USESO 2022

Hydrosphere
KEY

Instructions:

- Section I consists of 10 multiple choice questions, with each question worth 2 points. There is only one correct option on multiple choice questions
- Section II consists of 2 multipart free response questions
- A calculator is allowed; show all work for calculations unless otherwise stated
- Recommended time management: 30 minutes on each section

Section I

1. Consider a tropical cyclone with geostrophic winds located above a uniform open ocean. Which of the following best describes the effect the cyclone would have on the ocean circulation directly beneath it?

   A. Upwelling

   B. Downwelling

   C. Upwelling in the Northern Hemisphere and downwelling in the Southern Hemisphere

   D. Downwelling in the Northern Hemisphere and upwelling in the Southern Hemisphere

   E. Little to no effect

   Solution: Tropical cyclones are low-pressure systems. Although the pressure gradient force (PGF) drives the wind towards the center of the cyclone, winds given to be geostrophic (as in this question) will flow parallel to isobars from the Coriolis effect. As these winds exert drag on the ocean surface, the Coriolis effect causes a net transport of water 90° from the wind direction in a process known as Ekman transport. Ekman transport is directed outwards from this cyclone regardless of hemisphere because the final direction of water movement is 180° from the pressure gradient in this idealized case: from the PGF, geostrophic winds make up 90°, and the effect of wind on water movement accounts for the other 90°. The result is Ekman suction, where deeper water upwells to compensate for surface water moving outwards.

2. An oceanographer measures the horizontal flow velocity in a water column at a latitude of 45°N and finds two highs: one at the surface of 1 m/s east and another near the bottom of 3 m/s south. Assuming water movement is only affected by ideal Ekman transport, which of the following is closest to the direction of net horizontal flow through the column?

   A. ESE

   B. SSE

   C. S

   D. SSW

   E. SW

   Solution: Top flow: Net Ekman transport has a 45° difference from surface flow (recall that due to the Coriolis effect, surface flow is 45° from wind direction and net Ekman transport is perpendicular to wind direction). Since the oceanographer is located in the Northern Hemisphere, the Coriolis effect acts clockwise and the top of the water column experiences south-east Ekman transport. Bottom flow: the Ekman spiral acts in the opposite direction. By the same reasoning as before, bottom flow nets south-west.

   Given that the bottom flow is three times as strong as the top flow, the two flows sum to a net flow direction of south-south-west (the actual angle is approximately 18.5° from south).

3. Amphidromic points are locations that have zero tide amplitude for a harmonic constituent of a tide. Which of the following is the primary cause of the circular rotation of tides in a basin around an amphidromic point?

   A. Water temperature

   B. Basin depth

   C. Height of tidal crests

   D. Coriolis effect

Solution: While all of these factors in part determine the location of amphidromic points, the Coriolis effect is most relevant to their circular rotation. Since tides are considered over long distances, the Coriolis effect is the most important factor as it deflects water in a basin around the central amphidromic point rather than affecting speed or period.

4. The surface topography of ice sheets typically plays a larger role than the bed topography in determining the direction of subglacial (beneath the glacier) water flow. Suppose that at a glacier bed, water flows uphill from point A to point B. Which of the following **must** be true?

   A. The ice surface is level while the bed topography is not.

   B. The ice surface elevation is greater at point A than point B.

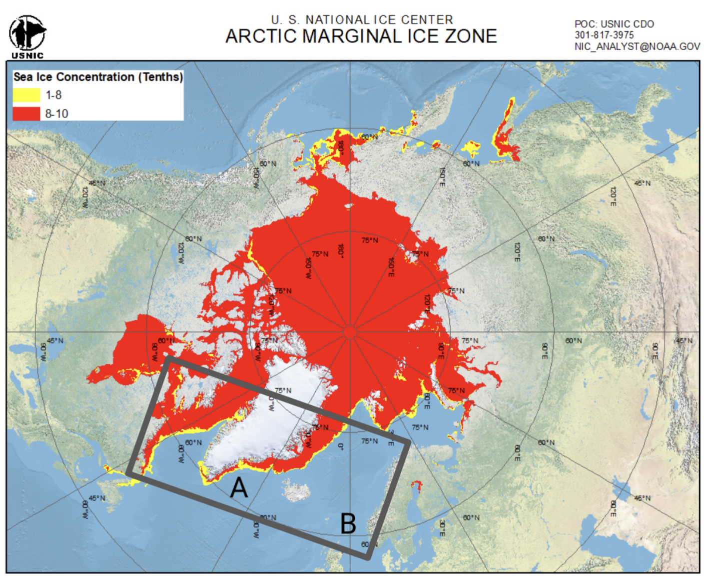
   C. The difference between the surface and bed elevation is greater at point A than point B.

   D. The slope of the surface topography is greater than the bed topography.

   E. The slope between points A and B are in the same direction for surface and bed topography.

Solution: In contrast to subaerial hydrologic settings where water flows without overlying ice, ice overburden pressure in subglacial settings largely determines the direction of waterflow between two given points, with lesser influence from bed slope. Water will flow from points of high pressure to points of low pressure, and accordingly, points of thicker to thinner ice. Ice thickness is equal to the difference between ice surface elevation and bed elevation.

5. Shown below is a map of Arctic sea ice cover. Sea ice extent in the map is higher than the annual average extent of ice cover.



Which of the following statements is/are true?

I) The map could represent the extent of Arctic sea ice cover in October.

II) The pattern of ice cover in the boxed region is created by clockwise gyres.

III) Dissolved surface oxygen levels at A are likely higher than at B.

A. I only

B. II only

C. III only

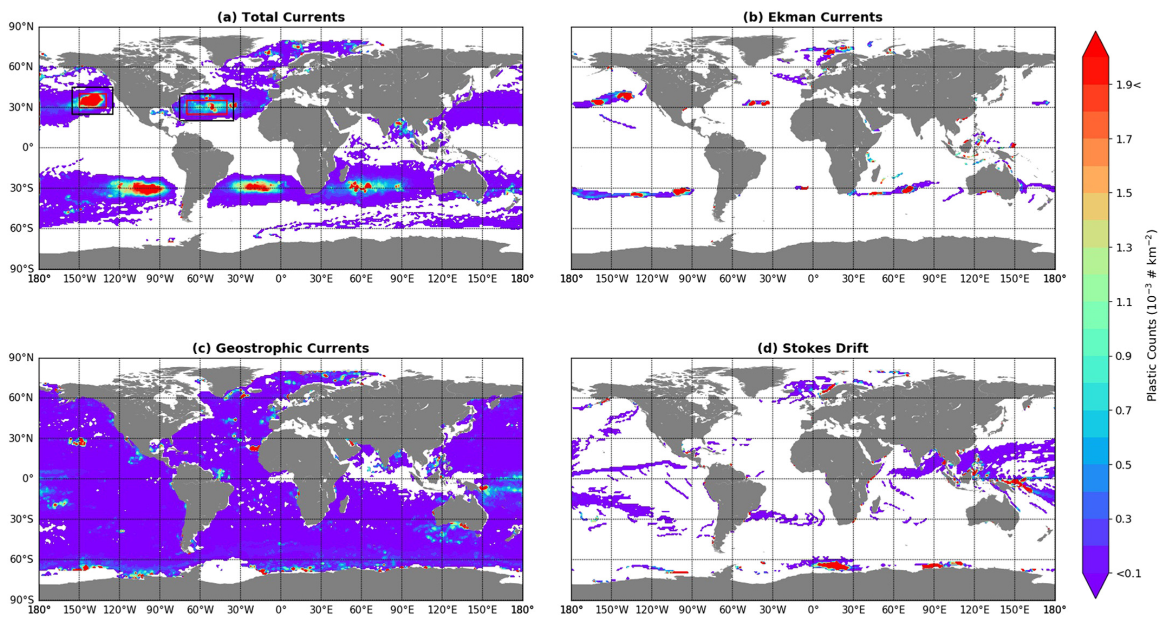
D. I and II

E. I and III

F. II and III

Solution: Arctic sea ice typically peaks in March, corresponding to the greatest rate of increase in daylight, and reaches its minimum in September, corresponding to the greatest rate of decrease in daylight. Thus, October sea ice is likely to be lower than annual averages, not higher - I is false. Subpolar gyres are counterclockwise in direction. The southward currents along eastern Canada and eastern Greenland and the northward currents along western Greenland and Europe's west coast are part of such gyres, explaining the sea ice that extends along eastern coastlines - II is false. Finally, dissolved oxygen levels decrease with increasing temperature and salinity. Proximity to cooler waters and fresh meltwater results in more dissolved oxygen at A than at B, which is affected by a warm current - III is true.

6. The global distribution of microplastics is controlled by ocean currents. A Lagrangian particle-tracking experiment is conducted in an ocean model using estimates of isolated components of overall surface flow (geostrophic, Ekman, and Stokes drift). Plastic particles are spread evenly on the surface ocean and left to drift. The particle density after 13 years is shown below.



(Onink et al., 2019)

Which of the following statements is/are true?

I) The microplastic distribution is largely controlled by geostrophic currents since most ocean currents are in geostrophic balance.

II) Microplastics tend to congregate in areas where there is Ekman-driven downwelling.

A. I only

B. II only

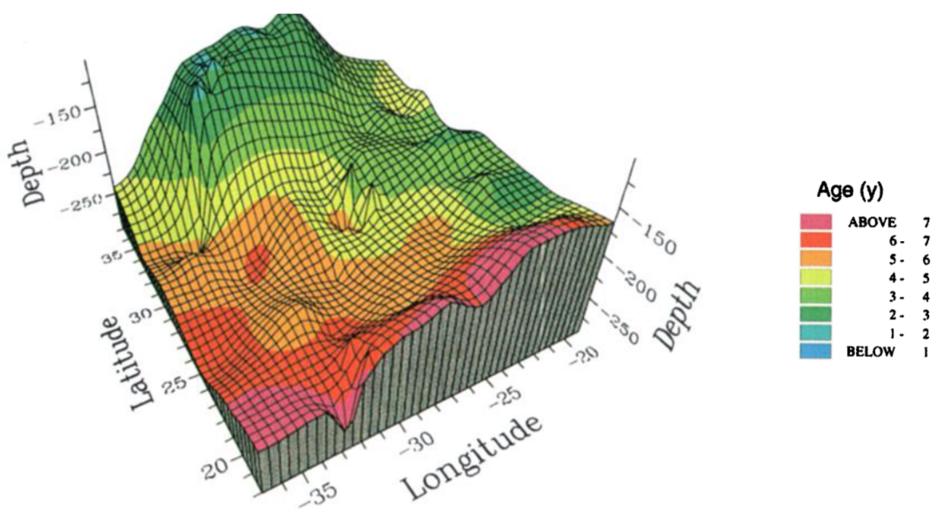
C. I and II

D. None

Solution: From the experiment with only geostrophic currents, we see that the microplastics are far too spread out compared to the distribution with all flow components. This indicates that geostrophic currents tend to spread microplastics, while Ekman and Stokes flow components tend to concentrate them. Further, microplastics congregate where there is surface Ekman convergence. By a mass conservation argument, those areas also experience Ekman-driven downwelling.

7. Tritium (^{3}H) is a radioactive isotope of hydrogen that decays to helium-3 (^{3}He). Measuring the distribution of these isotopes is useful in studying the ventilation and circulation of the upper ocean.

The concentrations of ^{3}H and ^{3}He are collected from a section of the North Atlantic. At each location, a subsequent radioactive decay age is calculated using the concentrations of ^{3}H and ^{3}He. Shown below is the ^{3}H$-$^{3}He age on the 1026.6 kg m^{-3} isopycnal.



(Jenkins, 1998)

Which of the following is **not** true? (*Hint: consider how the calculated age changes with depth along the isopycnal.*)

A. ^{3}H is introduced into the ocean from the atmosphere

B. The ^{3}H$-$^{3}He age is an imperfect indicator of the time-since-surface-ventilation due to mixing

C. The flow through this section is primarily southeast, parallel to ^{3}H$-$^{3}He isochrons

D. The average ^{3}H$-$^{3}He age over the 1027 kg m^{-3} isopycnal would be greater than the average age over the 1026.6 kg m^{-3} isopycnal

Solution: We begin by noting that the ^{3}H$-$^{3}He age is smallest near the surface and increases with depth, hinting that it is an indication of the "ventilation" age (i.e., the time since a water parcel has had contact with the air). However, since water parcels intermix, the instantaneous concentrations at any point do not represent the true ventilation age of the parcel. The flow direction can be inferred to be along the isopycnal towards the southwest, as we expect the ^{3}H$-$^{3}He age to increase downstream. This is an example of water mass subduction.

8. Which of the following statements is/are true about carbon cycling in the ocean?

I) Nonaggregated dead organic matter has a greater carbon input than aggregated organic matter.

II) Ocean circulation can bring old carbon from the seafloor to the surface.

III) There is less carbon stored in the ocean than the atmosphere.

A. I only

B. II only

C. I and II

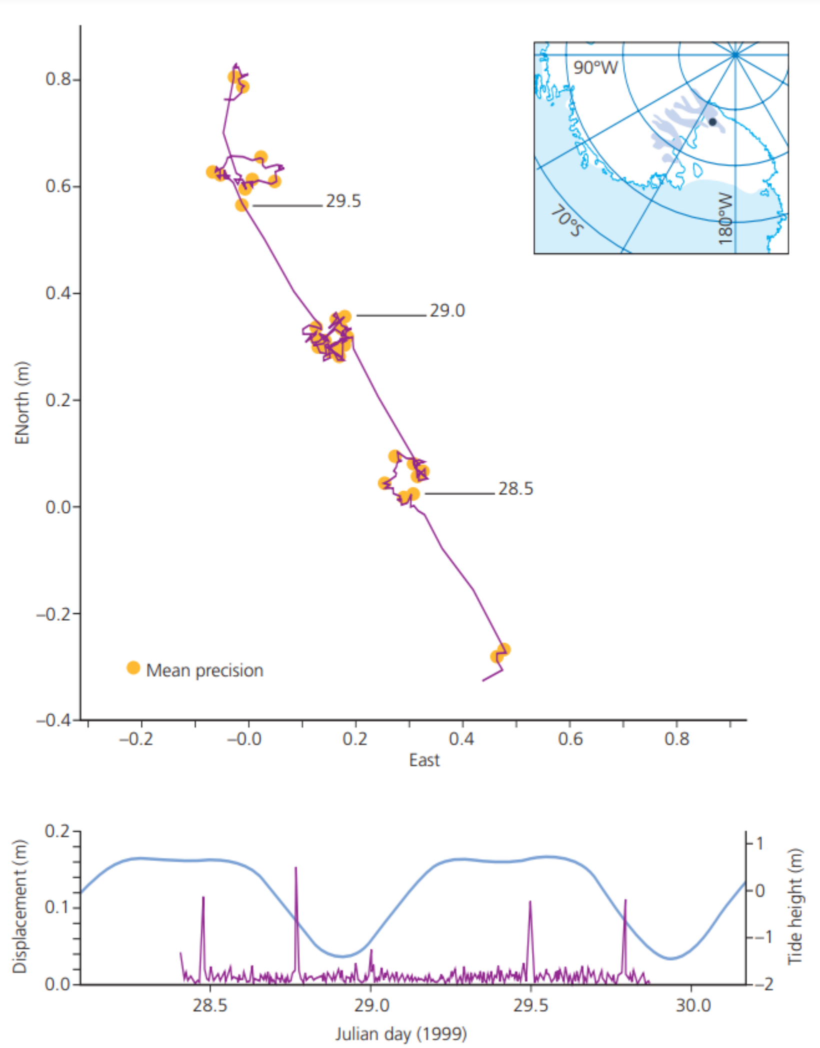
D. II and III

E. I, II, and III

F. None

Solution: Aggregated clumps of organic matter sink faster than small particles of organic matter. A faster transport time decreases the likelihood of being consumed or decomposing before reaching the seafloor - I is false. Deep circulation can slowly bring carbon from the seafloor to the atmosphere - II is true. The amount of carbon stored through the ocean is magnitudes greater than land, so III is false.

9. The Whillan's Ice Stream is located in the West Antarctic Ice Sheet and exhibits a stick-slip cycle of motion at its grounding zone. Shown below is this motion (purple line) and the tidal height (blue line) at the grounding zone of the Whillan's Ice Stream. Which of the following statements are true regarding this ice stream?



(Bindschadler, 2003)

I) The grounding zone of the Whillan's experiences a semidiurnal tidal pattern.

II) The correlation between stick-slip and the tidal pattern are likely stronger at spring tide than at neap tide.

III) During flood tide, the increase in backstress likely outweighs the reduction in normal stress from the increased buoyancy of the ice stream.

A. I only

B. II only

C. III only

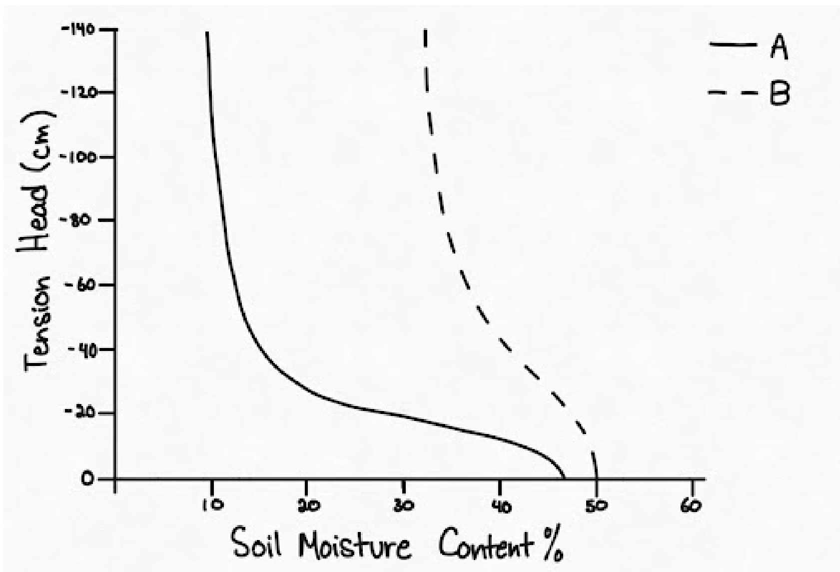
D. I and II only

E. II and III only

F. I, II and III

Solution: Because we only see one trough, or one low tide each day, it must experience a diurnal tidal pattern - I is false. The larger tidal range at spring tide would lead to greater changes than at neap tide - II is true. III is also true, because we do not see a spike in glacial movement during the flood tide, meaning the forces holding the glacier back must exceed the forces that would allow it to move forward more easily.

10. The diagram below plots soil moisture content versus tension head for two soils. Tension head is defined as the attractive force between soil particles and the water molecules as a result of adhesion. Given this information, which of the following is **false**?



A. Soil A has a larger average particle size than soil B.

B. Soil B would serve as a good aquitard.

C. After a rainstorm that completely saturates the soil, plants could draw more water from Soil A than Soil B.

D. During a period without precipitation, Soil A would maintain its moisture content more effectively than Soil B.

Solution: As soil moisture is lowered to below saturation, capillary forces (adhesion) between the water and the surface of the soil particles make water harder to withdraw, resulting in the tension head. Larger particle sizes correspond to less surface area for adhesion to occur such that more water can be removed before the tension head starts increasing in magnitude - A) is true. Likewise, we can infer that it has very small particles and it is also difficult for water to move through (low permeability), so B) is true. Plants can not draw water once the magnitude of the tension head is too high, so C) is true. However, because A has a lower tension head at high moisture content, that moisture can more easily escape during a period without precipitation. D) would be false and the correct answer.

Section II: Problem 1

Question	1	2	3	4	5	Total
Points	5	4	4	1	1	15 (30%)

As anthroprogenic climate change intensifies and we continue to draw on water resources, the hydrologic cycle continues to be altered. The following questions ask you to think about potential changes to our freshwater systems.

1. The following parts ask about lake mixing in light of climate change.

   (a) (1 point) Which of the following types of lakes is most likely to be the first to experience decreased lake turnover as a result of global warming?

   A. Warm monomictic (mixes once annually in winter)

   B. Cold monomicitc (mixes once annually in summer)

   C. Dimictic (mixes twice annually in spring and fall)

   D. Polymictic (mixes throughout year)

   (b) (2 points) Explain your reasoning to the question above.

   Solution: Lake turnover occurs in the absence of density stratification, requiring the water column to be isothermal assuming salinity effects are negligible. In warm monomictic lakes, surface water cools to the same temperature as the bottom water in the winter. Increased warming reduces winter surface cooling, which in turn reduces turnover. In cold monomictic lakes, increased warming would help bring surface waters to the same temperature as bottom waters, increasing turnover. In dimictic lakes, it would help with warming surface waters in the spring, and would simply delay fall turnover. Polymictic lakes are shallow and do not have seasonal turnovers. (Solution scored only on part relevant to warm monomictic lakes.)

   (c) (2 points) Name two potential consequences of reduced lake turnover on lake chemistry. Explain why for each consequence.

   Solution: Possible answer 1: Lower oxygen content in the hypolimnion. Little oxygen can be generated in the hypolimnion without turnover as it is too dark for photosynthesis and does not have contact with the atmosphere. Possible answer 2: Lower nutrient content in surface waters. In summer, nutrients rather than sunlight is limiting, so nutrients are depleted at the surface. Bottom waters have more nutrients from respiration that would be reintroduced to the surface upon mixing. Possible answer 3: Higher concentrations of toxic gases in deeper waters. Less overturning leads to the release of toxic gases from decomposition that would otherwise be released into the atmosphere.

2. Below is the before (A) and after (B) of the Drweca River in Poland before and after channelization (channel straightening).

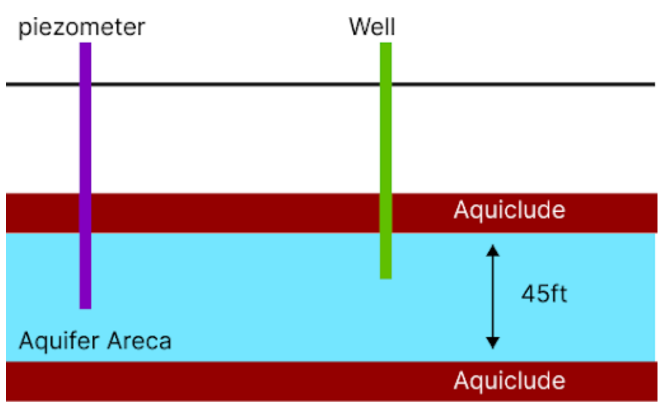
Answer the following questions regarding this area.

(a) (2 points) How is downstream flooding expected to change? Be sure to mention the lag time between precipitation and flooding along with the height of the flood peak.

> **Solution:** Downstream flooding is likely to become more intense with a higher flood peak and a shorter lag time (i.e. more "flashy").

(b) (2 points) Would you expect the land in this image to become more or less fertile as a result of channelization? Explain your response.

> **Solution:** Less fertile. Channelization tends to increase the water velocity in the region where the water is channelized, directing the water downstream and inhibiting flooding (aside from downstream the flood risk). This reduction in flooding means that the floodplains are less frequently replenished with nutrient-rich sediments.



3. (4 points) Aquifer Areca, shown in the image above, is an idealized confined aquifer with a uniform thickness of 45 ft and an area of 1000 acres. After 280,000 cubic feet of water is extracted from the aquifer by the well, the piezometer senses a pressure drop of 0.25 psi (pounds per square inch). Assuming that the water is drawn evenly from the entire aquifer, what is the compressibility α of the aquifer in m s^2 kg^{-1}? **Show your work**, box your answer, and give your answer to 3 significant figures. Relevant formulas and units are given below:

Storativity (S): $S = S_s b$ (for confined aquifers only)
Defined as the volume of water that can be released per horizontal area per unit decline in hydraulic head. In this equation, S_s represents specific storage and b represents the thickness of the aquifer.

Specific storage (S_s): $S_s = (\rho g(\alpha + \eta\beta))$
Defined as the volume of water that can be released per volume of aquifer per unit decline in hydraulic head. In this equation, ρ represents the density of water, g represents gravitational acceleration, α represents aquifer compressibility, η represents porosity, and β represents the compressibility of water.

ρ	1000 kg m^{-3}
g	9.81 m s^{-2}
η	0.35
β	4.4×10^{-10} m s^2 kg^{-1}
1 ft^3 of water	62.4 lbs
1 acre	43,560 ft^2
1 m	3.28 ft

Solution:
Step 1: Solve for Storativity

$$\frac{62.4\text{lbs}}{\text{ft}^3} \div \frac{144\text{in}^2}{\text{ft}^2} = 0.433\text{psi}$$

From this, we know that each ft increase in pressure head correlates to a 0.433 increase in psi.

$$0.25 \div 0.433 = 0.577$$

Therefore, the 0.25psi drop corresponds to a 0.577 ft drop in hydraulic head. Knowing this, we can divide the total volume released by the area and the decrease in hydraulic head to get Storativity, the unit volum released per unit area per unit decrease in hydraulic head.

$$S = \frac{280,000\text{ft}^3}{43,560\text{ft}^2 \cdot 1000 \cdot 0.577\text{ft}} = 0.01114$$

Step 2: Solve for Specific Storage (S_s)

$$S_s = \frac{S}{b} = \frac{0.01114}{45\text{ft}} = 2.476 \times 10^{-4}\text{ft}^{-1}$$

Step 3: Solve for Aquifer Compressibility
First, convert from freedom units to SI units, as all units for the Specific Storage equation and Compressibility are in SI units.

$$S_s = \frac{2.476 \times 10^{-4}}{\text{ft}} \times \frac{3.28\text{ft}}{\text{m}} = 8.121 \times 10^{-4}\text{m}^{-1}$$

Then, plug into the equation for Specific Storage and solve for α, aquifer compressibility

$$\frac{8.121 \times 10^{-4}}{\text{m}} = \frac{1000\text{kg}}{\text{m}^3} \times \frac{9.81\text{m}}{\text{s}^2} \times (\frac{\alpha\text{m s}^2}{\text{kg}} + 0.35 \times \frac{4.4 \times 10^{-10}\text{m s}^2}{\text{kg}})$$

rearranging, we get

$$\alpha = 8.263 \times 10^{-8}$$

So, the compressibility of the aquifer is 8.263×10^{-8}m s^2 kg^{-1}

4. (1 point) Land subsidence occurs as a result of overdrawing water from an aquifer. If land starts subsiding drastically faster per unit amount of water pumped out of, it is a sign that the aquifer has most likely transitioned from a(n):

   A. Elastic to inelastic compaction.

   B. Inelastic to elastic compaction.

   C. Pressure head greater than zero to a pressure head of zero.

   D. Pressure head of zero to a pressure head greater than zero.

   Solution: Generally, the rate of compaction suddenly increases when an aquifer transitions from elastic to inelastic compaction. The aquifer may still be saturated, just with a lower pressure head that can not support the weight of the sediments above it, so D and C are incorrect.

5. (1 point) **True/False**: In areas with nitrate and phosphate contamination in well water, streams are likely disconnected from the water table.

   Solution: False. Nitrate and phosphate contamination from well water is generally due to overdrawing of water from a well, leading to water intrusion from nearby freshwater sources as the direction of groundwater flow flips from flowing towards the surface water flow and instead towards the well. Because contamination from the freshwater is carried into the groundwater, this means that the groundwater is connected to the surface water.

Section II: Problem 2

Question	1	2	3	4	5	6	Total
Points	2	5	3	2	2	1	15 (30%)

Sea level has fluctuated throughout geologic history on time scales as long as tectonics to those as short as present climate change. The following questions address some important considerations for the causes and effects of sea level change in both historical and modern contexts.

1. (2 points) Counter to what one might expect, the average sea surface height (SSH) at any given location does not always conform to the height of the geoid. Briefly explain how ocean circulation contributes to this discrepancy.

   Solution: Major gyres (a consequence of prevailing winds, the rotation of Earth, and the location of land masses) occur in approximate geostrophic balance to create broad, gently undulating variations in SSH. Similar processes occur with smaller eddies. Since SSH depends on wind and land in addition to the gravity of the Earth at a particular location, we should expect for SSH to differ from the geoid.

2. One long-term influence on sea level is the creation and splitting of supercontinents, which affects the total volume of ocean basins as well as the global climate.

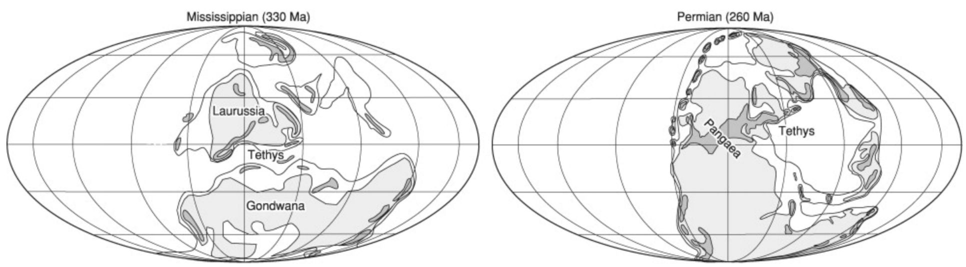


Figure 1: Arrangement of continents over two geologic periods.

   (a) (3 points) Compared to the Permian, is the Mississippian associated with higher or lower sea level? Explain using relationships between the supercontinent cycle, seafloor spreading, and ocean basin volume.

   Solution: The Mississippian period is associated with higher sea level than the Permian. In general, when continents are apart (here they are about to form Pangea), greater seafloor spreading from mid-ocean ridges produces relatively hot, young oceanic lithosphere that is less dense and more buoyant than the cool, old lithosphere present in the Permian. Young lithosphere allows for a lower ocean basin volume, contributing to higher sea levels during this period.

   (b) (2 points) The supercontinent cycle also impacts climate, another major influence on sea level. Explain whether the change in climate from the Mississippian to Permian period enhances or reduces the effect of ocean basin volume on sea level.

   Solution: The change in climate enhances the effect of the change in ocean basin volume. The collision of continents build some of the largest mountain belts, lowering atmospheric carbon dioxide via silicate weathering. Weakened greenhouse effects promote glaciers formation, which lowers sea level by storing water over land rather than in the ocean. Moreover, in potentially transporting land to high latitudes, supercontinents can create favorable conditions for ice sheet formation.

Increasing ocean heat content drives sea level rise because of the thermal expansion of water.

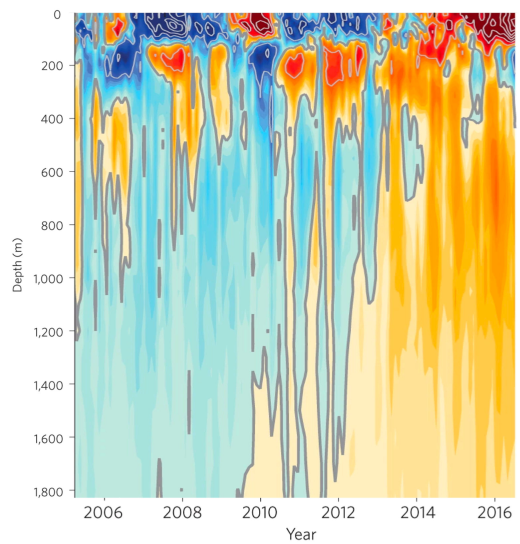


Figure 2: Average ocean temperature by depth and year. Intervals of 0.05 °C are marked by gray contours, with warm and cool colors representing warming and cooling anomalies, respectively. (Wijffels et al., 2016)

3. (a) (1 point) At which of the following depth ranges would one best detect relatively long term changes in ocean heat content?

   A. 0 m

   B. 75–125 m

   C. 200–250 m

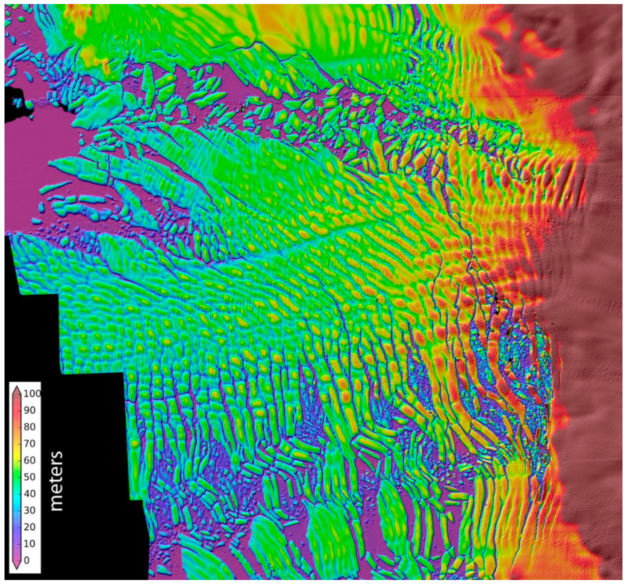
   D. 300–400 m

   E. $>$ 800 **m**

   (b) (2 points) Justify your previous answer.

   Solution: At any depths above about 700-800 meters, temperature appears to fluctuate on shorter time scales and are more likely caused by internal variability than an external forcing. While this does not necessarily rule out the overall warming of deep water over the 2006-2016 period as also being a product of natural variability of a longer period, it is reasonable to presume that deep water provides a stronger signal for long-term ocean warming trends.

4. (2 points) The figure below illustrates the fracturing ice shelf of the Thwaites Glacier to the right (color indicates elevation). Warming waters also contribute to sea level rise by inducing ice melt. Briefly describe how ice shelf break up can lead to the acceleration of Thwaites.



Solution: The breakup of the ice shelf is thought to remove the 'buttressing' effect that prevents greater ice flow, especially because ice shelves like the one from Thwaites are held in place by an embayment.

5. (2 points) Despite melt from the Greenland ice sheet significantly contributing to global sea level rise, little local sea level rise has been observed at the Greenland coast so far. Describe two reasons why this may be. (*Hint: both relate to gravity.*)

Solution: First, since the Greenland Ice Sheet is rapidly losing mass, the land mass uplifts by isostatic rebound. As global mean sea level rises, uplifting land experiences less local sea level rise than land that is static or undergoing subsidence. Second, the loss of mass decreases the gravitational attraction of water towards Greenland.

6. (1 point) Other locations across the globe experience much more severe effects of sea level rise, such as many island and atoll nations. Current changes in sea level exacerbate coastal flooding even where coasts are at an elevation greater than the highest high tide. Name one possible cause responsible for this.

Solution: Storm surge or tsunami