USESO 2021

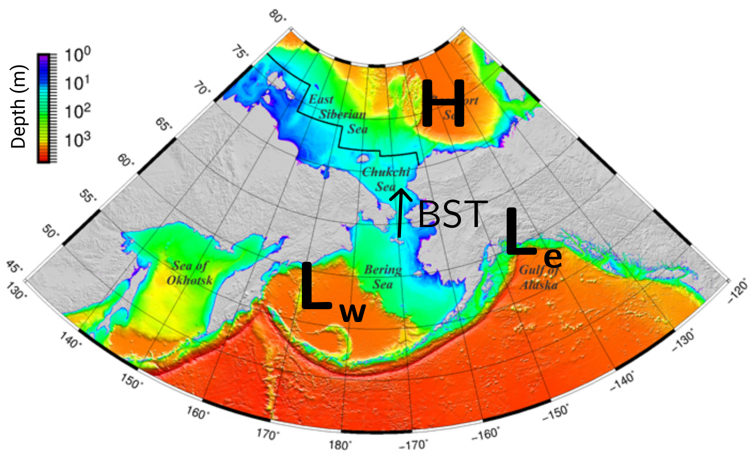
Hydrosphere
KEY

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 non-graphing, non-programmable calculator is allowed; show all work for calculations
- Recommended time management: 30 minutes on each section

Section I

1. (2 points) The Bering Strait Throughflow (BST) is an important quasi-geostrophic current transporting water from the Pacific to the Arctic Ocean. Its variability is mostly forced by wind, which affects the sea surface height.



The Beaufort High and Aleutian Low, shown above, are two semipermanent atmospheric pressure systems. Wind forcing in the Bering Strait is driven primarily by variability in the *strength* of the Beaufort High (shown as H) and variability in the *position* of the Aleutian Low (westernmost is L_w, easternmost is L_e).

Which of the following combinations generates the strongest BST?

A. Strong Beaufort High, western Aleutian Low

B. Strong Beaufort High, eastern Aleutian Low

C. Weak Beaufort High, western Aleutian Low

D. Weak Beaufort High, western Aleutian Low

Solution: The Beaufort High is a clockwise circulation, so a stronger Beaufort High induces stronger Ekman transport away from the western coast. This decreases the western sea surface height (SSH) and strengthens the geostrophic flow. The zonal position in the Aleutian Low also controls the SSH anomaly in the Bering Strait. When the Aleutian Low is in the west, there is Ekman transport towards the eastern coast of the Bering Strait, which enhances the quasi-geostrophic flow (stronger pressure gradient).

2. (2 points) A geologist investigates a marine terrace, shown below.

Which of the following could have been responsible for the formation of the marine terrace?

I) A decrease in eustatic sea level

II) Regional tectonic subsidence

III) Relatively high resistance to erosion of the exposed rock

A. I, only

B. II, only

C. I and II

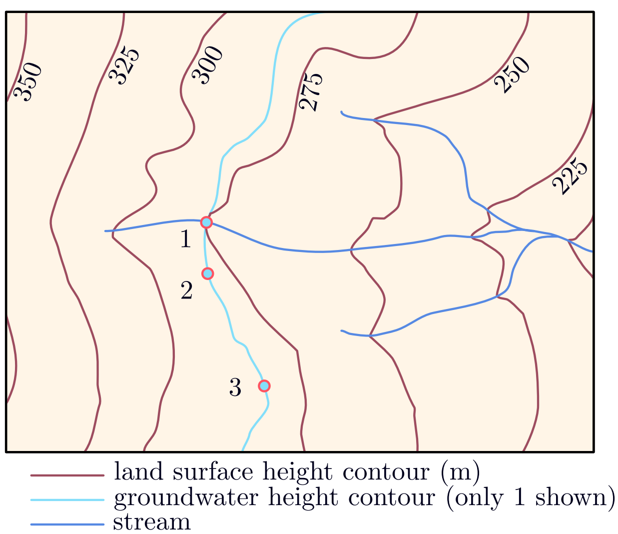
D. I and III

E. II and III

F. I, II, and III

Solution: When sea level falls, the former wave-cut platform is exposed, forming the marine terrace. Marine terraces can also be formed by uplift; subsidence is the opposite process and can cause the terrace to be submerged. The sea cliff is formed by wave action; the steepness of the cliff suggests bedrock which is resistant to erosion.

3. (2 points) The figure below shows a topographical map with streams fed by groundwater. As seen with the light blue line, contours of groundwater usually follow surface topography.



If the overall permeability of the ground is increased, what are the most plausible resulting groundwater heights at the points 1, 2, and 3, respectively? Assume existing streams remain fed by groundwater.

A. 275 m; 270 m; 270 m

B. 275 m; 270 m; 260 m

C. 270 m; 270 m; 270 m

D. 255 m; 270 m; 270 m

E. 280 m; 275 m; 285 m

Solution: The groundwater surface usually resembles a subdued version of the surface topography. Assuming a homogeneous ground material (unrealistic), the permeability of the ground determines how subdued the groundwater surface is. Since the stream remains groundwater-fed, at point 1 the groundwater height must be equal to the surface height, 275 m. Groundwater heights at points 2 and 3 should both be lower, as water percolates downwards more easily. However, the height at Point 3 lowers more because it is at a greater height to begin with.

4. (2 points) Which of the following contributes the most to the abundance of nutrients in deep water?

   A. Downwelling of agricultural runoff

   B. Dissolution of seafloor sediments

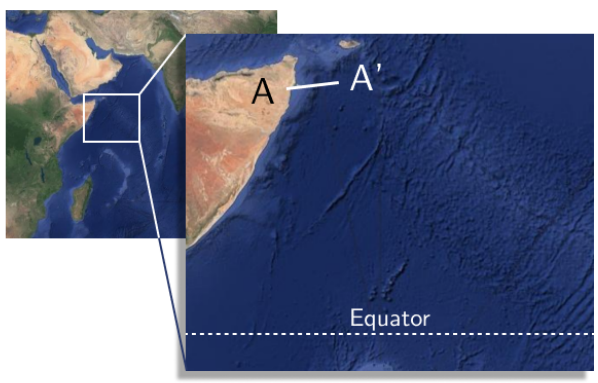
   C. Greater solubility in cold water

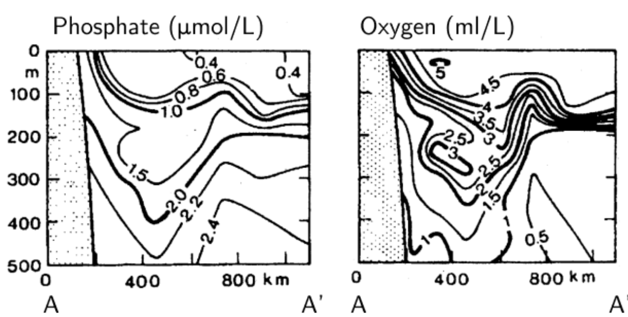
   D. Largely anoxic conditions

   E. Minimal primary production

Solution: Primary production removes nutrients such as nitrate and phosphate from water. This typically takes place in the photic zone, limiting nutrients. In deep water, respiration exceeds primary production and leads to an excess of nutrients.

5. (2 points) The figure below shows phosphate and dissolved oxygen profiles off of the coast of Somalia. The transect is denoted on the map with endpoints at A and A'.





   (a) During which month were these profiles taken?

      A. December

      B. April

      C. August

(b) During this month, towards which direction does the depth-averaged transport passing through the transect flow?

A. North

B. South

C. East

D. West

Solution: Consulting the phosphate and oxygen curves, we find that there is strong upwelling on the Somali coast. This indicates that the wind stress must be southwesterly, which corresponds to the Southwest Monsoon. This occurs during summer months → August. Considering the wind during August, the Somali current must flow north through the transect.

6. (2 points) Tropical cyclones (hereafter referred to as cyclones) are transient, powerful phenomena that have profound effects on large scale ocean circulation. The Kuroshio Current is the western boundary current of the subtropical Pacific Gyre.

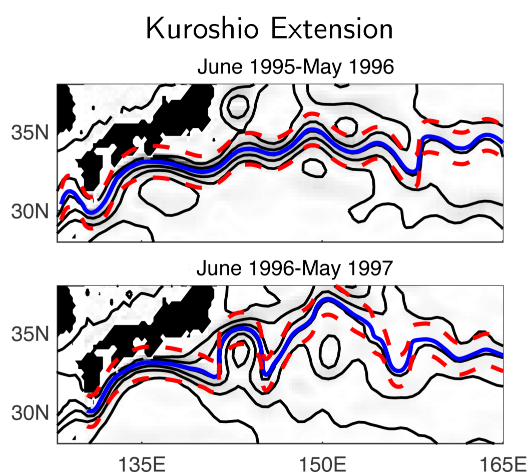


Figure 1: Schematic of Kuroshio paths.

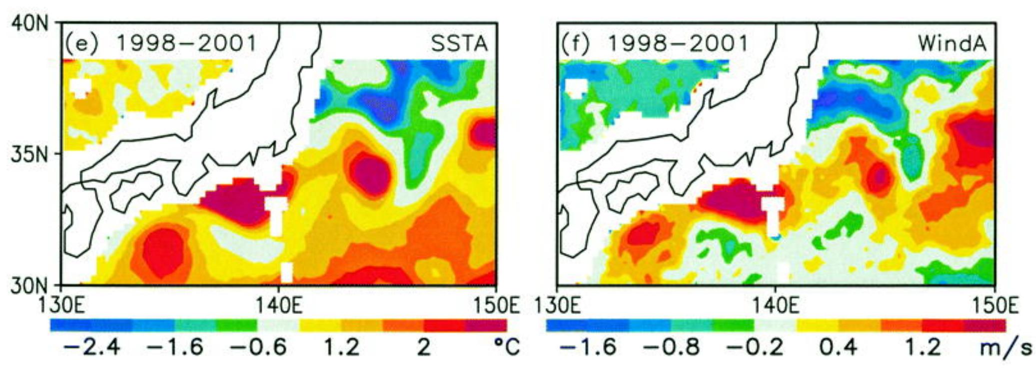


Figure 2 (Nonaka and Xie, 2003): the 1998 minus 2001 anomalies of annually-averaged sea surface temperature (SST) and surface wind velocity, both of which are taken as annual means. Note that the dates do not correspond with Figure 1.

Which of the following best describes how cyclones interact with the Kuroshio?

I) Cyclones enhance the strength of cold core eddies in the Kuroshio

II) The dissipation time of cyclones is several orders of magnitude faster than that of ocean eddies

III) Cyclones generate warm SST anomalies in their wake

A. I only

B. III only

C. II and III

D. I and II

E. I and III

F. I, II, and III

Solution: Cold core eddies are cyclonic and form when the meander "pinches off" on the south side of the Kuroshio. Tropical cyclones enhance their motion and drive Ekman suction, sustaining the cold core. The ocean is much more viscous than the atmosphere; ocean eddies (and turbulent motion in general) are larger in scale and dissipate over a much longer timescale than those in the atmosphere. As such, transient cyclones are able to drive longer term (seasonal to even interannual) changes in the ocean. Finally, while the figure shows a clear positive correlation of SST with surface winds, this does not show the effect of cyclones. Cyclones create strong divergence of water in their wakes, which drives mixing and cooling of SST. In fact, notice in the figure that the anomalies in wind follow the structure of the Kuroshio, rather than the other way around. This is an example of ocean-to-atmosphere forcing, which seems to be less common than atmosphere-to-ocean forcing.

7. (2 points) Oceanographers collect samples of marine sediment, described in the table below.

Sample	Description
A	Black shale and pyrite with trace hydrogen sulfide (H_2S)
B	Red and brown clays interbedded with manganese nodules
C	Crystalline chert and opal

Which of the following is most likely true about the marine sediment samples?

A. Samples A and B represent sediment commonly found near hydrothermal vents, whereas Sample C represents terrigenous sediment widely found in abyssal plains

B. Samples A and B indicate regions of significant downwelling, whereas Sample C indicates a region of significant upwelling

C. Samples A and B are likely found in deep marine environments, whereas Sample C is likely found in warm, shallow waters

D. Samples A and B formed in regions with relatively low productivity, whereas Sample C formed in a region with relatively high productivity

E. Samples A and B are sourced from continental shelf deposits, whereas Sample C is sourced near a mid-ocean ridge

Solution: Black shale and pyrite, along with hydrogen sulfide gas, suggest an anoxic environment with poor circulation. The fine grained clays in Sample B are terrigenous (originally from land) and are likely found with hydrogenous/authigenic manganese nodules in an abyssal plain. Thus, Samples A and B indicate pelagic/deep sea environments with limited circulation and productivity. Both chert and opal are formed from silica, and chert especially is typically formed from biogenic silica, more abundant in productive environments. Siliceous sediment is more common in cold, deep waters as opposed to calcareous sediment.

8. (2 points) The abundance of oxygen-18 (δ^{18}O, defined as a normalized ratio of $^{18}O/^{16}O$) in seawater is affected by various physical and chemical processes. Which seawater parameter best correlates with δ^{18}O of surface ocean water?

   A. Temperature

   B. Salinity

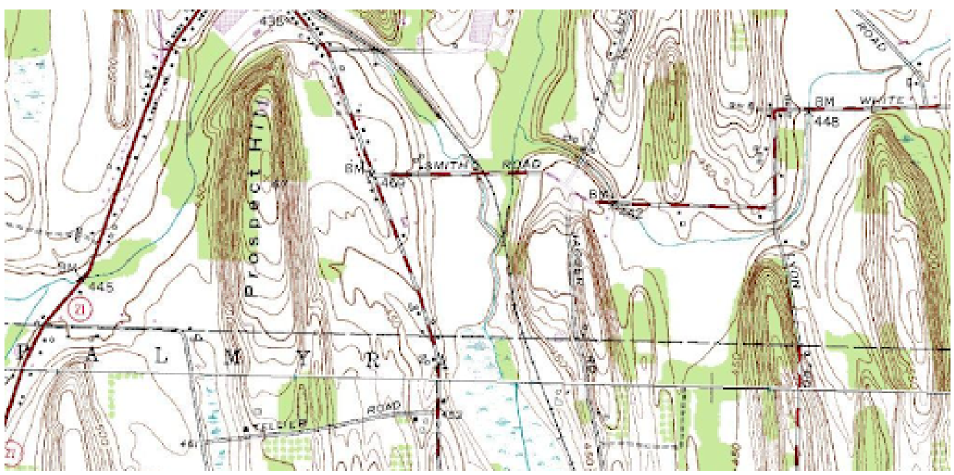
   C. Sea surface height

   D. Density

   E. Dissolved oxygen

Solution: At the ocean surface, evaporation increases salinity as well as δ^{18}O. Lighter $^{16}OH_2$ is preferentially evaporated, which increases the proportion of $^{18}OH_2$ in the surface ocean.

9. (2 points) The figure below is a topographic map of an area previously covered by an ice sheet.



   (a) Prospect Hill is an example of which of the following landforms?

      A. End moraine

      B. Lateral shear moraine

      C. Roche moutonnée

      D. Drumlin

      E. Crag and tail

   Solution: Prospect Hill is a typical drumlin, an elongated, asymmetrical glacial landform that often occurs in groups called "drumlin fields."

(b) In which direction did the ice sheet flow? (Assume north is towards the top of the page.)

A. North to south

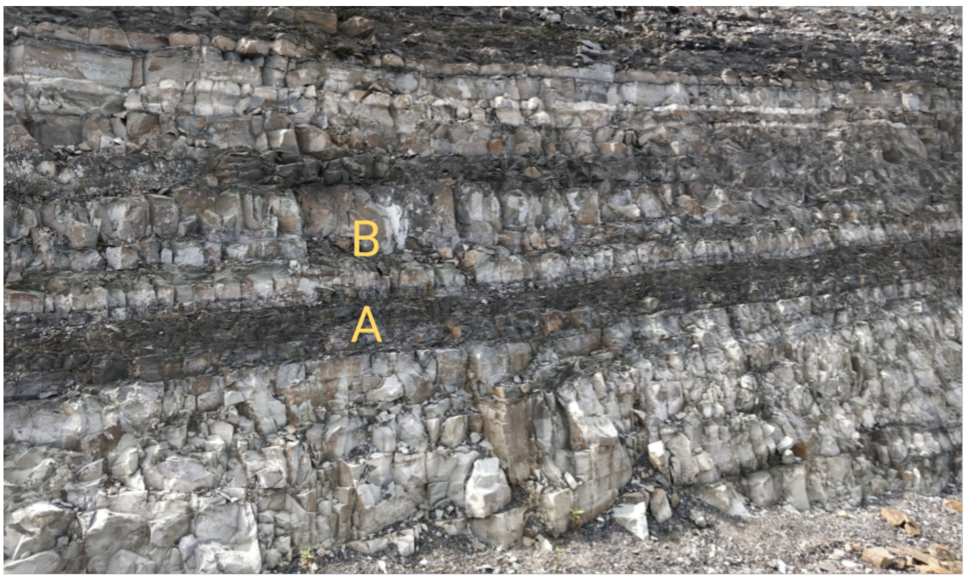
B. South to north

C. East to west

D. West to east

Solution: The stoss (upstream) end of drumlins are steeper than the lee (downstream) end. As seen from the contour lines on the map, the steeper end of Prospect Hill faces north.

10. (2 points) In the image below, Rock A is layered and does not effervesce with hydrochloric acid while Rock B effervesces strongly with hydrochloric acid.



Which of the following processes most likely occurred between the formation of A and B? Assume no overturning.

A. Local downwelling of asthenosphere

B. Eruption of a basaltic volcano

C. Formation of a supercontinent

D. Onset of widespread glaciation

E. Intrusion of metasomatic fluids into the rock body

Solution: Based on appearances and interactions with hydrochloric acid, Rock A is likely to be shale and Rock B is likely to be limestone. A transition from shale to limestone corresponds with the depositional environment changing from being shallow marine to deep marine, which is known as a marine transgression. Since transgressions are caused by relative sea rise, either sea level must rise or the coastline must subside, which could result from local asthenospheric downwelling.

Section II: Problem 1

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

The ocean plays a major role in regulating climate change and climate variability. The Atlantic Meridional Overturning Circulation (AMOC) is an important arm of thermohaline circulation.

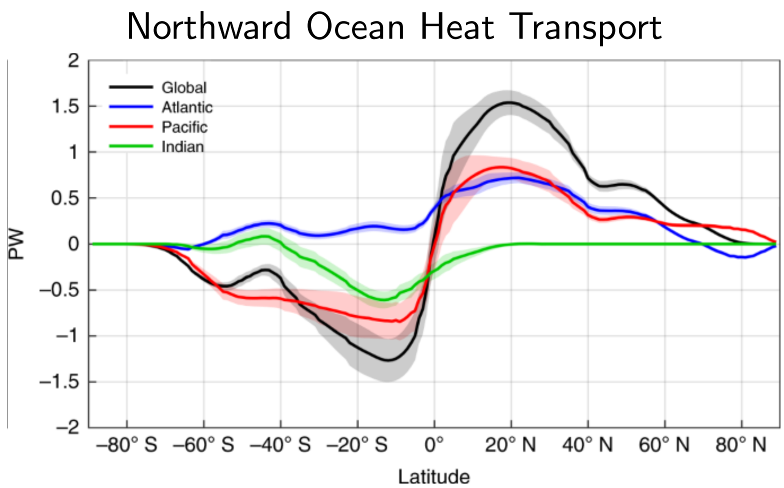


Figure 1: Northward ocean heat transport (measured in petawatts, 10^{15} W). Note the blue curve for the Atlantic Ocean.

1. (3 points) Estimates show that the northward ocean heat transport (OHT) at the equator is slightly positive. Use this fact to justify that the average position of the ITCZ is not at the equator. Is it north or south of the equator?

   Solution: To maintain climatological equilibrium in both hemispheres, we should expect the total heat transport across the equator to be zero. Thus, the atmosphere has a mean southward heat transport at the equator. Indeed, the ITCZ is slightly north of the equator.

2. (3 points) AMOC is projected to weaken as a result of anthropogenic forcing. Briefly explain how this will affect the position of the intertropical convergence zone (ITCZ). Justify your answer.

   Solution: For weakened AMOC, there will be less northward OHT, which means there will be less southward AHT at the equator. As such, the ITCZ should move south (see Bjerknes compensation).

A dominant mode of atmospheric variability in the Atlantic is the North Atlantic Oscillation (NAO), which has been shown to force variability onto AMOC.

The effects of NAO on AMOC were studied in a coupled climate model by applying surface heat fluxes associated with positive phase NAO on the ocean (see figure 2). In one model experiment, the heat fluxes were applied with full amplitude and at once, a "switch on."

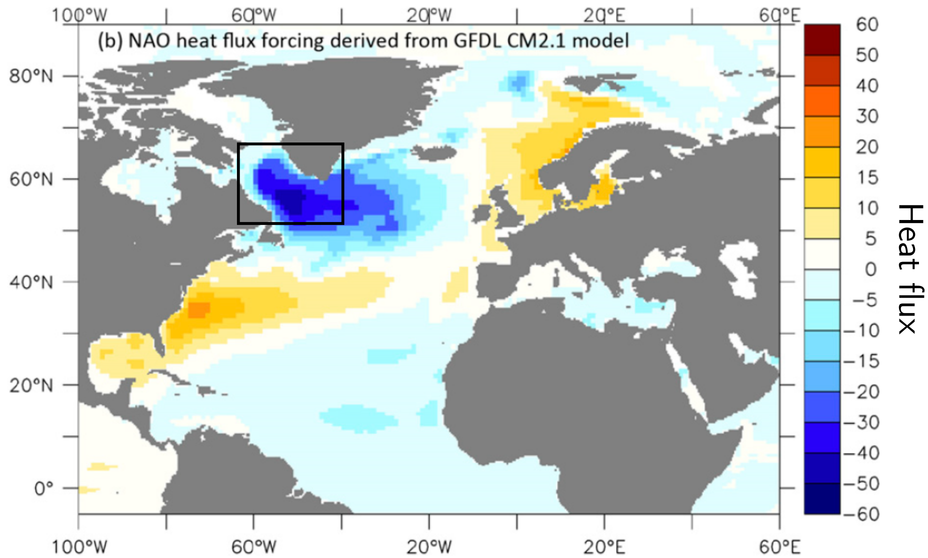


Figure 2 (modified after Delworth and Zeng, 2016): ocean heat fluxes ($W\,m^{-2}$) corresponding to an increase of NAO index by one standard deviation. The box shows the Labrador Sea.

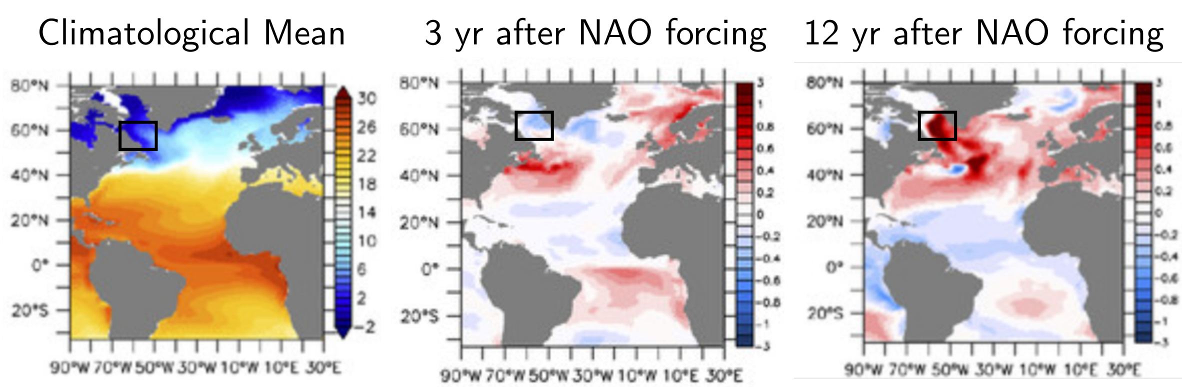


Figure 3 (modified after Delworth and Zeng, 2016): sea surface temperature (SST) during three stages: leftmost is the climatological mean, while the other panels show anomalies from the mean after positive NAO heat flux forcing has been applied. Red is warmer, blue is colder.

3. While a positive phase NAO imposes significant negative heat flux in the Labrador Sea (boxed), the SST actually warms by 1 - 2 deg C 12 years after the heat flux forcing is applied.

   (a) (2 points) Briefly explain how AMOC strength changes as a result of NAO forcing.

   Solution: Negative heat flux in downwelling regions like the Labrador Sea initially cools (densifies) the surface water (see 3 yr after NAO forcing). This enhances deep convection, which strengthens AMOC. Enhanced zonal density gradient also leads to stronger AMOC.

(b) (2 points) Considering your answer in (a), briefly account for the warming of SSTs despite the negative heat flux forcing in the Labrador Sea.

> **Solution:** Strengthening in AMOC leads to greater northward heat transport. This heat flux from the tropics counteracts the negative air-sea heat flux, which warms the SST.

Tectonic movements can affect the climate by changing pathways of the overturning circulation. The Drake Passage is an important body of water that connects the Pacific and Atlantic Oceans south of the tip of South America. The Drake Passage used to be closed such that there was no ocean throughflow.

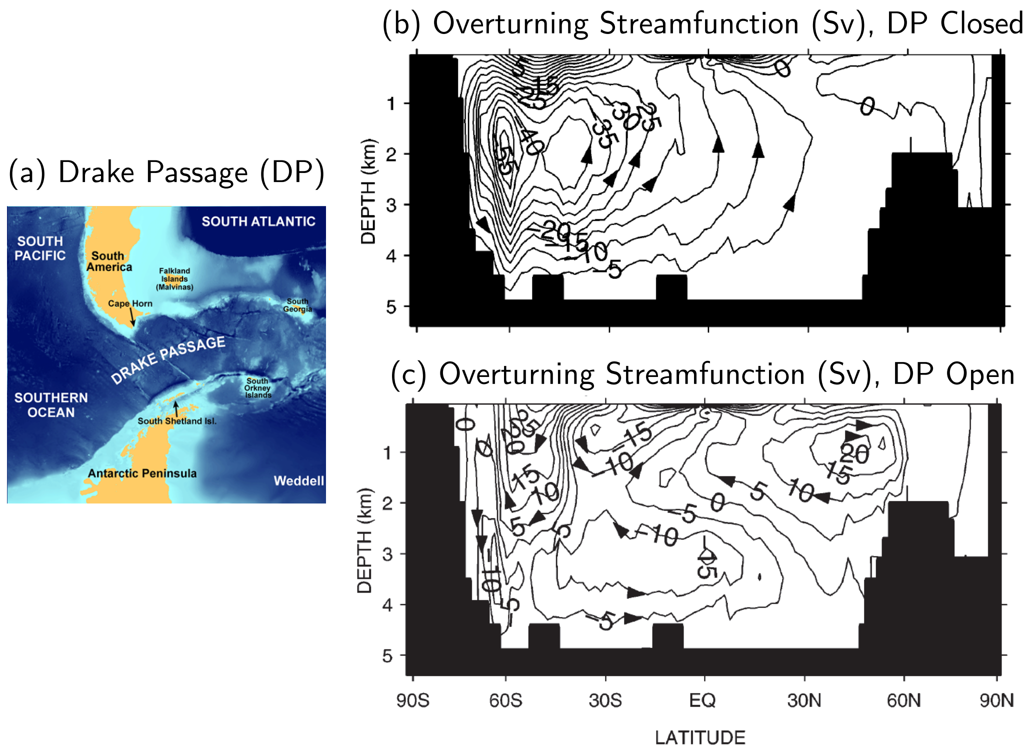


Figure 4 (modified after Sijp and England, 2004): (a) the Drake Passage (DP). (b) the global meridional overturning streamfunction, measured in Sverdrups (1 Sv = $1*10^6$ m^3/s), when the DP is closed. The magnitude of the overturning streamfunction is a measure of how strong the overturning circulation is, while the sign indicates the direction of overturning. Zonally-averaged currents go parallel to the isolines, as denoted by the arrows. (c) same as in (b), but when the DP is open.

The effect of the Drake Passage (DP) on the overturning circulation was studied in an idealized GCM, as shown in figure 4(b) and 4(c).

4. (2 points) Which of the following is true?

I) There is no meridional overturning in the North Atlantic when the DP is closed.

II) Deep water formation occurs in both the Northern and Southern Hemisphere when the DP is closed.

A. I only

B. II only

C. I and II

D. Neither I nor II

Solution: Referring to 4b, we see that the overturning cell is localized in the south; there is no North Atlantic MOC and no deep water formation in the Northern Hemisphere.

5. (3 points) It has been hypothesized that the opening of the DP had significant climatic effects on Antarctica. Justify how the opening of DP led to significant cooling of Antarctica. *(Hint: how did ocean circulation change?)*

Solution: When the DP was closed, there was significant deep water formation around Antarctica. This must be driven by a source of water from the tropics, which corresponds to a significant southward heat flux. As such, when the DP opened and deep water formation began in the NH, this southern overturning cell weakened, cooling Antarctica as a result. Further, the Antarctic Circumpolar Current was able to flow around the continent, also cutting off warm water from the tropics.

Section II: Problem 2

Question	1	2	3	4	5	6	7	8	9	Total
Points	1	2	1	1	2	1	1	3	3	15 (30%)

Salinity is one of several key properties of seawater.

1. (1 point) Besides continental erosion of rocks and runoff from rivers and streams, identify one other source of oceanic salt.

   Solution: Salt sources include outgassing from volcanoes, hydrothermal vent activity, and ions from dissolved gases in the atmosphere/dry deposition.

2. (2 points) Which of these is/are reasonable mechanisms describing the effect of temperature changes on ocean salinity? Assume factors that are not mentioned remain constant. (*)

   A. A decrease in global tropospheric temperatures reduces the saturation vapor pressure, increasing precipitation and lowering ocean surface salinity.

   B. A decrease in global tropospheric temperatures causes sea ice formation, resulting in brine rejection and decreasing overall ocean salinity.

   C. Increased tropical sea surface temperatures (SSTs) results in added moisture to the air, increasing rainfall and lowering tropical ocean surface salinity.

   D. Increased tropospheric temperatures in a coastal region causes greater freshwater fluxes, lowering deep water salinity relative to surface salinity.

   Solution: Brine rejection would increase the salinity of the surrounding ocean. Higher temperatures do not necessarily increase the freshwater flux, and freshwater would lower surface salinity, not deep water salinity.

3. (1 point) What is the effect of a decrease in global average temperatures on the Cl^- (chloride ion) to Na^+ (sodium ion) ratio in seawater?

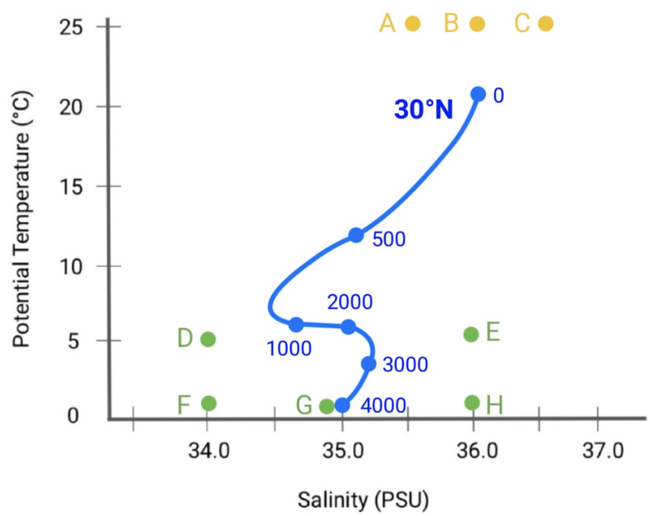
   A. Increases the Cl^- to Na^+ ratio

   B. Decreases the Cl^- to Na^+ ratio

   C. Does not affect the Cl^- to Na^+ ratio

   Solution: According to the Law of Constant Proportions/Marcet's Principle, the ratio of major ocean ions (including chloride and sodium ions) remains constant.

Consider the following T-S (temperature-salinity) diagram. The blue curve represents a column of seawater at 30°N. The numbers correspond to water depth in meters (e.g., "500" = 500 m below the surface). Points labeled A through H represent seawater at various potential temperatures and salinities at other latitudes.



4. (1 point) Identify the letter or letter(s) of the water mass(es) with the highest density.

> **Solution:** **H**. Water density increases with decreasing temperature and increasing salinity. Thus, in the T-S diagram shown, water density increases from the top left to the bottom right.

5. (2 points) Which yellow point (A, B, or C) most closely corresponds to seawater located at the surface at the equator? Briefly explain the similarity or difference in surface salinity at the two latitudes.

> **Solution:** Point A, because the surface salinity at the equator is lower than the surface salinity at 30°N. This is due to higher amounts of precipitation/lower surface air pressure at the equator relative to 30°N.

6. (1 point) An oceanography student wants to plot a curve on the T-S diagram that represents a column of seawater at 55°N. Which points represent the surface water and the bottom water of the column, respectively?

   A. AH

   B. BH

   C. DF

   D. DG

   E. EF

   F. EG

> **Solution:** Surface water at 55°N has a lower surface temperature and a lower salinity (due to lower evaporation relative to precipitation) than surface water at 30°N. Bottom waters are more saline and denser than surface waters. Curve DG is the only alternative that is consistent with these conditions.

7. (1 point) Assume that water masses E and G are isopycnal (at the same density) and equal volumes of E and G are mixed together. Will the combined water mass upwell, downwell, or do neither?

   A. Upwell, because the final water mass will have a lower density than the initial density

   B. Downwell, because the final water mass will have a higher density than the initial density

   C. Neither, because the final water mass will have the same density than the initial density

   Solution: Temperature has a greater effect on water density in tropical regions compared to polar regions. This explains the slightly concave-down shape of isopycnal curves (connecting water masses of equal density, not shown on the provided diagram). Since density increases towards the bottom right of the T-S diagram, two water masses with equal density will become more dense when mixed.

8. (a) (1 point) A climate model predicts both an increased SST and increased evaporation relative to precipitation at 55°N. These factors alone would cause the amount of CO_2 dissolved in seawater at 55°N to:

   A. Increase, resulting in greater ocean acidification

   B. Decrease, resulting in more CO_2 released to the atmosphere

   C. Remain unchanged, since temperature, evaporation, and precipitation have no effects on dissolved CO_2

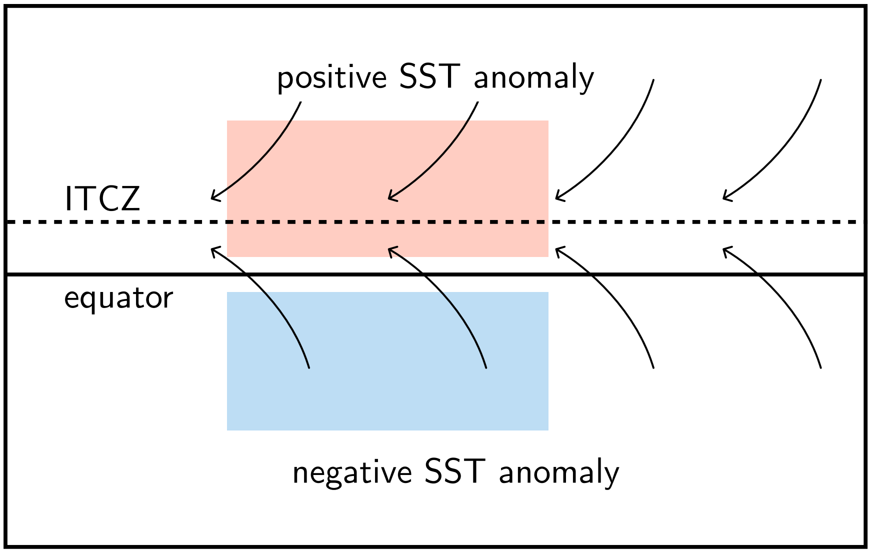
   D. Inconclusive from the information given

   Solution: Increased SSTs would cause less CO2 to be dissolved, since gases are less easily dissolved in warmer waters. Surface salinity would increase with greater evaporation, and gases dissolve less easily with higher salinity, so both changes would cause less CO2 to be dissolved (and more to be released into the atmosphere).

   (b) (2 points) Justify your answer.

   Solution: Increased SSTs would cause less CO2 to be dissolved, since gases are less easily dissolved in warmer waters. Surface salinity would increase with greater evaporation, and gases dissolve less easily with higher salinity, so both changes would cause less CO2 to be dissolved (and more to be released into the atmosphere).

9. (3 points) The wind-evaporation-SST (WES) feedback is an interesting phenomenon found in tropical ocean-atmospheric coupling. Consider an initial meridional SST dipole like the one given in the figure. Describe the steps of the WES feedback and classify it as a positive or negative feedback. (Hint: how does the SST dipole affect winds?)



Solution: The SST anomalies shown create a pressure gradient resulting in north-flowing wind. With the Coriolis effect, wind south of the equator would have an easterly component while wind north of the equator would have a westerly component. SE trades strengthen; NE trades weaken. With greater evaporative cooling south of the equator, the negative SST anomaly increases, making WES feedback positive.

END OF EXAM