



USESO 2026

National Open Exam

Section II

Instructions:

- Section II consists of 4 multipart problems that further assess geoscience knowledge in the form of free-response and multiple choice questions.
- A calculator is allowed. Show all work for calculations.
- Any space on the page may be used for scratch paper, but only work on your Answer Sheet will be graded.
- Print your **USESO Student ID** on every page of the Answer Sheet.

Problem 1

Question	1	2	3	4	5	Total
Points	2	3	2	4	4	15 (25%)

This problem will examine melt production and chemistry at mid-ocean ridges (MOR) and subduction-zone oceanic-island-arcs (OIA).

1. (2 points) **Briefly describe** the mechanism and relative depth of magma generation at MORs and at OIAs, respectively.

Solution: At MORs, magma is generated through decompression melting at diverging plates near the surface. At OIAs, volatile addition from the subducting slab causes mantle melting at greater depths than MORs.

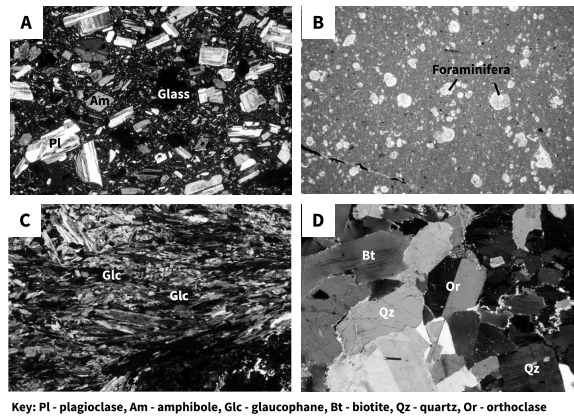
2. Researchers can use the chemical composition of the melt to determine what minerals were settling out of the melt and thus the pressure at which the magma existed.
 - (a) (2 points) Why might researchers examine samples of glass from mid-ocean ridges instead of the basalts that are produced in order to determine the chemical composition of the melt? **Explain.**

Solution: Glasses are homogenous and preserve the chemical composition of the melt, while basalts are composed of minerals that have fixed chemical proportions and differentiate as the lava cools or flows.

- (b) (1 point) Why might glass found at the surface of an OIA be less useful for discerning the chemical composition of the melt source than glass from a MOR? **Explain.**

Solution: Melts erupted at OIAs have experienced higher degrees of chemical contamination and fractional crystallization as they travel to the surface from the original melt source. Thus, it is less representative of the original melt.

3. Shown are four thin sections of rocks formed under different environments, with a selection of minerals labeled. Each sample has a field of view of 7 mm across.



- (a) (1 point) Which thin sections would you expect to be the primary constituent of OIA volcanoes?
- A. A
 - B. B
 - C. C
 - D. D
- (b) (1 point) **Justify** your choice.

Solution: OIAs are expected to be composed of mafic to intermediate volcanic rocks. Choice B contains foraminifera in matrix, indicating sedimentary origins. The alignment of crystals in choice C and the presence of glaucophane are characteristic of metamorphic rocks. Choice D contains large, interlocking crystals found in felsic plutonic rocks. Choice A is most representative of OIA volcanoes as it contains glass and minerals of intermediate composition.

4. As a plate subducts under an OIA, a metamorphic process called eclogitization changes the mineral makeup of the plate to favor mineral phases stable under higher pressures.

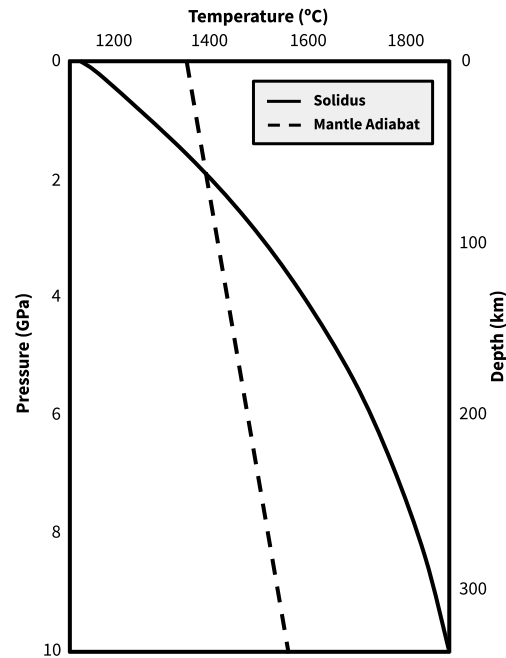
- (a) (2 points) **Explain** how this process can create earthquakes.

Solution: As temperature and pressure increase along a subducting slab, phase transitions cause mineral volumes to decrease, leading to brittle fracture, releasing seismic energy.

- (b) (2 points) How does eclogitization affect the rate of subduction? **Explain.**

Solution: At higher pressures, minerals transition into phases with higher densities. The increased density of the plate increases slab pull and thus the rate of subduction.

5. Consider the graph below illustrating typical mantle conditions. The solid line traces the solidus, the temperature at which the mantle begins to melt under different pressures. The dotted line traces the ideal mantle adiabat, the temperature-depth path followed by mantle material as it moves adiabatically.



- (a) (2 points) Notice that according to the diagram, melting should begin around 2 GPa (~ 70 km depth), where the adiabat intersects the solidus. **Explain** why empirical evidence suggests that the mantle is nearly entirely solid at this pressure.

Solution: The mantle does not actually follow the adiabat as it conductively loses heat to its surroundings, causing the geotherm to cross the solidus at much shallower depths than depicted in the diagram, if at all.

- (b) (2 points) **Describe** how you would expect the solidus beneath an MOR and OIA, respectively, to differ (or remain the same) compared to the typical solidus depicted in the diagram.

Solution: The solidus at MOR's would remain the same as in the diagram. The solidus at OIA's would be shifted to the left, or towards lower temperatures, due to volatiles depressing the melting point.

Problem 2

Question	1	2	3	4	5	Total
Points	2	2	2	5	4	15 (25%)

This problem will explore several phenomena related to atmospheric circulation.

1. Between 30°S and 30°N , energy is moved primarily by convection in the Hadley cell. For each of the following scenarios, **indicate** whether cloud formation near the equator would increase or decrease and **briefly explain** your reasoning.

- (a) (1 point) Increase in sea surface temperature near the equator.

Solution: An increase in sea surface temperature would increase the rate of evaporation which results in an increase in cloud formation.

- (b) (1 point) Increase in explosive volcanic activity near the equator.

Solution: Explosive volcanism releases dust particles that act as cloud condensation nuclei, allowing condensation to occur more easily, increasing cloud formation.

2. Cloud formation can play a significant role in poleward heat transport.

- (a) (1 point) How does condensation during cloud formation affect local atmospheric temperatures? **Explain.**

Solution: Condensation releases latent heat of vaporization into the atmosphere, increasing the local temperature.

- (b) (1 point) Given your answer to (a), how would you expect increased cloud formation near the equator to affect poleward heat transport? **Explain.**

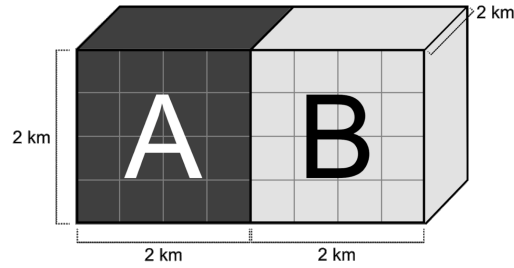
Solution: Since cloud formation warms the surrounding air, the existing circulation would carry more heat per unit mass of air, increasing the magnitude of poleward heat transport.

The primary method of atmospheric heat transport in the mid latitudes is through eddies which form due to baroclinic instability, a condition where air masses of different densities meet and mixing occurs.

3. (2 points) Would you expect the typical latitudinal temperature gradient to be greater along a 900 mb isobaric surface or a 300 mb isobaric surface? **Explain.**

Solution: The 900 mb surface is closer to Earth's surface than the 300 mb surface, resulting in a greater temperature gradient due to latitudinal variations in solar insolation. Large scale mixing is also more effective at smoothing temperature gradients at higher altitudes with less impedance from surface topography.

4. To better understand the thermodynamics of baroclinic instability, we can construct a toy example with two immiscible (cannot mix), incompressible fluids placed adjacent to each other as shown in the figure. Let the density of A be $1 \frac{\text{kg}}{\text{m}^3}$, the density of B be $2 \frac{\text{kg}}{\text{m}^3}$, and the acceleration due to gravity (g) be $10 \frac{\text{m}}{\text{s}^2}$.



- (a) (3 points) **Calculate** the change in gravitational potential energy of the system after it reaches its lowest energy state. *Hint: find and use the center of gravity of the fluids to simplify the calculation.*

Solution: The starting state has the center of masses of the two air parcels at 1 km in altitude which allows us to calculate the gravitational potential energy (GPE) of the initial state as:

$$\text{GPE}_{A\text{-init}} = (2 \text{ km})^3 \cdot 1 \frac{\text{kg}}{\text{m}^3} \cdot 1 \text{ km} \cdot 10 \frac{\text{m}}{\text{s}^2} = 8 \times 10^{13} \text{ J}$$

$$\text{GPE}_{B\text{-init}} = (2 \text{ km})^3 \cdot 2 \frac{\text{kg}}{\text{m}^3} \cdot 1 \text{ km} \cdot 10 \frac{\text{m}}{\text{s}^2} = 1.6 \times 10^{14} \text{ J}$$

$$\text{GPE}_{\text{init}} = 8 \times 10^{13} \text{ J} + 1.6 \times 10^{14} \text{ J} = 2.4 \times 10^{14} \text{ J}$$

At its lowest potential energy state, A floats as a 1 km thick layer above B , leaving the center of gravity of B at a height of 0.5 km and A at a height of 1.5 km. Similarly the potential energy of the final state can be calculated as:

$$\text{GPE}_{A\text{-low}} = (2 \text{ km})^3 \cdot 1 \frac{\text{kg}}{\text{m}^3} \cdot 1.5 \text{ km} \cdot 10 \frac{\text{m}}{\text{s}^2} = 1.2 \times 10^{14} \text{ J}$$

$$\text{GPE}_{B\text{-low}} = (2 \text{ km})^3 \cdot 2 \frac{\text{kg}}{\text{m}^3} \cdot 0.5 \text{ km} \cdot 10 \frac{\text{m}}{\text{s}^2} = 8 \times 10^{13} \text{ J}$$

$$\text{GPE}_{\text{low}} = 1.2 \times 10^{14} \text{ J} + 8 \times 10^{13} \text{ J} = 2.0 \times 10^{14} \text{ J}$$

The difference can then be calculated as:

$$\text{GPE}_{\text{low}} - \text{GPE}_{\text{init}} = 4 \times 10^{13} \text{ J}$$

- (b) (1 point) Now suppose that A and B are perfectly miscible. **Calculate** the new change in gravitational potential energy of the system from its initial state?

Solution: When the two fluids are mixed, the altitude of the center of gravity remains the same as the initial state for both fluids. There is no change in gravitational potential energy. This can also be determined from the following calculation:

$$\text{GPE}_{\text{mixed}} = 4 \text{ km} \cdot (2 \text{ km})^2 \cdot 1.5 \frac{\text{kg}}{\text{m}^3} \cdot 1 \text{ km} \cdot 10 \frac{\text{m}}{\text{s}^2} = 2.4 \times 10^{14} \text{ J} = \text{GPE}_{\text{init}}$$

- (c) (1 point) In the case of part (a) where the two fluids are immiscible, **describe** how the resulting circulation in our model explains the heat transported by the baroclinic instability mechanism.

Solution: In the case of part (a), air mass A will float up on top of air mass B, while air mass B will sink down below air mass A. Taking air mass A to be warm and equatorial and air mass B to be cold and polar, the movement of each air mass into the other's area will cause net poleward heat transport.

5. Climate change is affecting the typical latitudinal heat distribution on Earth and thus Earth's thermal gradients.

- (a) (2 points) Modeling baroclinic instability as we did in 4(a), **describe** the average effect of climate change on meridional circulation in the middle latitudes.

Solution: Climate change tends to warm higher latitudes more than lower latitudes. This would reduce the temperature gradient across the Earth's surface, decreasing the baroclinic instability and therefore decreasing the degree of mixing.

- (b) (2 points) Is the evolution of the planet's heat distribution under climate change due to baroclinic instability a positive or negative feedback loop? **Explain.**

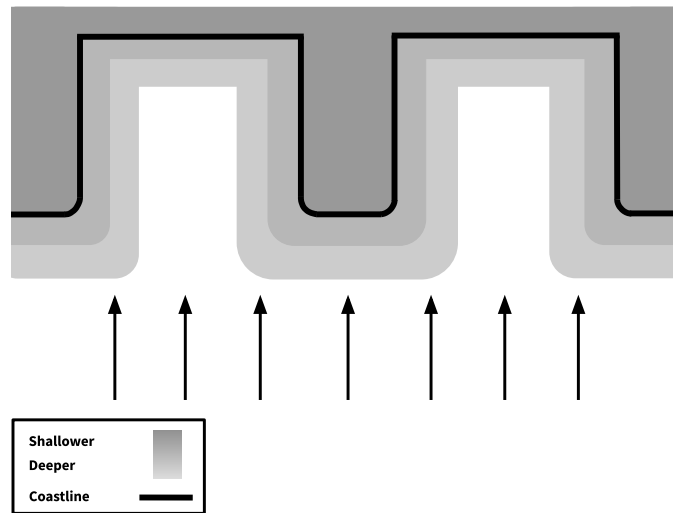
Solution: Lower poleward heat transport would increase the thermal gradient, which works to counteract the asymmetric heating due to climate change. This describes a negative feedback loop.

Problem 3

Question	1	2	3	Total
Points	6	3	6	15 (25%)

This problem will explore several aspects of coastal circulation.

1. Bays and headlands are recessed and jutting features, respectively, formed along a coastline that is undergoing differential erosion. The arrows in the figure below represent the direction of waves approaching the coast.



- (a) (2 points) **Draw** a continuation of each arrow showing how the wave flow patterns would be affected by the bathymetry.

Solution:

Waves undergo shoaling, slowing them down and bending them towards the headlands.

- (b) (2 points) Based on the arrows you drew, would you expect bays or headlands to experience more erosion? Which would you expect to experience more deposition? **Briefly explain.**

Solution: As waves bend toward headlands, their energy is concentrated, leading to increased erosion. Bays are subject to the opposite effect, causing increased deposition.

- (c) (2 points) Considering the influence of bays and headlands on wave patterns, do they exhibit a positive or negative feedback loop with coastline profile in the long run? **Briefly explain.**

Solution: By the erosion and deposition patterns described in part (b), bays and headlands typically evolve towards a flat coastline. Since the formation of bays and headlands encourages their destruction, this is a negative feedback loop.

2. Within certain bays, standing waves may develop. Standing waves, also known as stationary waves, are vertical oscillations of water that appear to slosh up and down within an ocean basin without noticeable lateral movement of crests and troughs. The period for a standing wave in a rectangular bay can be calculated using Merian's formula,

$$T = \frac{4l}{\sqrt{gh}},$$

where T represents the oscillation period, l represents the basin length, h represents the depth of water in the basin, and g is the acceleration due to gravity.

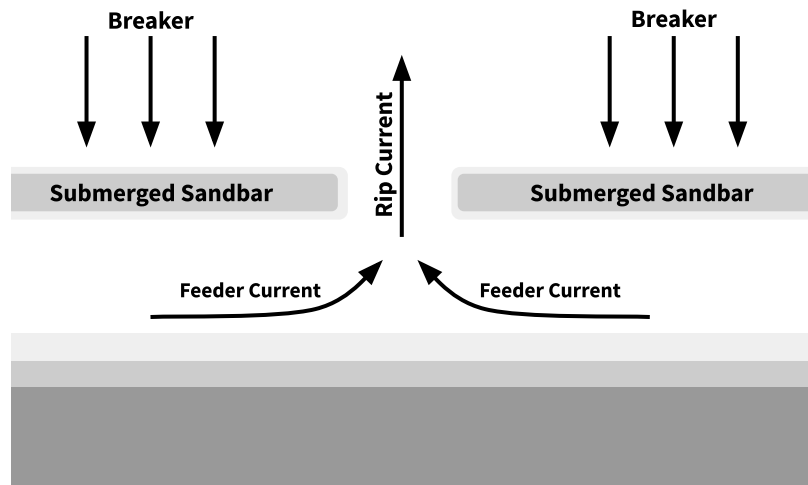
- (a) (1 point) The Bay of Fundy in Canada experiences particularly extreme resonance with semidiurnal tides. Given that a lunar day lasts 24 hours 50 minutes, **identify** the theoretical period of waves in the Bay of Fundy.

Solution: At resonance, the tidal period matches the driving period, in this case the period of semidiurnal tides. Semidiurnal tidal cycles happen twice a day with a period of 12 hours, 25 minutes.

- (b) (2 points) The Bay of Fundy experiences deepening due to erosion from strong tidal currents. Would you expect the amplitude of tides in the bay to increase or decrease over time? **Briefly explain.**

Solution: Since the Bay of Fundy is at resonance, any change in the bay's resonant period will bring it away from resonance, decreasing tidal amplitudes. As bay depth is a factor in the resonant period, changes to the depth will decrease tidal amplitude.

3. Rip currents also play a significant role in coastal erosion. Rip currents are strong, narrow surface currents that return backwash on a shore. The figure below shows a simplified process of their formation.



(a) (2 points) Based on the model described in the figure above, do rip currents tend to increase or decrease the rate of formation of future rip currents? **Briefly explain.**

Solution: Rip currents cut deeper channels into sandbars as they flow out to sea, reducing the resistance to later flow through the channel. This would increase the rate of future rip current formation.

(b) Would you expect rip currents to be relatively strong or weak under the following conditions? **Briefly explain** your answer for each condition.

i. (1 point) Low tide (as opposed to high tide).

Solution: When water levels are low, sandbars act as more effective barriers and trap water on their coastward side. The trapped water then seeks to backwash through the channels between sandbars, strengthening rip currents.

ii. (1 point) Strong onshore winds.

Solution: Strong onshore winds would push more water towards the coast over sandbars. The excess water is then funneled through the channels between sandbars, strengthening rip currents.

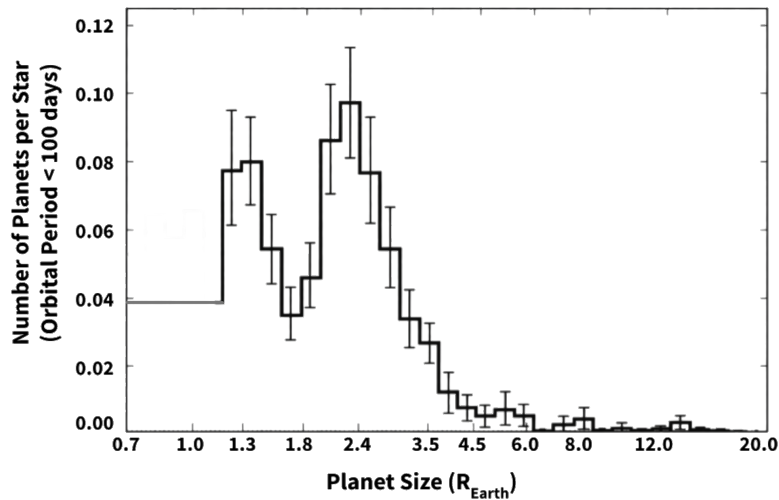
(c) (2 points) Based on the model described in the figure above, are rip currents more likely to form on active or passive continental margins? **Briefly explain.**

Solution: Extensive sandbars are necessary for rip currents to form. As stable regions with low tectonic disturbance have larger sediment accumulations, sandbars and thus rip currents are more likely to form on passive continental margins.

Problem 4

Question	1	2	3	4	5	6	Total
Points	2	2	3	4	3	1	15 (25%)

The “small planet radius gap” or “radius valley” was discovered by the California-Kepler survey of exoplanets in 2017. In this survey, scientists studied tidally-locked exoplanets close to their host stars (period < 100 days) and plotted the frequencies at which they found exoplanets compared to their radius, as shown in the figure below. This problem will explore several features of these exoplanets.



- (2 points) Scientists noticed a dip in the occurrence of radii between 1.5 and 2 Earth radii, which they attributed to the presence or absence of an atmosphere. Would you expect planets with these short periods to be primarily rocky planets or gaseous planets? **Explain.**

Solution: In accretion disks during solar system formation, dense materials that make up rocky planets sink toward the star while lighter materials are pushed towards the margins under radiation pressure. Since these exoplanets are relatively close, they are likely made up of the denser components and are primarily rocky planets.

Scientists have found that these exoplanets frequently evolve from above to below the radius valley.

- (2 points) Current modeling suggests that this evolution happens relatively quickly. If the evolution happened at a slower rate, would you expect the “valley” on the histogram to be shallower or deeper? **Briefly explain.**

Solution: The valley exists because there are relatively few planets observed within the “radius valley”. Since the planets’ transitions from above to below the valley happen so quickly, there is little time in which a planet can be observed in the “radius valley”. If the process were slower, the planets would spend more time at radii between 1.5 and 2 Earth radii and be observed at higher frequencies within the “radius valley”, making the valley shallower.

3. One of the primary explanations for this evolution is the atmospheric photoevaporation hypothesis. Photoevaporation occurs when incident stellar energy heats the top of the atmosphere enough for gas to escape the planet's gravity.

Mass of Hydrogen Molecule (m)	3.32×10^{-27} kg
Mass of Planet (M)	6×10^{24} kg
Planetary Radius (R)	9000 km
Gravitational Constant (G)	$6.67 \times 10^{-11} \frac{\text{Nm}^2}{\text{kg}^2}$

- (a) (2 points) **Derive** the formula for the escape velocity of hydrogen gas, v_{esc} , using the formulas for kinetic energy and gravitational potential energy. **Calculate** v_{esc} , in meters per second, using the values in the table above.

Solution: A particle reaches escape velocity when the kinetic energy of the particle equals the gravitational potential energy:

$$\frac{1}{2}mv^2 = \frac{GMm}{R}$$

Solving for v gives:

$$v = \sqrt{\frac{2GM}{R}} = 9430 \text{ m/s}$$

- (b) (1 point) The root mean squared velocity v_{rms} for hydrogen gas at temperature T Kelvins can be approximated as $112\sqrt{T} \frac{\text{m}}{\text{s}}$. **Calculate** the temperature, in Kelvin, required at the top of the atmosphere in order for a molecule of hydrogen gas moving at v_{rms} to escape.

Solution: Setting the previously found escape velocity equal to v_{rms} gives the temperature required for hydrogen gas to escape:

$$9430 \text{ m/s} = 112\sqrt{T}$$

$$T = 7090 \text{ K}$$

4. Because of the tidally locked nature of these exoplanets, large temperature gradients can develop between their Sun-side and space-side hemispheres.

- (a) (2 points) What general effect would the presence of an atmosphere have on the magnitude of these temperature gradients? **Explain.**

Solution: Because of the heat capacity and high mobility of the atmosphere, circulation of the atmosphere works to redistribute heat from the hot dayside hemisphere to the cold nightside hemisphere. This decreases the temperature gradients.

- (b) (2 points) These temperature gradients can cause an exoplanet to undergo atmospheric collapse, a positive feedback loop in which the atmosphere is deposited onto the planet's cold side as a solid. **Explain** the mechanism behind this feedback loop.

Solution: The atmosphere flows toward the cold nightside hemisphere in order to equalize heat distributions. If the atmosphere begins depositing on this side, the pressure will drop, pulling air from the warm side of the planet. This newly pulled air then also deposits, creating a positive feedback loop.

5. One common method astronomers use to detect thin exoplanet atmospheres is thermal phase-curve analysis. Typically, a planet's brightness is due to a combination of reflection of the host star's light and blackbody radiation. When a planet transits its host star, the reflection component becomes insignificant and the planet appears to dim.

- (a) (2 points) Would you expect a tidally locked exoplanet with an atmosphere to exhibit a smaller or larger drop in observed light compared to a similar exoplanet with no atmosphere? **Explain.**

Solution: As the star transits, the only radiation observed from the planet is blackbody radiation from the nightside hemisphere of the planet. In the presence of an atmosphere, heat can be efficiently redistributed from the hot side to the cold side, making the cold side warmer than it would be without the atmosphere. Via the Stefan-Boltzmann law, this will cause more radiation to be emitted, reducing the drop in observed light.

Note: Real thermal phase-curve analysis uses slightly different reasoning with observations of the whole star-planet system instead of planet only observations.

- (b) (1 point) **Explain** why this method is significantly less useful for detecting atmospheres if the exoplanet is not tidally locked.

Solution: Without tidal locking, there is no permanent day and night side due to rotation.

6. (1 point) Thermal phase curves can also give insight into the behaviors of the atmospheres of exoplanets. What atmospheric pattern explains the stationary Kelvin and Rossby wave response to equatorial heating that shifts thermal hotspots eastward on tidally locked exoplanets?

Solution: Matsuno-Gill pattern.

END OF SECTION II