USESO 2024

Training Camp Exam

Free-Response

KEY

Instructions:

- Section II consists of 5 multipart problems that further assess geoscience knowledge predominantely in the form of free-response questions.
- You have 2 hours and 15 minutes to complete this section.
- Any type of calculator is allowed.
- Participating in this exam is agreement to our Academic Integrity Policy.

Problem 1

Question	1	2	3	4	Total
Points	4	3	6	7	(20%)

This problem explores several aspects of clay minerals and their effect on climate and the environment.

1. Two of the most common types of clays are illite and smectite. These two minerals have similar structures, an example of which is shown below.

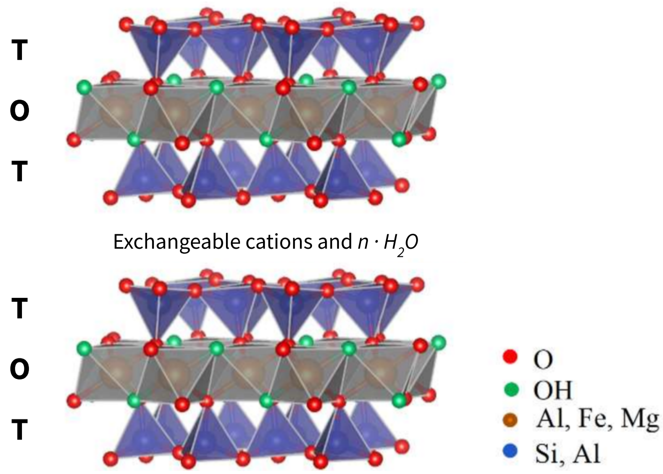

Figure 1: The tetrahedral-octahedral-tetrahedral structure common to illites and smectites.

The primary difference between these minerals is the presence of substitutions within the mineral. The sheets in illites generally have strong negative charges because cations with smaller charges substitute into the structure, most commonly Al^{3+} for Si^{4+} and Mg^{2+} for Al^{3+}. This substitution occurs to a lesser extent overall in smectites.

(a) (2 points) Cation exchange capacity (CEC) refers to the ability of cations to enter and leave a mineral. In clays, this exchange primarily occurs in the region between mineral layers. A high CEC allows clays to supply important nutrients to plants. Would illites or smectites be better for growing plants in soil? **Explain.**

Solution: Smectites would be better for growing plants. Cation exchange in clays comes from the layer of exchangeable cations between clay layers, held in place by the negative charge on each layer. Since smectites generally have a weaker layer charge, they will hold interlayer cations more weakly, allowing more exchange and increasing their CEC.

(b) (2 points) A geologist isolates two samples of clays and identifies the relative presence of various elements in its structure. Their results are represented below.

Element	Sample A	Sample B
Si	7.82	6.40
Al (substituted)	0.18	1.60
Al (base)	2.92	3.25
Fe	0.60	0.40
Mg	0.48	0.35
Ca	0.10	0.05
Na	0.16	0.10
K	0.35	1.45

Which sample is composed of illite and which is composed of smectite? **Explain.**

Solution: A is smectite, B is illite. The primary minerals substituting in the samples are Al, Fe, and Mg; Ca, Na, and K are more commonly held between clay layers. Sample B has a higher total concentration of these three elements than Sample A, indicating more substitution has occurred and Sample B is likely an illite.

2. (3 points) These minerals can be compared to talc, another sheet-based silicate with a similar T-O-T structure.

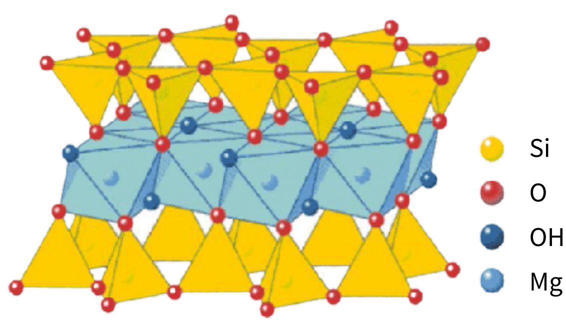

Figure 2: The structure of a single layer of talc, $Mg_3Si_4O_{10}(OH)_2$.

Pure talc is uniquely soft because it has weak intermolecular forces between layers. **Explain** how substitutions within the mineral's layers, such as Na^+ replacing Mg^{2+} in the middle layer, would affect talc's hardness **and** one other property.

Solution: Talc's hardness would increase, as this would create a net charge on the layer that would attract cations and create stronger ion-based bonds rather than LDFs. This would affect various other properties of talc: it would lead to a higher CEC as cations enter between layers, it could likely make talc expandable as water is allowed to enter the structure, or it could make talc layers physically larger and less dense.

3. Clays are secondary minerals formed from the weathering of primary minerals, one of the major drivers of changes in climate on Earth. Researchers recently simulated a small change in Earth's surface composition and found that it increased carbon burial by nearly 50%. Their results are shown below.

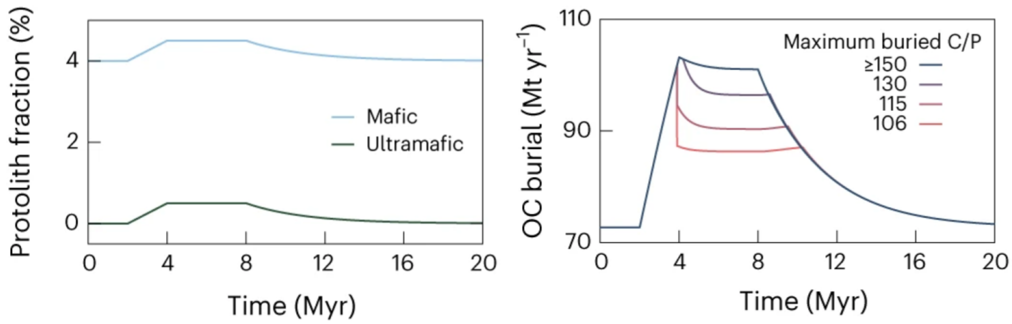

Figure 3: Simulation of surface composition change and the resulting effect on organic carbon (OC) burial. Adapted from Murray & Jagoutz 2024.

One carbon sequestration feedback involves ions like Ca^{2+} and Mg^{2+} entering the ocean after being released by weathering. One equation for the release of these ions, involving the weathering of Mg-rich olivine to form a clay mineral, is as follows:

$$8\,Mg_2SiO_4 + 2\,(Al^{3+}, Fe^{3+}) + 26\,H^+ \longrightarrow Mg_2 \cdot 7\,(Al, Fe)_2Si_8O_{20}(OH)_4 + 13.3\,Mg^{2+} + 8\,H_2O + 6\,H^+$$

(a) (2 points) **Briefly explain** how ions like Ca^{2+} and Mg^{2+} result in carbon sequestration when they enter the ocean.

> **Solution:** Calcium and magnesium ions bond with free carbonate ions in the ocean, creating solid compounds that deposit as sediment and remove carbon from circulation.

(b) (2 points) **Briefly explain** why the weathering of felsic minerals would be unlikely to result in the process described in part (a).

> **Solution:** Felsic minerals generally have low concentrations of calcium and magnesium, the ions necessary for the previously described process.

(c) (2 points) Despite the small change in composition, the study predicted a 40% increase in average clay mineral surface area, allowing them to absorb more carbon and increase direct carbon burial. **Explain** why mafic and ultramafic minerals account for an unusually large proportion of clay mineral formation.

> **Solution:** Mafic and ultramafic minerals weather more rapidly than other minerals, so even a small amount of them will result in a large amount of the weathering that creates secondary clay minerals.

4. The Middle Eocene Climatic Optimum (MECO) was an extended warming period about 40 million years ago. Recent research suggests that this warming caused a transition from *congruent* weathering, involving the complete dissolution of primary minerals into ions, to *incongruent* weathering, leaving some remnants of secondary clay minerals.

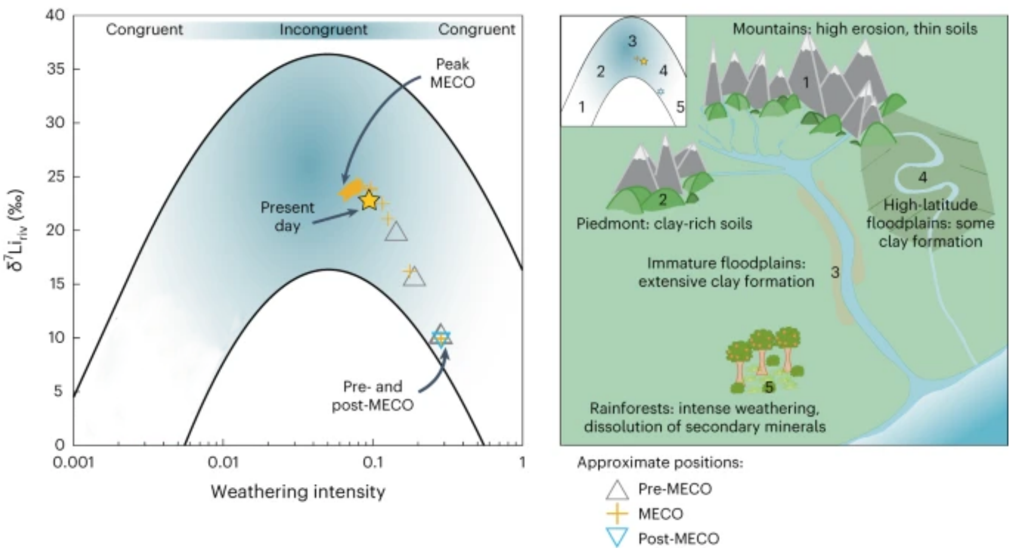

Figure 4: A shift in weathering intensity caused a transition to incongruent weathering, associated with high riverine ^{7}Li concentrations, during the MECO. "Weathering intensity" equals $\frac{W}{W+E}$, where W is the rate of weathering and E is the rate of erosion. Adapted from Krause et al. 2023.

Based on Figure 4, the chemical equation given in question 3, and your answers to parts 3(a) through (c), answer the following three questions:

(a) (1 point) Which of the following most likely describes typical conditions on Earth both before and after the MECO?

A. High sea levels and dry climates

B. High sea levels and wet climates

C. Low sea levels and dry climates

D. Low sea levels and wet climates

Solution: The least erosion typically occurs in dry, high-elevation regions. Since the pre- and post-MECO conditions have unusually low erosion rates, they likely had a higher proportion of these arid climates.

(b) (4 points) Does the shift in weathering conditions during the MECO constitute a positive or negative feedback loop? **Explain.**

Solution: Positive feedback loop. Instead of completely dissociating primary minerals into Ca and Mg ions, incongruent weathering creates clay minerals that keep some of these ions locked up, reducing their concentration in the ocean. Since Ca and Mg ions in the ocean result in carbon sequestration, this shift will increase atmospheric carbon and worsen the existing warming event in a positive feedback loop.

(c) (2 points) Based on the present-day conditions labeled in Figure 4, if a shift in the same direction occurred today, would it constitute a positive or negative feedback loop? **Explain.**

Solution: Negative feedback loop. Based on the graph, today's conditions are close to the peak of incongruent weathering. A shift in the same direction would result in more congruent weathering, which would put more ions into the ocean and cause more carbon sequestration, thus mitigating the initial warming event in a negative feedback loop.

Problem 2

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

This problem explores the structures, compositions, and effects of two Paleogene intrusions in North America.

The first intrusion is the Bungalow pluton, a **felsic** intrusion near the Idaho-Montana border. The intrusion formed throughout the Paleocene and Eocene and contains biotite-rich granite and granodiorite.

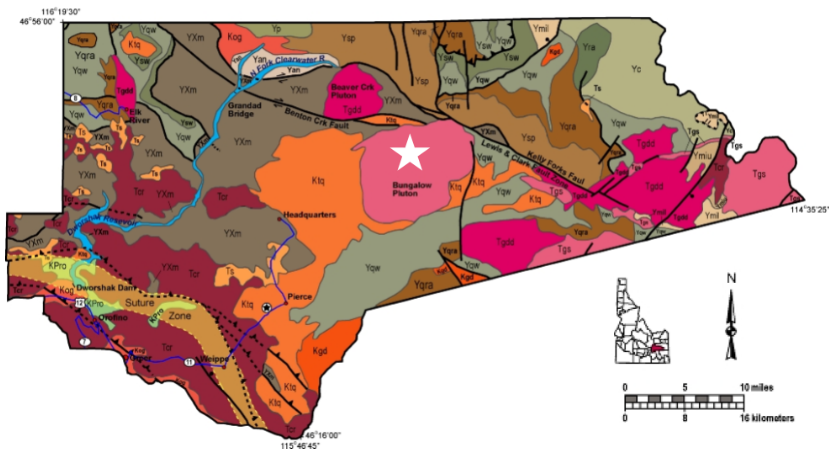

Figure 1: Map of the Bungalow pluton (marked by a white star) and the surrounding area. Adapted from the Digital Atlas of Idaho.

The second intrusion is the Skaergaard intrusion, a **mafic** intrusion on the eastern coast of Greenland that formed during the late Paleocene. The intrusion formed within a plateau of basalt and gabbro and is one of the largest mafic intrusions in the world.

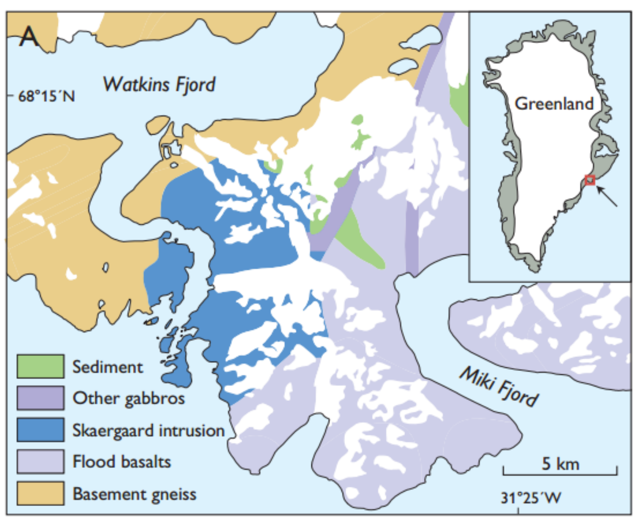

Figure 2: Map of the Skaergaard intrusion (dark blue) and surrounding area. Adapted from Nielsen 2016.

1. The image below shows two thin sections, one found in each intrusion. Sample A, seen in plane-polarized light below, contains augite (Aug), magnetite (Mag), and plagioclase (Pl). Sample B, seen in cross-polarized light below, contains quartz (Qz) and plagioclase.

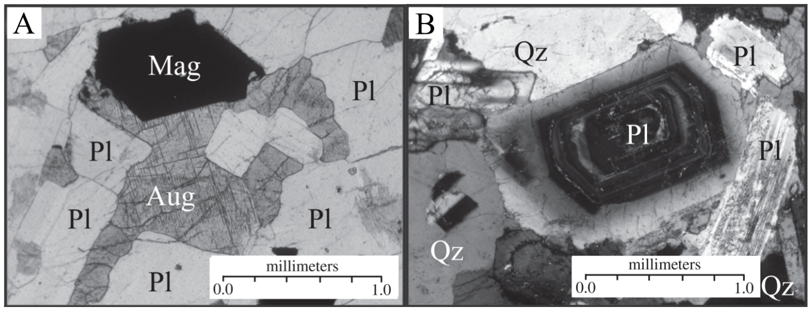

Figure 3: Thin sections from the Bungalow pluton and Skaergaard intrusion. Adapted from *Essentials of Igneous and Metamorphic Petrology* by Robert and Carol Frost.

(a) (1 point) **Identify** which thin section came from the Bungalow pluton and the Skaergaard intrusion, respectively.

> **Solution:** Sample A is from the Skaergaard intrusion and Sample B is from the Bungalow intrusion. This can be inferred from the samples' mineral compositions: Sample A contains augite and magnetite, which are most common in mafic rocks, while Sample B contains quartz, which is most common in felsic rocks.

(b) **Identify** whether each of the following statements are true or false. **Explain** your reasoning.

i. (2 points) Magnetite is generally more euhedral than plagioclase.

> **Solution:** True. Magnetite is high on the crystalloblastic series because it has a simple crystal structure that forms readily, while plagioclase is low on the series and is typically anhedral. This is apparent in the thin section of Sample A: magnetite has clearly defined crystal faces, while plagioclase mostly fills in the space left by other minerals.

ii. (2 points) Sample B formed in a magma chamber with weak convection.

> **Solution:** False. The alternating color of the central plagioclase crystal in Sample B is an example of oscillatory zoning, which typically indicates a changing magma composition or strong convection that brought the crystal to different parts of the magma chamber it formed in.

iii. (2 points) The plagioclase in Sample B is isotropic.

> **Solution:** False. Plagioclase is anisotropic, a property that can be inferred from the thin section. Under cross-polarized light, two perpendicular filters absorb any light that is not altered in polarization as it passes through the crystal. Isotropic minerals appear pure black in cross-polarized light because they by definition do not alter light that passes through. Since the plagioclase in Sample B has variations in color and is gray instead of black, it cannot be isotropic.

2. Since the Bungalow pluton and Skaergaard intrusion are approximately the same size, their differences in formation and composition can be directly compared.

   (a) (3 points) **Briefly describe** one reason why intrusions near the surface often have a felsic or intermediate composition. Why would the presence of large flood basalts surrounding the Skaergard intrusion make it more likely to be mafic?

   Solution: As magma passes through thick continental crust, it undergoes strong differentiation and assimilates material from the crust, both of which make it more felsic. Because the Skaergaard intrusion is surrounded by mafic crust, it will assimilate more mafic material, making its bulk composition more similar to that of the surrounding crust.

   (b) (2 points) When they reached the upper crust, would the Bungalow pluton or Skaergaard intrusion likely have resulted in greater planetary warming? **Explain.**

   Solution: The Bungalow intrusion would have resulted in greater warming. Felsic magmas typically have more gas content because their high viscosity traps lots of gas. It has also likely undergone more differentiation than the Skaergaard intrusion, indicating that it formed from a larger source of magma that had a higher total gas content. When that gas is released, it is primarily composed of greenhouse gases that result in warming.

3. The Skaergaard intrusion is separated into several distinct layers as shown below.

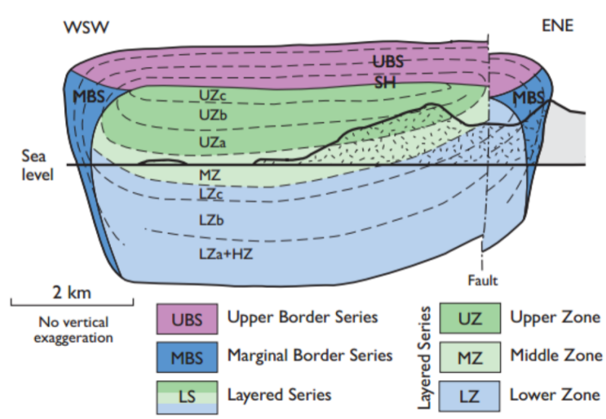

Figure 4: Cross-section of distinct layers within the Skaergaard intrusion. Adapted from Nielsen 2016.

   (a) (1 point) A core is drilled in the center of the intrusion to collect samples from the entire Upper Border Series and Layered Series. Which of the following best describes how the silica content of the intrusion changes as the depth of the core increases?

      A. Uniformly increases

      B. Uniformly decreases

      C. Increases, then decreases

      D. Decreases, then increases

(b) (2 points) **Justify** your answer to the previous question.

> **Solution:** Intrusions lose heat on all sides, so they will crystallize first at the edges. While much of this material will be denser and naturally settle to the bottom, some early crystallization does occur along the walls and roof of the intrusion. As such, the earliest and therefore most mafic rock will form in the UBS and LZ, while the most felsic rock will form in the UZ. The Skaergaard intrusion is the typical example of a large magma body undergoing fractional crystallization; for further reading, see e.g. Irvine et al., 1998.

(c) (2 points) Notice that much of the Skaergaard intrusion is currently above sea level and exposed to the surface. **Propose a mechanism** by which the intrusion may have been uplifted from its original position.

> **Solution:** Multiple answers accepted. The most likely mechanism is that because the intrusion is so old, the layers above it likely underwent erosion, reducing the pressure on the intrusion and causing it to rise isostatically.

4. (3 points) To study the effects of each intrusion on the surrounding rock, researchers collect hornfel samples at the same distance away from each intrusion. Sample C, seen in plane-polarized light below, contains epidote and chlorite crystals in a groundmass composed mostly of muscovite and quartz. Sample D, seen in cross-polarized light below, contains andalusite and cordierite crystals in a groundmass composed mostly of biotite.

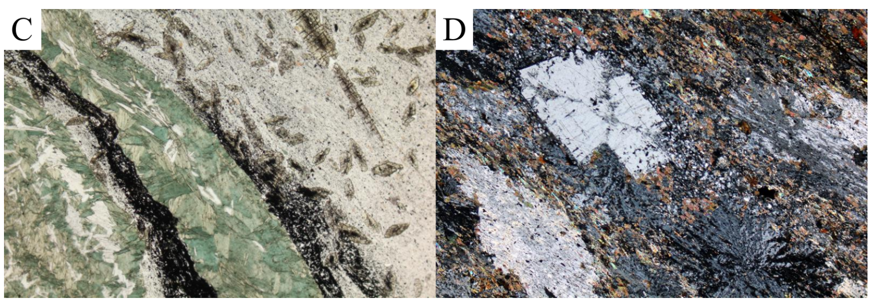

Figure 5: Samples from aureoles surrounding the Bungalow and Skaergaard intrusions. Adapted from Alessandro Da Mommio.

Based on the conditions necessary for these samples to form, which sample likely comes from the Bungalow pluton and Skaergaard intrusion, respectively? **Explain.**

> **Solution:** Sample C is from the Bungalow pluton and Sample D is from the Skaergaard intrusion. Andalusite and cordierite, present in Sample D, are higher-grade metamorphic index minerals than the muscovite and chlorite found in Sample C. Thus, Sample D must have formed due to higher-grade contact metamorphism, likely produced by a hot mafic intrusion like the Skaergaard intrusion.

Problem 3

Question	1	2	3	4	Total
Points	3	5	4	8	20 (20%)

This problem explores various aspects of tropical weather and climate.

1. The El Niño-Southern Oscillation (ENSO) has wide-ranging impacts on the tropical atmosphere.

   (a) (1 point) **Identify** the effects of El Niño conditions on vertical wind shear **and** hurricane activity over the Atlantic Ocean.

   Solution: El Niño increases vertical wind shear in the Atlantic Ocean, which disrupts hurricane formation and decreases hurricane activity in the region.

   (b) (2 points) The effect of El Niño on Hadley cell strength has been found to be zonally asymmetric (i.e. varying across longitudes). Abbreviate the central/eastern Pacific Hadley cell as CEHC and the western Pacific Hadley cell as WPHC. **Describe** the effect of El Niño conditions on the CEHC **and** WPHC. **Justify** your answer.

   Solution: El Niño would strengthen the CEHC and weaken the WPHC. El Niño weakens the Walker circulation, leading to less sinking air or more rising air over the eastern Pacific, strengthening the ascending branch of the CEHC. Less rising air over the western Pacific from the Walker circulation would weaken the ascending branch of the WPHC. Additionally, enhanced storm activity over the eastern Pacific and resulting latent heat release in the upper troposphere would strengthen the ascending branch of the CEHC, while reduced latent heat release over the Western Pacific would weaken the WPHC. For more information, see Li et al. 2023.

2. Some coupled climate models tend to exhibit biases in sea-surface temperature (SST).

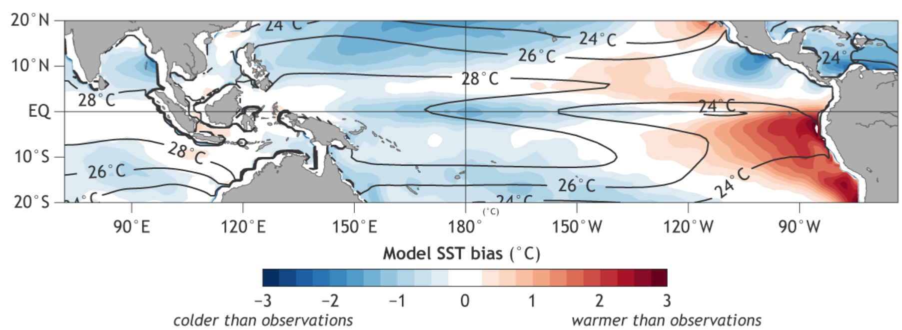

Figure 1: Diagram of model sea surface temperature and bias. Adapted from NOAA.

   (a) (2 points) Compared to observations, models likely show greater ______ of eastern Pacific surface winds and a(n) ______ anomaly in central Pacific 200 hPa winds.

   A. convergence; easterly

   B. convergence; westerly

   C. divergence; easterly

   D. divergence; westerly

Solution: Warm sea surface temperatures in the eastern Pacific induce an anomalous low pressure region associated with surface wind convergence. Under normal conditions, upper-level winds are westerly; low pressure in the eastern Pacific results in divergence aloft and weakened upper-level westerlies or even easterlies. (Note: 200 hPa is in the upper troposphere.)

(b) (3 points) Marine stratocumulus (Scu) clouds are flat, low-level clouds that typically require an inversion to form, as shown in the sketch below.

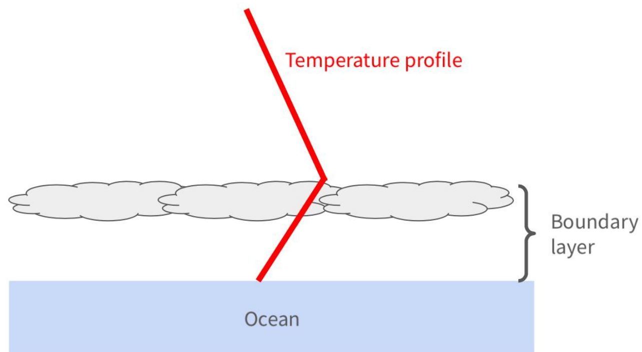

Figure 2: Sketch of Scu clouds and a temperature inversion above the ocean.

A lack of Scu clouds is projected in some coupled models with a warm SST bias. Consider the effect of removing some Scu clouds from the sketch above, which would result in a feedback loop. **Describe** the steps of this loop and **classify** the loop as either positive or negative. *(Hint: how would boundary layer mixing change?)*

Solution: A reduction in Scu cloud cover would result in warmer boundary layer temperatures and SSTs, which would decrease inversion stability and increase mixing in the boundary layer. As boundary layer air mixes with warmer, drier air above, cloud cover is further reduced as clouds evaporate and relative humidity lowers. This is an example of a positive feedback loop.

This feedback is called the marine stratocumulus feedback. For further reading, see e.g., Wood 2012 or Philander et al. 1995. Accurate modeling of this feedback is crucial for constraining estimates of future warming/climate sensitivity (Myers et al. 2021) and is key to reducing uncertainties in future ENSO changes.

3. The Madden-Julian Oscillation (MJO) is an intraseasonal oscillation in the tropics that consists of a propagating disturbance with a dipole structure. The following time versus longitude plot shows anomalies (shaded) in outgoing longwave radiation (OLR) associated with the MJO, averaged from 15°S to 15°N. The green and purple contours may be ignored.

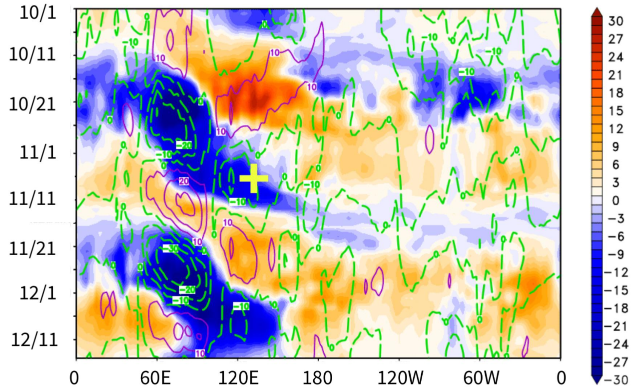

Figure 3: Plot of OLR anomalies from early October to mid-December. Adapted from Sahai et al. 2016.

(a) (1 point) From the figure, identify the direction of propagation and estimate the period of the MJO.

A. Westward, 30-40 days

B. Westward, 50-60 days

C. Eastward, 30-40 days

D. Eastward, 50-60 days

Solution: As time progresses downward, the anomalies move to the right, which is the eastward direction. The anomalies repeat at each position roughly every 30-40 days.

(b) (3 points) Consider the yellow cross labeled above at 135°E (around the western Pacific) on November 6, 2011. Based on the plot, **explain** whether there would likely be a risk of drought or flooding at this location and time. Would an ongoing La Niña at this time enhance or reduce this risk?

Solution: There would be a risk of flooding. Anomalously low OLR is associated with very cold high-level cloud tops resulting from thunderstorms and deep convection. An ongoing La Niña would enhance this risk because precipitation in the western Pacific is enhanced during La Niña events.

4. Tropical cyclones are key features of the tropical atmosphere and climate system.

(a) (2 points) Consider the following satellite image of Hurricane Frances approaching the east coast of Florida. The direction of the storm is shown and several locations are labeled.

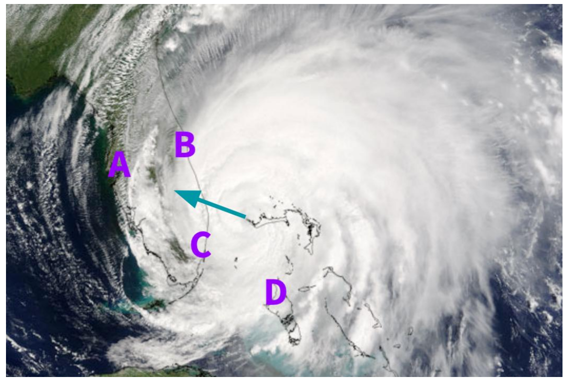

Figure 4: Satellite image of Hurricane Frances. Adapted from NASA Earth Observatory.

Which of the following statements is/are true?

I) Southwest winds are blowing at A

II) Over the next several hours, the greatest increase in storm surge risk occurs at C

III) The pressure tendency (rate of pressure change) is positive at D

A. I only

B. II only

C. III only

D. I and II

E. II and III

Solution: Since a hurricane is a low-pressure system and winds blow counterclockwise and inward around lows in the Northern Hemisphere, A should be experiencing north or northeast winds - I is false. Since the storm is moving towards the northwest, B would be exposed to the greatest surge as the storm's forward and rotational motion combined result in the highest winds. Winds at C would be blowing offshore - II is false. Since the low-pressure system is moving away from D, the pressure tendency should be rising (positive) - III is true.

(b) (1 point) Which of these, if any, is/are true about lapse rates in tropical cyclones?

I) The environmental lapse rate is typically less than the moist adiabatic lapse rate

II) Above the lifting condensation level (LCL), the lapse rate of an air parcel increases with height

A. I only

B. II only

C. I and II

D. None

Solution: An environmental lapse rate (ELR) less than the moist adiabatic lapse rate (MALR) would indicate an absolutely stable atmosphere, which would prevent rising air and storms. Air in tropical cyclones is usually conditionally unstable (MALR < ELR < DALR, the dry adiabatic lapse rate) - I is false. A parcel above the LCL would by definition follow the MALR, which depends on temperature. As temperature decreases with height, the MALR would increase and approach the DALR - II is true.

(c) (2 points) High concentrations of dust aerosols can inhibit tropical cyclone formation. For a given amount of moisture present, **explain** how increasing dust concentration prevents the formation of raindrops. As part of your response, **indicate** how the equilibrium vapor pressure of droplets would be affected.

Solution: Dust aerosols act as cloud condensation nuclei. By increasing the amount of dust, the same amount of moisture would be distributed among more dust particles, reducing the droplet size. Smaller droplets are more curved and have greater equilibrium vapor pressures than larger, less curved droplets, making them evaporate more readily.

(d) (2 points) **Explain** how reducing the translation speed (forward motion) of a tropical cyclone over the ocean may change its intensity by affecting the flow of underlying ocean currents.

Solution: As a tropical cyclone moves slowly over the ocean, the counterclockwise winds deflect underlying ocean currents outward via Ekman transport, leading to upwelling of colder waters and a reduction in the storm intensity.

(e) (1 point) A recent study found a relationship between tropical cyclone rain rate and translation speed.

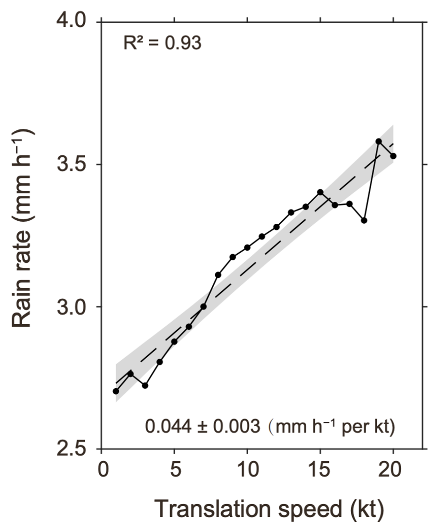

Figure 5: Graph of tropical cyclone rain rate versus translation speed. Adapted from Tu et al. 2022.

Based on the figure, **describe** the implications this relationship has on the total precipitation that a location would experience as translation speed varies. Disregard the effect of other factors such as storm size.

Solution: The relationship between total precipitation and translation speed is inconclusive. While faster storms bring heavier rain according to the figure, this is compensated by the fact that rain falls for a shorter duration at any given location.

Problem 4

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

This problem explores several aspects of lakes.

1. A lake in the shape of a trapezoidal prism with volume 3.1×10^9 m^3 is shown below. Assume that the dominant source of water inflow and outflow is through two circular openings with radius $r = 2.6$ m and $v_{\text{in}} = v_{\text{out}} = 0.08$ m/s.

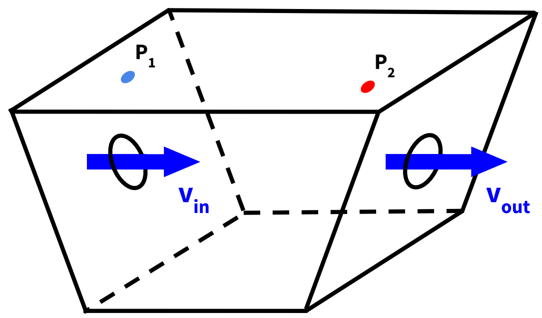

Figure 1: Diagram of a lake in the shape of a trapezoidal prism.

(a) (2 points) A pollutant is added to the lake at a rate of 220 kg/day. Given that the pollutant is soluble in water and mixes uniformly throughout the lake, **calculate** the steady-state concentration in ppm that the pollutant would reach. **Show your work.** (Note: 1 kg/m^3 = 1000 ppm.)

> **Solution:** The average amount of time water will spend in the lake is calculated as $\frac{\text{water volume}}{\text{removal rate}} = \frac{3.1 \times 10^9}{\pi \times 2.6^2 \times 0.08} = 1.8 \times 10^9$ seconds. This value is also known as residence time of water (τ_w). Given steady-state conditions and uniform mixing, the residence time of the pollutant (τ_p) must equal τ_w. Thus, $\frac{\text{pollutant volume}}{\text{addition rate}} = \tau_w$, meaning the total volume of pollutant in the lake is 4.6×10^6 kg. Dividing by total lake volume, the concentration of the pollutant is 1.5×10^{-3} kg/m^3 = 1.5 ppm.
>
> Alternatively, the concentration of the pollutant in the lake is equal to the concentration of the polluted inflow given steady-state conditions. Dividing the mass flow rate of the pollutant ($\frac{220}{60 \times 60 \times 24}$ kg/s) by the volumetric flow rate of water ($\pi \times 2.6^2 \times 0.08$ m^3/s) and converting to ppm results in the same answer.

(b) (1 point) Now assume that the lake loses water through evaporation. If v_{in} stays the same while v_{out} decreases to 0.06 m/s and the lake remains in equilibrium, **calculate** the new steady-state concentration in ppm that the pollutant would reach. **Show your work.**

> **Solution:** We can assume that no pollutant leaves the lake through evaporation, meaning that the residence time of the pollutant would increase due to a lower outflow rate. In this new scenario, $\tau_p = \frac{\text{pollutant volume}}{\text{addition rate}} = \frac{\text{water volume}}{\text{removal rate}} = \frac{3.1 \times 10^9}{\pi \times 2.6^2 \times 0.06}$, resulting in a pollutant concentration of 2 ppm. Note that this value is also equal to $\frac{.08}{.06} \times 1.5$ ppm.

(c) (2 points) If the surrounding water table slopes toward the lake, **explain** how an increase in hydraulic conductivity would likely affect the pollutant concentration.

Solution: The pollutant concentration in groundwater is likely to be lower than the concentration in the lake. A water table sloping toward the lake would thus result in relatively clean groundwater flowing into the lake as hydraulic conductivity increases, reducing pollutant concentration.

2. (2 points) A hydrologist records a periodic oscillation in water level at two points on the surface of the lake (labeled P_1 and P_2 in Figure 1). Their data is displayed below.

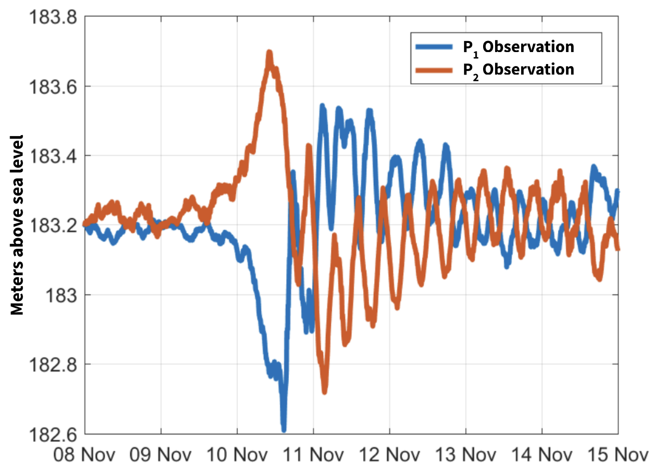

Figure 2: Graph of water level versus time. Adapted from Jay Austin, UMN Duluth.

Explain why the water why the oscillations maintain a constant period despite gradually decreasing in amplitude.

Solution: The oscillations were formed as a storm created a disturbance with frequency matching a multiple of the enclosed lake's resonant frequency. Because the factors of the lake influencing its resonant frequency remain constant (e.g. basin geometry), the period remains constant. The technical term for this oscillatory phenomenon is a seiche.

3. Lake Furnas is a warm monomictic lake (mixing once annually in winter) located on an island in the North Atlantic. A chemical tomography of Lake Furnas and a map of the surrounding region are provided below. The bright yellow asterisks on the lake's surface in Figure 3a represent flares of highly concentrated CO_2.

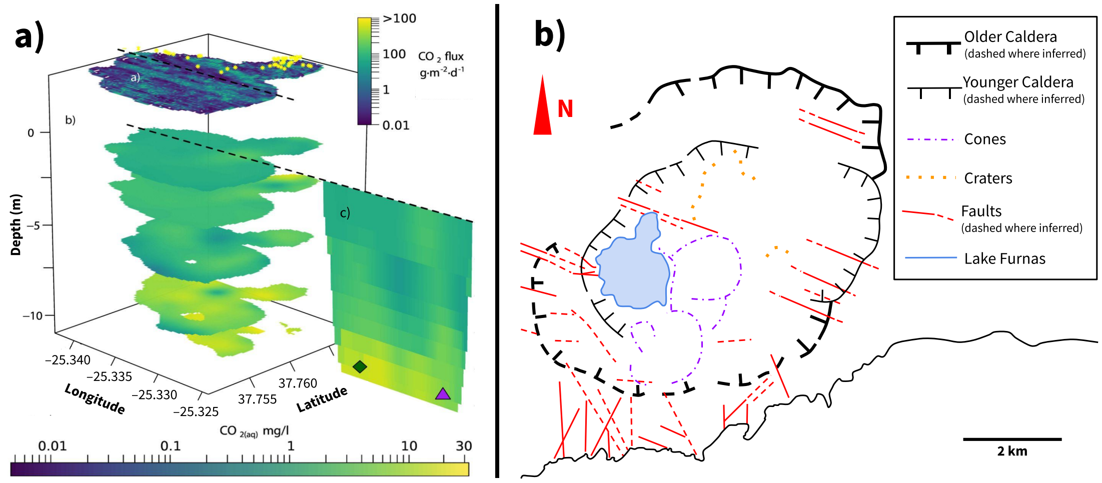

Figure 3a: Chemical tomography of Lake Furnas revealing the spatial distribution of CO_2. Adapted from Tamburello et al. 2024. **Figure 3b**: Map of the region surrounding Lake Furnas. Adapted from Guest et al. 1999.

(a) (2 points) **Describe** the likely mechanism responsible for producing these flares.

> **Solution:** The CO_2 measured in high concentrations at the surface of the lake likely originated from the active Furnas volcano. Volcanic gases escaped from the volcano through vents (fumaroles) located at the bottom of the lake.

(b) (1 point) Are the subsurface structures of these flares better represented by the region above the green diamond or purple triangle in Figure 3a?

A. Green diamond, because the concentration of CO_2 is greater at depth

B. Purple triangle, because the concentration of CO_2 is lower at depth

C. Green diamond, because the concentration of CO_2 near the surface and at depth are relatively different

D. Purple triangle, because the concentration of CO_2 near the surface and at depth are relatively similar

> **Solution:** The CO_2 plume above the purple triangle is shown to extend closer to the surface, indicating stronger degassing at depth.

(c) (2 points) **Explain** what general direction you would expect the flares to align. Give your answer in degrees clockwise from north (e.g. an east-west alignment could be indicated as either 90°or 270°).

> **Solution:** Given that the CO_2 gas predominantly originates from fumaroles at the lake bottom connected to the underlying volcano, the flares would align with the direction of tectonic structures near the lake. Thus, they would follow the direction of the WNW-ESE faults shown on the map (i.e. around 110°or 290°).

4. To better understand the structure of Lake Furnas, a scientist creates several profiles of its waters as shown below.

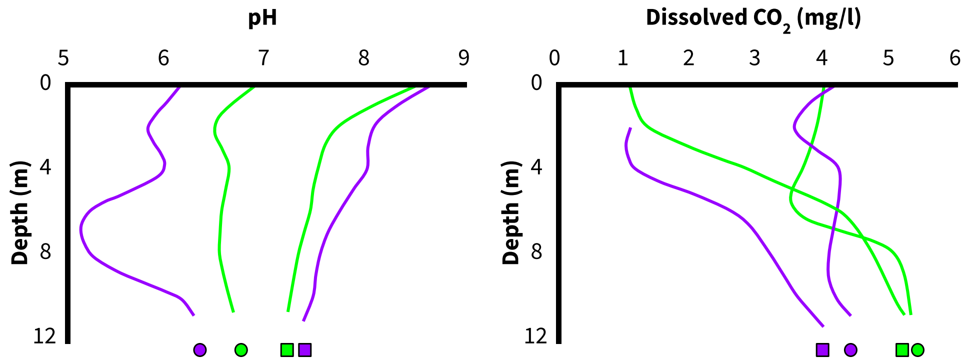

Figure 4: Profiles of pH and dissolved CO_2 for Lake Furnas. Lines marked with the same shape correspond to the same month of sampling; lines of the same color correspond to the same sampling location. Adapted from Andrade et al. 2016.

(a) (2 points) Were samples for the lines marked with squares most likely taken closer to May or November? **Justify** your answer using the mixing regime of the lake.

> **Solution:** The lines marked with squares correspond to higher pH values and lower levels of dissolved CO_2 near the surface. As warm monomictic lakes are more stratified in summer compared to winter, less CO_2 from the fumaroles near the bottom of Lake Furnas would reach the surface closer to May.

(b) (2 points) Were samples for the lines colored green most likely taken from a location in the northern, southwestern, or southeastern region of the lake? **Justify** your answer.

> **Solution:** The green lines correspond to significantly higher levels of CO_2 at depth. Because the CO_2 flares are located in the northern region of Lake Furnas, the fumaroles releasing CO_2 into the lake are likely clustered in the northern region of the lake.

5. High-activity, hyperacidic volcanic lakes are conventionally considered to be perfectly mixed reservoirs due to consistent heating provided by the volcanic source. However, a separate model explores the possibility of these lakes being stratified as shown in Layer A in the diagram below.

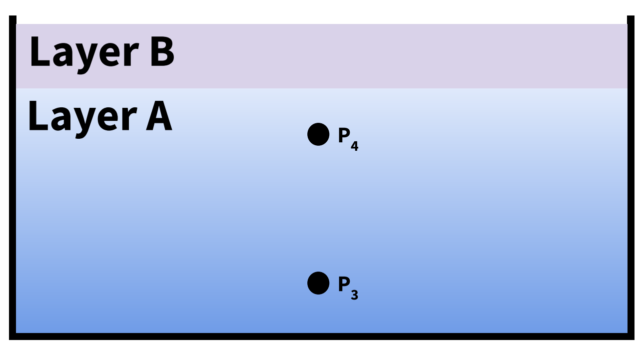

Figure 5: A simplified cross-section of a high-activity volcanic lake.

(a) (1 point) Assume that Layer A is in equilibrium. Compared to water at P_3, water at P_4 has a ______ temperature and ______ salinity.

A. higher; higher

B. higher; lower

C. lower; higher

D. lower; lower

> **Solution:** D. Water at P_3 has a higher temperature than water at P_4 as it is located closer to the volcanic heat source. Thus, water at P_4 must have a lower salinity to remain on top despite being colder.

(b) (2 points) A burst of heavy rain falls upon the lake and forms Layer B as depicted in Figure 5. Given that chemical diffusion within the lake occurs at a significantly faster rate than thermal conduction, **explain** how the stability of the lake's stratification would likely change shortly afterward. *(Hint: Consider how the formation of rainwater in the atmosphere influences its properties.)*

> **Solution:** The influx of rainwater would likely lower the temperature and salinity of water near the top of the lake. Because chemical diffusion occurs at a significantly faster rate than thermal conduction, the salinity of the top would increase at a faster rate than temperature. Thus, the top layer would become denser and stratification would weaken, potentially triggering lake overturning.

(c) (1 point) If this model is correct, **identify** a new hazard people living near high-activity volcanic lakes might face.

> **Solution:** A new hazard would include the build-up and sudden release of CO_2 gas, comparable to the 1986 Lake Nyos limnic eruption.

Problem 5

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

This problem explores various aspects of planet formation.

1. (4 points) Asteroids can provide clues about the nature of primitive solar system material. Consider an asteroid on an elliptical orbit observed at a distance of 1.92 AU from the Sun. Using the table below, **calculate** the velocity of the asteroid in m/s given that the total energy of its orbit may be expressed as $\frac{-GMm}{2a}$, where a is the semi-major axis of the orbit. **Show your work.**

Gravitational constant (G)	6.67×10^{-11} N $\cdot$ m^2/kg^2
1 AU	1.50×10^{11} m
Mass of Sun (M)	1.99×10^{30} kg
Mass of asteroid (m)	4.80×10^{16} kg
Semi-major axis (a)	2.51 AU

Solution: The total energy of the asteroid's orbit is equal to the sum of its kinetic and potential energy. Thus, $\frac{-GMm}{2a} = \frac{1}{2}mv^2 - \frac{GMm}{r}$, or $v = \sqrt{GM(\frac{2}{r} - \frac{1}{a})} = 2.39 \times 10^4$ m/s.

2. (2 points) Consider the model of planet formation displayed below.

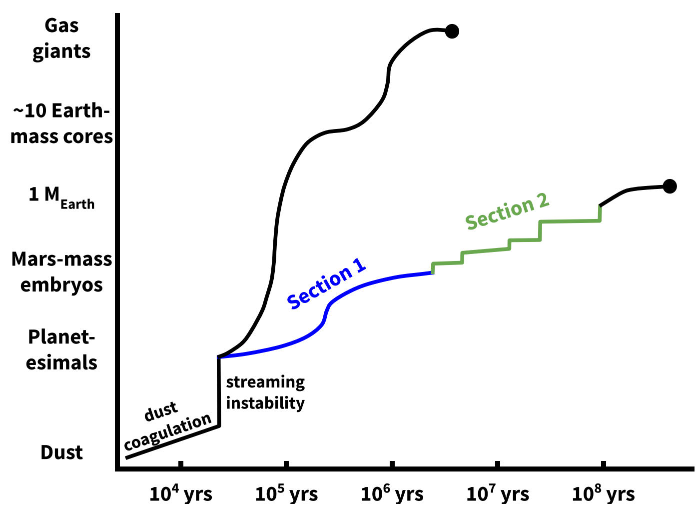

Figure 1: A model of planet formation. Adapted from Raymond & Morbidelli 2022.

Briefly describe the difference between the mechanisms responsible for the increases in mass along Section 1 versus Section 2.

Solution: The accretion of relatively small pebbles by the larger planetesimal results in the gradual increases in mass along Section 1. Meanwhile, giant impacts between the developing planet and other large bodies result in the sudden increases in mass along Section 2.

3. As seen in Figure 1, the coagulation of dust plays a critical role in early planetary development. However, the surrounding gas exerts a drag force on the dust that causes it to drift inward within the protoplanetary disk, disrupting planet formation by accreting dust to the central star instead of growing planet embryos.

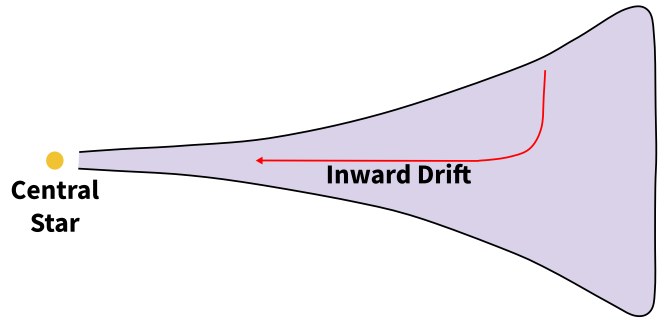

Figure 2: Simplified schematic showing the motion of a small dust particle experiencing inward drift toward the central star. Adapted from C.P. Dullemond, Universität Heidelberg.

(a) (3 points) Using only gas density (ρ), change in pressure (ΔP), and change in radial distance (Δr), **write an expression** for the force exerted on gas particles per unit mass (f_{gas}) by the radial pressure gradient within the protoplanetary disk.

Solution: $f_{gas} = -\frac{1}{\rho} \cdot \frac{\Delta P}{\Delta r}$. The pressure gradient force per unit mass is directly proportional to the pressure gradient and inversely proportional to density. The negative sign indicates that as pressure increases radially outward, the force on the gas is directed in the opposite direction (inward). This is comparable to the pressure gradient force experienced by air parcels in Earth's atmosphere.

(b) (2 points) Small dust particles are not significantly influenced by f_{gas}. Considering how this affects their relative motion within the protoplanetary disk, **explain** whether small dust particles accumulate at local minimums or maximums in pressure.

Solution: As the small dust particles are essentially unaffected by f_{gas}, they experience an effective force in the opposite direction of f_{gas} given an accelerated reference frame. Thus, when pressure increases with distance and f_{gas} is directed inward, the dust particles are effectively directed outward and are able to accumulate at pressure maxima instead of being accreted to the star.

(c) (2 points) The efficiency of the dust's motion with respect to gas is controlled by the Stokes number (St), which is calculated by dividing a dust particle's stopping time (the time taken for the particle's velocity to adjust to that of the surrounding gas) by orbital period. **Explain** why dust particle size can be used as a proxy for St and **indicate** whether a low St corresponds to smaller or larger particles.

Solution: Particle size is a proxy for Stokes number because the same force must be applied for a longer duration to "stop" a larger particle moving at the same velocity. A low St therefore corresponds to smaller dust particles.

4. The streaming instability is a mechanism for seeding planetesimal formation that occurs after dust coagulation. Four panels depicting the evolution of this instability through time are displayed below.

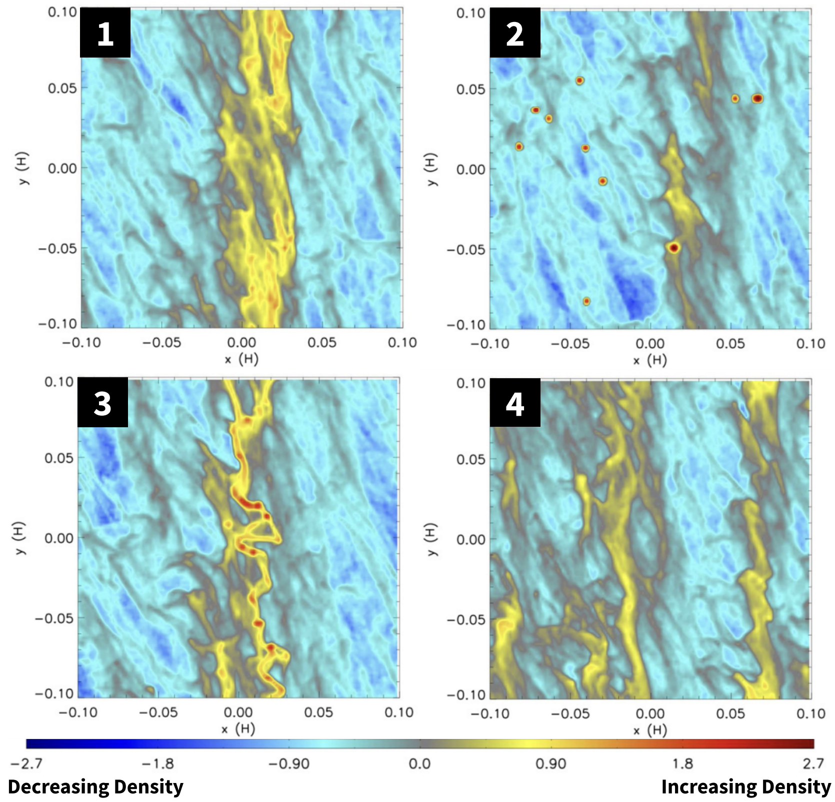

Figure 3: Panels depicting evolution of the streaming instability with color gradient correlating to vertically integrated surface density. Adapted from Simon et al. 2016.

(a) (2 points) **Order** the panels chronologically from the first to last to form and **briefly explain** your answer. Format your ordering as a string of numbers (e.g. "1234").

> **Solution:** The streaming instability clumps material together and ultimately facilitates the development of small, high-density planetesimals. The ordering that reflects this process is 4132.

(b) (1 point) **Identify** the first panel in which the developing planetesimals exhibit self-gravitation. Format your answer as a single number.

> **Solution:** The activation of self-gravitation can be determined by the presence of dense clusters of material, which are first visible in Panel 3.

5. There are multiple hypotheses that explain how Earth may have acquired water during its formation. One such hypothesis involves a mechanism termed "pebble snow" and is depicted below.

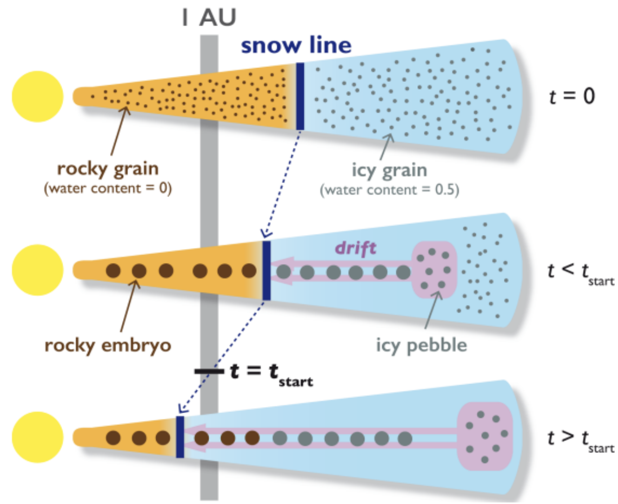

Figure 4: Snapshots of the evolution of a protoplanetary disk in which water may have been delivered to rocky planets by icy pebbles that drifted inward as the snow line moved closer to the Sun. The pink region represents the location in the disk where icy pebbles grow from dust. Adapted from Meech & Raymond 2019.

Non-carbonaceous and carbonaceous chondrites are two classes of meteorites that are believed to have been formed in the inner and outer solar system, respectively. Earth's water has a deuterium/hydrogen ratio close to that of carbonaceous chondrites, suggesting that they could have delivered water to Earth via pebble snow.

Explain whether each of the following statements support or refute the validity of pebble snow as the dominant source of Earth's water.

(a) (2 points) There are no known classes of chondritic meteorites with compositions that lie between carbonaceous and non-carbonaceous chondrites.

> **Solution:** If carbonaceous chondrites traveled inward to deliver water to Earth, we would expect some mixing to occur between carbonaceous and non-carbonaceous meteorite material given that the two classes overlapped temporally. Because this phenomenon has not been observed, the validity of the pebble snow model is refuted.

(b) (2 points) As the protoplanetary disk contracted, the radial velocity of retreating gases was greater than the speed at which the snow line moved inward.

> **Solution:** Given that gases in the protoplanetary disk retreated faster than the snow line, Earth's water was likely not simply the result of condensation beyond the snow line. This supports the validity of the pebble snow model.

END OF FREE-RESPONSE