctic Circumpolar Current, but they would cool to create the same cold, salty water if they entered the region. Rainfall is the only change that would decrease the salinity of the water, decreasing its density and preventing AABW formation.

6. Ephemeral streams are characterized by flow almost exclusively after precipitation events. After a storm, the stream's discharge is typically lowest downstream because:

**A. The water table is located below the stream**

B. Water evaporates quickly in arid environments

C. Average flow velocity increases downstream

D. Capacity decreases downstream

**Solution:** Ephemeral streams typically form in regions where precipitation is rare, such as in deserts. These regions typically have a low water table because there is rarely rainfall to recharge groundwater. This means ephemeral streams are typically losing streams, in which some water infiltrates into the ground as the stream flows further.

7. Volcanic explosivity can evolve over time due to various internal and external mechanisms. Which of the following conditions would likely increase the probability of a highly explosive eruption?

I) A decrease in overburden pressure due to rapid snow melt

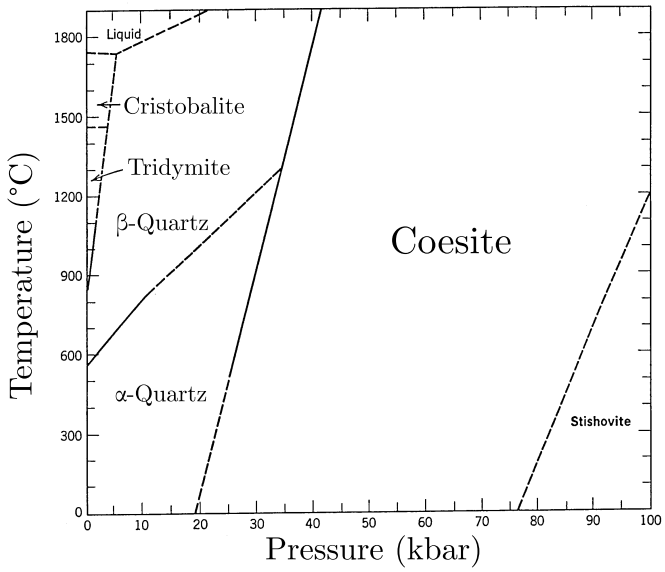
II) Assimilation of felsic country rock in the associated magma chamber

III) The exposure of confined groundwater to hot magma

A. I only B. I and II C. II and III **D. I, II, and III**

**Solution:** Volcanic explosivity is largely driven by lava viscosity and volatile content. A decrease in overburden pressure decreases the solubility of volatiles in the melt, potentially triggering an explosive eruption as gases rapidly exsolve - I is true. The assimilation of felsic country rock would cause an increase in magma viscosity as the melt becomes more silica-rich - II is true. Lastly, hot magma rapidly healing confined groundwater can cause an explosive phreatic eruption - III is true.

8. Pictured below is a phase diagram for $SiO_2$. Lunar regolith sampled during the Apollo missions was found to have high proportions of $SiO_2$ in the metastable coesite phase. Which of the following processes best explains the occurrence of this mineral?




A. Compression at thrust faults on the surface of the moon

B. Subduction and subsequent uplifting from the moon's mantle

**C. Shock from meteorite impacts during the late heavy bombardment**

D. Strong heating of the moon's surface by the early earth

**Solution:** The moon lacks the seismic activity necessary to form thrust faults and subduction. Heating would transform the quartz into high (beta) quartz rather than coesite. Shock metamorphism yields high pressure increases with relatively low temperature increases, which typically forms the coesite seen on the lunar surface.

9. The addition of carbon dioxide to the atmosphere results in a series of reactions that create carbonic acid in seawater, resulting in ocean acidification. Which of the following correctly explains the feedback loop that ocean acidification creates in its interactions with oceanic organisms?

A. Positive, because it promotes carbon sequestration

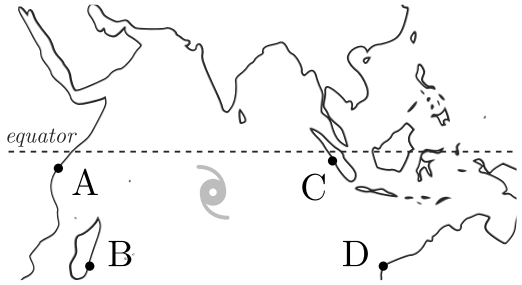
**B. Positive, because it inhibits carbon sequestration**

C. Negative, because it promotes carbon sequestration

D. Negative, because it inhibits carbon sequestration

**Solution:** Carbon sequestration in water occurs as marine organisms form calcium carbonate shells, which then deposit on the ocean floor as they die. An increase in oceanic carbon dioxide results in the formation of carbonic acid, decreasing the pH of the water. This decreased pH causes existing calcium carbonate to dissolve and converts the carbonate marine organisms need to unusable bicarbonate, making it harder for them to sequester carbon. Carbon sequestration is one method by which carbon dioxide is removed from the atmosphere, so this change will increase the presence of carbon dioxide and further increase ocean acidification in a positive feedback loop.

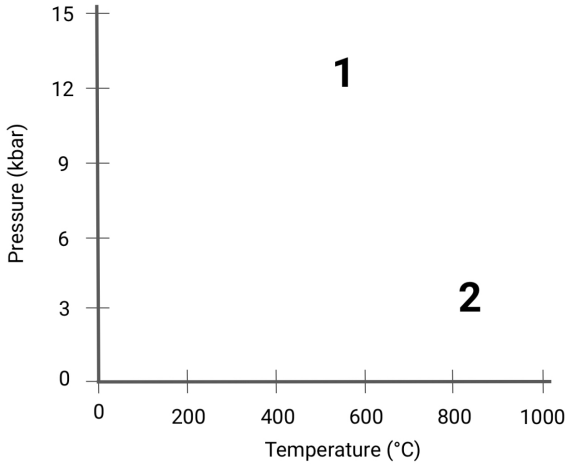
10. The map below shows the position of a tropical cyclone in the Indian Ocean with the equator marked by the dashed line. At which of the labeled points on the map would the cyclone most likely make landfall?




A. A **B. B** C. C D. D

**Solution:** Tropical cyclones almost always travel westward due to the presence of trade winds at the equator. Cyclones never travel along the equator because the weakened Coriolis force would cause them to dissipate. Winds typically travel counterclockwise around the subtropical high in the center of the Indian Ocean, so cyclones will be brought southward once they reach the coast. Thus, this cyclone will likely make landfall southwest of its initial location.

11. Two metamorphic rocks, labeled 1 and 2, were sampled from a mountain range near an active tectonic margin. They contain index minerals that formed in the pressure-temperature conditions plotted below.




Which of the following statements can be inferred about the two rocks?

I) Rock 1 is more likely to have formed within the subducting slab than Rock 2

II) Rock 1 is more likely to have formed by contact metamorphism than Rock 2

III) Neither Rock 1 nor Rock 2 is slate

A. I only B. II only C. I and II **D. I and III** E. II and III

**Solution:** Subduction zone metamorphism typically occurs at relatively high pressure and at low to intermediate temperature environments - I is true. Contact metamorphism is associated with proximity to a magmatic heat source, a high temperature but relatively low pressure environment. Rock 2 fits this description better than Rock 1 - II is false. Slate is a low-grade metamorphic rock typically formed under low temperatures and pressures, which does not correspond to either label 1 or 2 on the diagram - III is true.

12. The biggest effect that airplanes have on the climate is surprisingly not from $CO_2$ emissions, but from generating long cirrus-like clouds known as contrails. Which of the following effects on the radiative budget are the primary way by which contrails cause net warming?

A. Contrails reflect more shortwave radiation from the Sun than clear sky

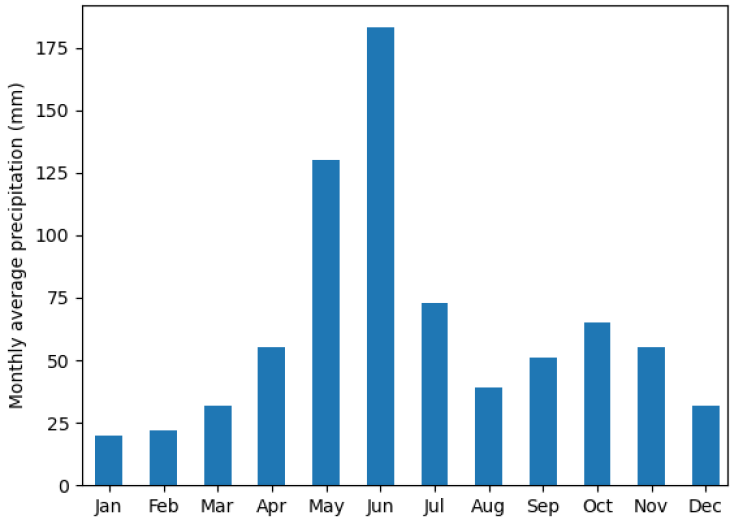
B. Contrails absorb more shortwave radiation from the Sun than clear sky

**C. Contrails radiate less longwave radiation to space than clear sky**

D. Contrails radiate more longwave radiation to space than clear sky

**Solution:** Like cirrus clouds, contrails exert the most effect on the longwave energy balance. Since contrails are cold, high clouds, they radiate less longwave radiation than clear sky. Since less energy is lost to space, contrails cause net warming.

13. Consider the following precipitation climograph. Which of the descriptions below best matches the location it represents?




**A. A point at 5°N within the zone of annual ITCZ migration**

B. An inland point at 20°N subject to regional monsoon circulation

C. A point at 35°N with a semi-arid climate at the edge of the Hadley cell during summer

D. A point at 60°N sensitive to jet stream shifts caused by the El Niño-Southern Oscillation

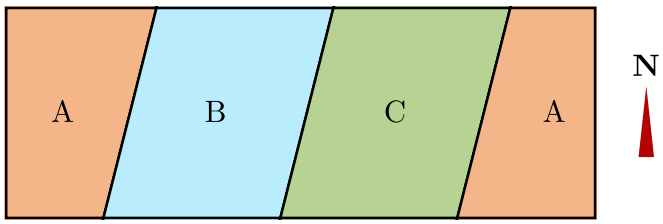
**Solution:** The climograph depicts a dry season in the winter with two peaks in precipitation. The ITCZ, a zone where converging winds cause clouds and precipitation, shifts south of the equator in winter and north during the summer. A point near the equator would thus experience two maxima as the ITCZ moves through towards the north in late spring/early summer, then towards the south in fall. An inland point subject to monsoons would experience one pronounced peak in precipitation in the summer wet season. The northern edge of the Hadley cell promotes sinking dry air, so such a location would have a dry season in the summer. Finally, ENSO may explain variations in climate from year to year (e.g. why one year's precipitation differs from the next) but does not explain seasonal variations (e.g. why summer precipitation is different from winter precipitation). This is a climograph from Accra, Ghana at a latitude of around 5°N.

14. Mercury's surface shows extensive faulting due to cooling and contraction rather than plate tectonics. Which of the following types of faults are prevalent on the surface of Mercury?

A. Normal **B. Reverse** C. Strike-slip D. Both normal and reverse E. Both reverse and strike-slip

**Solution:** Mercury's surface has shown contraction due to cooling. Contraction of the surface results in compressional forces on the surface, which are typically expressed as reverse faults. Normal faults would require tension, and strike-slip faults would require shear forces, neither of which are as significant.

15. The surface map below shows a partially eroded geological structure that includes multiple strata (A is youngest, C is oldest) and a reverse fault. Towards what direction does the fault dip?




**A. WNW** B. NNE C. ESE D. SSE E. SSW

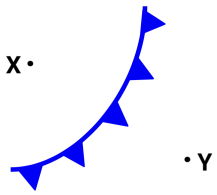
**Solution:** The geological structure in question is a fault-bend fold. The fault occurs along the boundary of beds C and A, as this represents a discontinuity in geologic time. Since C is older, the west side of the fault must have been uplifted, so it represents the hanging wall of the reverse fault. The fault plane must angle beneath the hanging wall, dipping WNW towards bed C.

16. A student is trying to identify where a thunderstorm could take place on a weather map using only pressure and temperature data. Which of the following conditions should the student look for?

A. Low-pressure system and cold air
C. High-pressure system and cold air
**B. Low-pressure system and warm air**
D. High-pressure system and warm air

**Solution:** Low-pressure systems support thunderstorm formation because air moves upwards, typically leading to condensation and more cloud formation. High-pressure systems tend to bring clear weather. Having air with high temperatures ahead of the thunderstorm intensifies the low pressure due to a larger temperature difference. Moreover, the warmer air is able to hold more moisture than cold air to form clouds and precipitation.

17. Consider the following surface weather map. Assume X and Y are both at sea level. Which of the following can be inferred?




I) X likely has denser air than Y
II) X likely has a higher relative humidity than Y
III) At Y, the air pressure is expected to increase, then decrease

**A. I only** B. I and II C. I and III D. II and III E. None

**Solution:** The triangles on the cold front are pointed in the direction of cold air advance, so X is behind the cold front and likely colder than Y. Cold air is denser than warmer air at the same/similar pressure (both X and Y are at the same elevation and an equal distance from the front) - I is true. Since air masses ahead of a cold front tend to be moist, and those behind tend to be dry, X is more likely to have a lower relative humidity than Y - II is false. As the front moves towards Y, the air pressure is likely to decrease, then increase after the frontal passage, since fronts also lie in troughs of low pressure - III is false.

18. Which of the following depositional environments typically have well-sorted, rounded sediment?

I) Mountain stream

II) Glacial outwash

III) Sandy desert

A. I only **B. III only** C. I and III D. I, II, and III E. None

**Solution:** A mountain stream and glacial outwash plain are depositional environments near the source of sediment formation, so sediments are typically not weathered enough to be well-sorted and rounded. Sediment in desert environments is sorted by wind and rounded by abrasion.

19. Jaime finds a carbon film with the following isotopic composition:

| Isotope | mol % |
|---|---|
| $^{12}$C | 98.1% |
| $^{13}$C | 1.03% |
| $^{14}$C | 0.522% |
| $^{14}$N | 0.347% |
| $^{15}$N | <0.001% |

He knows that the half-life of one of the isotopes is around 5,700 years but cannot remember which! Which of the following is closest to the age of the sample?

A. <100 years B. 2400 years **C. 4200 years** D. 7500 years

**Solution:** This question requires familiarity with carbon dating, which relies on the radioactive decay of $^{14}$C to $^{14}$N, a process that takes around 5700 years. The following calculation can be done to reach the answer:

$$(.522 + .347) * \frac{1}{2}^{\frac{x}{5700}} = .522$$

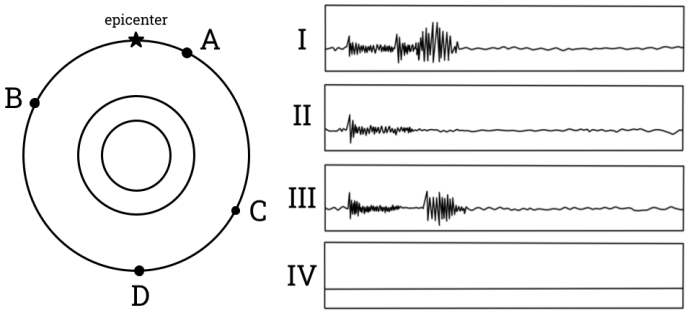
$$\frac{1}{2}^{\frac{x}{5700}} = \frac{.522}{.522+.347}$$

$$-\frac{x}{5700} = \log_2 \frac{.522}{.522+.347}$$

$$x = -5700 \log_2 \frac{.522}{.522+347}$$

$$x = 4191.24$$

20. An earthquake was recorded at four seismic stations around the globe, A, B, C, and D. The diagram below represents a cross-section of the Earth with the locations of the stations and the epicenter of the earthquake, as well as an excerpt from a seismogram produced by each station.




Which list best matches each seismogram, ordered from I to IV, with the seismic station at which it was recorded?

A. A, C, B, D  B. B, A, C, D  C. A, B, D, C  **D. A, D, B, C**

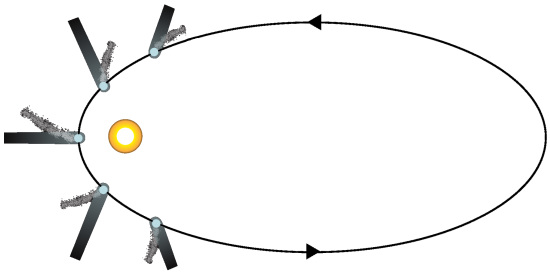
**Solution:** S-waves can be distinguished from P-waves by a higher amplitude than P-waves. A larger time interval between the arrival of P-waves and S-waves indicates a greater distance from the epicenter. Station A is the closest station to the epicenter, so we expect the shortest time between P-waves and S-wave arrival seen in Seismogram I. Station B is slightly farther from the epicenter than Station A; Seismogram III has a slightly longer time interval. As S-waves cannot travel through the Earth's liquid outer core, only P-waves reach Station D, where seismogram II only shows P-waves. Station C resides in the so-called shadow zone where seismic waves are minimal, so it must have recorded seismogram IV.

21. As climate change melts the Greenland ice sheet, the resulting meltwater enters the northern Atlantic Ocean and remains at the surface instead of sinking to form the North Atlantic Deep Water. Which of the following best explains why glacial meltwater typically does not sink?

A. It has a low heat capacity
**C. It has very low salinity**
B. It has a low sediment capacity
D. It has very low viscosity

**Solution:** To sink in the ocean, water must be both cold and dense. Glacial meltwater is cold from being frozen, but because it typically forms from compacted snow, it has very low salinity and is not dense enough to sink.

22. The following diagram describes the orbit of a comet:



Which of the following statements is true about the comet?

I) The acceleration of the comet due to gravity is **always** perpendicular to its velocity

II) Radiation pressure directs the gas tail away from the Sun

III) If the comet's velocity at perihelion is instantaneously bumped up by $\Delta v$, the eccentricity of the resultant orbit will be greater than that of the original orbit

A. I only B. II only C. III only **D. II and III** E. I, II, and III

**Solution:** The acceleration always points toward the sun at any point in the orbit, but it is perpendicular to the direction of the velocity only at the perihelion and aphelion. The gas tail is directed away from the sun primarily by both radiation pressure and solar wind. Force in the same direction as velocity increases speed and intuitively increases the distance at aphelion and keeps distance at perihelion the same since the acceleration occurred at the perihelion. $e = \frac{r_a - r_p}{r_a + r_p}$ Increasing $r_a$ without changing $r_p$ increases the value of e for eccentricity.

**Questions 23** and **24** consider a hypothetical planet that is identical to Earth but has a day length of six hours.

23. On this planet, which of the following would likely be the most similar to Earth?

A. Number of atmospheric circulation cells

**B. Position of the intertropical convergence zone**

C. Strength of equatorial trade winds

D. Strength of the Coriolis effect at the poles

**Solution:** An increase in rotational velocity would result in a stronger Coriolis effect, creating more active circulation on Earth. This would result in stronger circulation-driven winds that would distribute heat more effectively throughout the atmosphere. It would also likely increase the number of circulation cells, since these are determined by the Coriolis effect; for example, Venus's weak effect means it only has one cell, while Jupiter's fast rotation creates much more than three cells. However, these cells would still be centered at the equatorial ITCZ, since nothing changes the fact that the equator is still the warmest part of Earth and air will typically rise there.

24. The increased rotational speed of this planet would cause water to move outward towards the equator, where it would submerge most of the land in the region. What effect would the resulting change in albedo and in atmospheric water vapor content have on the planet's climate, respectively?

**A. Warming; warming** B. Warming; cooling C. Cooling; warming D. Cooling; cooling

**Solution:** In this situation, the albedo of the planet would decrease and it would absorb more incoming radiation. This would cause a positive energy imbalance and result in warming, since more energy is added than is being lost. The increased ocean surface area, especially at the warmer equator, would result in more energy being absorbed by water and increase the amount of water vapor evaporating into the atmosphere. Since water vapor is a greenhouse gas, it would trap outgoing longwave radiation, again resulting in an increase in energy and warming.

25. Chlorofluorocarbons (CFCs) contribute to the depletion of Earth's ozone layer, believed to be the main cause of the 'ozone hole' in the 1990s. However, the ozone layer is found in Earth's stratosphere, and CFCs are heavier than other gases in air. Which of the following statements correctly explain why CFCs reach the stratosphere?

I) CFCs are insoluble in water

II) CFCs are relatively unreactive in the troposphere

III) Most rising air parcels move from the troposphere into the stratosphere

A. I only B. II only **C. I and II** D. II and III E. I, II, and III

**Solution:** CFCs are not soluble in water, making it harder to remove them from the atmosphere and contributing to their longevity. Additionally, CFCs are relatively unreactive in the lower atmosphere, making them long-lived and giving them ample time to be well-mixed and reach the stratosphere. While air parcels are occasionally transported from the troposphere into the stratosphere, this typically requires the presence of strong updrafts as the tropopause acts as a barrier to vertical mixing.

26. A researcher inserts two devices at the top of a glacier and 100 meters below its surface to measure its flow speed at different levels. Which of the following changes would likely increase the difference in flow speed between these two devices?

I) Increase in temperature throughout

II) Decrease in valley floor roughness

III) Influx of meltwater beneath the glacier

**A. I only** B. II only C. I and III D. II and III E. I, II, and III

**Solution:** The difference in internal flow speeds is due to plastic deformation due to stresses within the glacier. An increase in temperature makes the glacier less rigid and allows more deformation - I is true. A decrease in valley floor roughness would decrease the effect of friction, the main factor that slows down deeper ice, resulting in a smaller difference in flow speeds - II is false. An influx of meltwater would have the same effect and would increase the absolute speed of each device by promoting basal sliding, but it would also decrease the effect of friction and difference in speeds - III is false.

27. The frost line is the distance from the Sun at which a volatile compound can condense into a solid phase. Which of the following statements are true?

I) The frost line for water during planetary formation was closer to the Sun than it is today.

II) In other star systems, Jovian planets cannot be found within the frost line.

III) The frost line for carbon dioxide is closer to the Sun than the frost line for water.

**A. I only** B. II only C. III only D. II and III E. I, II, and III

**Solution:** Since the Sun was dimmer and cooler during the formation of the Solar System compared to the present, it was possible for water to condense into ice closer to the Sun. Jovian planets may be found closer to the parent star if they migrate inwards after planetary formation; these planets are typically called "hot Jupiters." Carbon dioxide has a lower freezing point than water, so it would require colder temperatures further away from the Sun to condense into ice crystals compared to water.

28. At which of the following boundaries in Earth's interior is there an increase in density and a sharp decrease in seismic velocity?

A. Between the crust and upper mantle

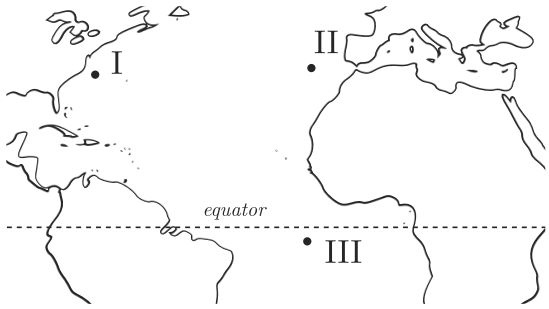
B. Between the upper mantle and lower mantle

**C. Between the lower mantle and outer core**

D. Between the outer core and inner core

**Solution:** These properties occur between the solid lower mantle and liquid outer core, in which P-wave velocity drops and S-waves cannot be transmitted. Moreover, there is an increase in density between the lower mantle (composed of silica and magnesium) and the outer core (composed of iron and nickel).

29. Pictured below is a map of the Atlantic Ocean with the equator marked by a dashed line. Which of the following correctly orders the average surface flow speed at the three marked points from **least to greatest**?




A. I, II, III B. I, III, II **C. II, III, I** D. II, I, III

**Solution:** Western intensification causes I (the Gulf Stream) to be the strongest and fastest current labeled. The opposite is true for II (the Canary Current) which is an eastern boundary current and is the weakest and slowest labeled current on the diagram. III is neither an eastern nor western boundary current and has a flow velocity between II and I.

30. Martian dust storms are not as strong as Earth's and are unlikely to damage any major equipment. Which of the following differences between the two planets contribute to this discrepancy?

I) There is relatively little water vapor in the Martian atmosphere

II) The Martian atmosphere is much thinner than the Earth's atmosphere

III) Mars has a higher temperature difference between the equator and poles

A. I only **B. I and II** C. II and III D. I, II, and III

**Solution:** On Earth, the release of latent heat into the atmosphere from the condensation of water fuels strong storms. Mars has very little water vapor in its atmosphere - I is true. Because Mars has a much thinner atmosphere than Earth, its winds carry less energy - II is true. The temperature difference between the equator and poles is lower on Mars than on Earth - III is false.

END OF SECTION I