USESO 2022

Open Exam

Section II - KEY

Instructions:

- Section II consists of 4 multipart questions that further assess geoscience knowledge in the form of free-response and multiple choice questions
- A non-graphing, non-programmable calculator is allowed; show all work for calculations

Note: The free-response solutions given here are example responses that would earn full points. There are other valid responses that may earn full/partial points.

Problem 1

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

Our current understanding of the plate tectonics system is based on an idea of a fractured crust with plates growing and shrinking at boundaries between plates. However it is thought that in the Archaean eon, pressure-temperature conditions were such that the lithosphere was contiguous and did not subduct. Instead the Earth is proposed to have operated through "drip tectonics."

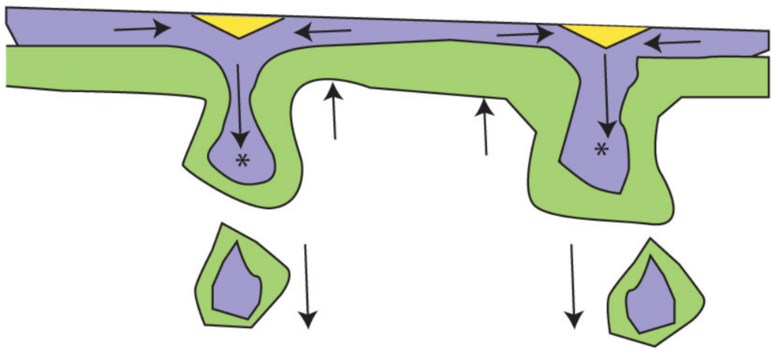


Figure 1: Simplified schematic of drip tectonics.

1. (2 points) Which of the following play a significant role in driving mantle convection?

   I) A large thermal gradient between the upper mantle and the core-mantle boundary

   II) A large compositional gradient between the asthenosphere and the core-mantle boundary

   A. I only

   B. II only

   C. I and II

   D. None

   Solution: Convection occurs due to an unstable density profile, which may be influenced by composition and temperature. Compositional differences exist, but due to the low thermal conductivity of mantle rock, thermal differences are far more pronounced.

2. The mechanisms of drip tectonics may still influence modern lithospheric evolution.

   (a) (1 point) In which of the following modern tectonic environments would a "dripping" lithosphere most likely be present?

   A. Continental orogen

   B. Oceanic hotspot

   C. Continental rift

   D. Mid-ocean ridge

   (b) (2 points) Briefly justify your answer above. How does dripping lithosphere at that tectonic environment influence its future evolution?

   Solution: Continental orogens typically have thick crust with a dense base, which can eventually sink and break off. This can cause isostatic uplift, volcanism, or igneous intrusion by rising asthenosphere.

3. Most preserved surface rocks from the Archaean eon are mafic to ultramafic in composition.
   (a) (1 point) What are two igneous rocks that comprise the majority of these deposits?

   Solution: Basalt and komatiite

   (b) (1 point) Today, intermediate and felsic rock are commonplace on the surface despite the mafic composition of the mantle. Identify all of the following locations in which you'd be likely to find predominantly felsic or intermediate rock.

   I) Continental rift
   II) Oceanic hotspot
   III) Oceanic-continental subduction zone
   IV) Mid-ocean ridge

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

   (c) (3 points) Explain how intermediate and felsic rocks form at the areas you identified in the previous part.

   Solution: Fractional crystallization—mafic minerals crystallize first, so magma gradually becomes more felsic with time. Partial melting and assimilation of continental crust into magma can also make the magma more felsic.

4. The age of Archaean rocks are often found using U-Pb dating in zircon ($ZrSiO_4$) crystals.
   (a) (1 point) Why is zircon a good mineral to analyze for U-Pb dating?

   Solution: Zircon contains uranium impurities when U^{4+} substitutes for Zr^{4+}. Zircon is also relatively hard and chemically inert, making it ideal for dating old rocks.

   (b) (3 points) The U-Pb system has two decay pathways: $^{238}U \longrightarrow {}^{206}Pb$ (half-life = 4.47 Ga) and $^{235}U \longrightarrow {}^{207}Pb$. A zircon crystal is analyzed with a mass spectrometer to determine the concentrations of U and Pb. The following results are obtained:

^{235}U	25.3 ppm
^{238}U	38.9 ppm
^{206}Pb	1.10 ppm
^{207}Pb	4.70 ppm

   Using the experimental data, determine the half-life of $^{235}U \longrightarrow {}^{207}Pb$.

Solution: The age of the zircon crystal can be determined using the $^{238}\text{U} \longrightarrow {}^{206}\text{Pb}$ pathway.

$$t = t_{1/2}\left(\log_{1/2}\frac{[^{238}\text{U}]}{[^{238}\text{U}]+[^{206}\text{Pb}]}\right) = 1.80\times10^{8}\text{ years}$$

The number of half-lives of $^{235}\text{U} \longrightarrow {}^{207}\text{Pb}$, $\tau_{1/2}$, passed during this time is:

$$\log_{1/2}\frac{[^{235}\text{U}]}{[^{235}\text{U}]+[^{207}\text{Pb}]} = 0.246$$

Thus, $\tau_{1/2} = \frac{1.80\times10^{8}\text{ years}}{0.246} = \boxed{7.32\ \times10^{8}\text{ years}}$.

5. (1 point) For each of the following geologic ages, give the corresponding period of which it is a subset: 1) Messinian; 2) Tortonian; 3) Valanginian; 4) Lutetian; 5) Lochkovian.

Solution: This question was not graded.

Problem 2

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

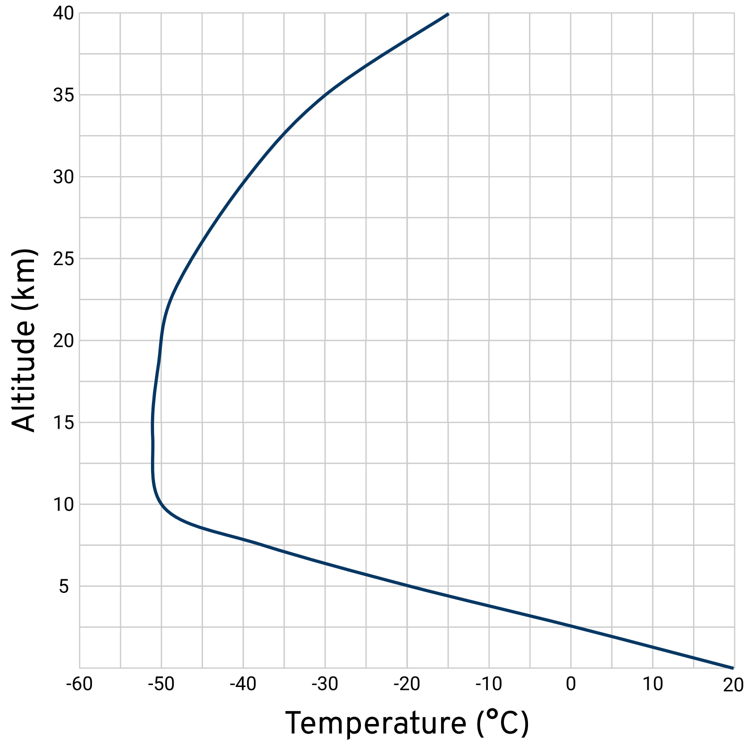


Figure 2a: Atmospheric profile plotting air temperature from the surface to 40 km altitude.

For all of the following questions, assume that the dry adiabatic lapse rate is a constant 10°C/km and the moist adiabatic lapse rate is a constant 6°C/km.

1. (2 points) Which of the following best describes the conditions at the surface?
   - A. Absolutely stable
   - B. Absolutely unstable
   - **C. Conditionally unstable**

Solution: The environmental lapse rate is about 8°C/km, so it is between the dry adiabatic lapse rate and moist adiabatic lapse rate.

2. A volcanic eruption occurs, creating a hot mass of air at approximately 100°C.
   - (a) (1 point) Why would a volcanic cloud never remain unsaturated as it rises?

Solution: By definition, to form a cloud, the air must be saturated for water vapor to come out of the air as water droplets. Volcanoes also release high amounts of water vapor, so there is plenty to saturate the air as it cools.

(b) (2 points) Assume the air parcel becomes saturated immediately after formation. Approximately how high will the volcanic cloud rise?

> **Solution:** About 24.5 km. The line has a slope of -6°C/km and intersects the x-axis at 100°C, so it will reach ambient temperature around 24.5 km.

3. (3 points) In the real world, the air parcel will not remain isolated, and it will be subject to more factors than just adiabatic heating or cooling. If the parcel is always saturated, would the actual cloud height be greater than or less than the predicted height? Why?

> **Solution:** Less. The cloud would lose heat to its surroundings, causing it to cool faster than predicted by adiabatic cooling.

4. (3 points) Would a volcanic cloud likely have a larger or smaller average droplet size than a typical cumulus cloud? Explain.

> **Solution:** Smaller. Sulfur dioxide and sulfate aerosols released from the volcano create an abundance of cloud condensation nuclei, much more than the typical cumulus cloud. This causes the formation of many small droplets.

5. A satellite image of a volcanic eruption and its associated ash cloud is shown below.

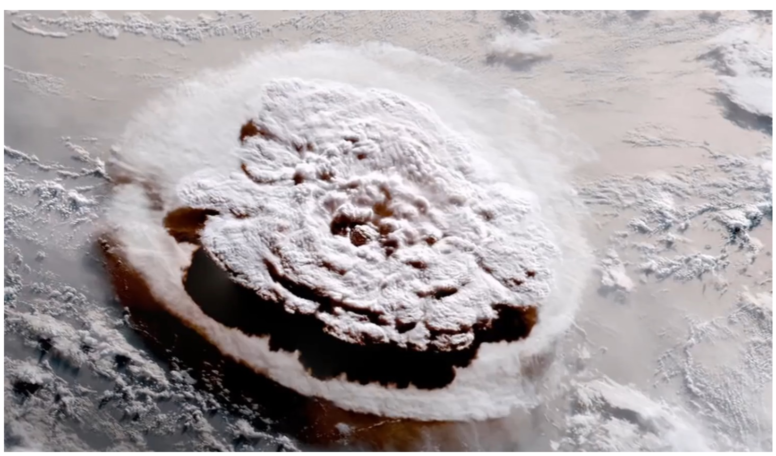


Figure 2b: An ash cloud.

(a) (1 point) Describe the general wind patterns that would be created by a volcanic eruption and a hot volcanic cloud.

> **Solution:** Air at the surface would be drawn inward by the low pressure, upward by the heat, and spread out aloft.

(b) (1 point) How would these wind patterns affect the spread of aerosols, dust, and debris?

> **Solution:** The upward motion would allow some aerosols to spread out in the upper troposphere and stratosphere, although they would eventually fall back to Earth's surface after traveling a significant distance.

(c) (2 points) Briefly describe how the release of volcanic aerosols can influence Earth's radiative balance and the average global surface air temperature.

Solution: Aerosols scatter incoming shortwave radiation—a net negative radiative forcing. This leads to lowered GSAT.

Problem 3

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

The Southern Ocean is special in many regards, though it still remains relatively poorly understood. Here, we will explore several aspects of its circulation.

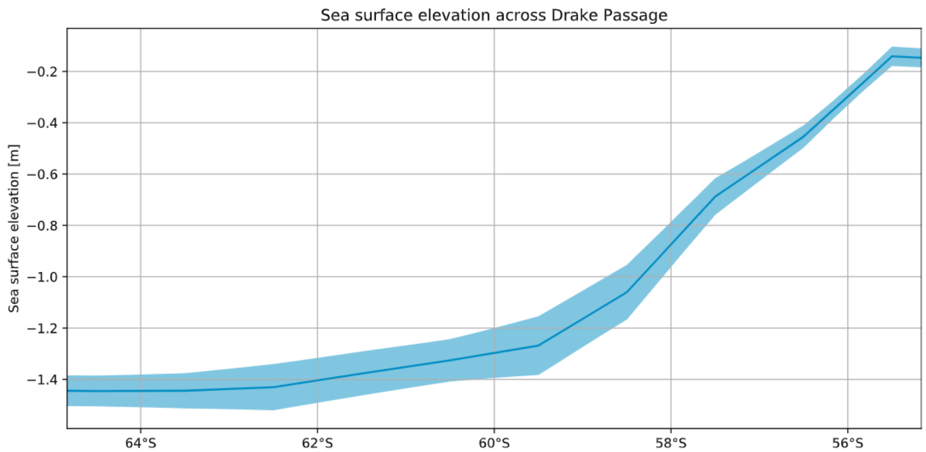


Figure 3a: A north-south transect of the sea surface height (SSH) along the Drake Passage, the narrowest section of the Southern Ocean between Cape Horn and the Antarctic Peninsula (see Figure 3c for a map).

1. The Antarctic Circumpolar Current (ACC) flows through the Drake Passage.

   (a) (1 point) Towards what cardinal direction does the ACC flow?

   Solution: East. Seen in the SSH profile, the pressure gradient force points south, so the Coriolis force must point north for geostrophic balance. Since the Coriolis force deflects towards the left in the Southern hemisphere, the net flow must be east.

   (b) (3 points) At what latitude(s) is the ACC the strongest through the Drake Passage? Justify your answer.

   Solution: The ACC is strongest at 58 °S. We see that the meridional SSH gradient is greatest there; the zonal velocity is proportional to the meridional pressure gradient because the ACC is in geostrophic balance.

2. (3 points) A recent study found that there is a robust trend in the strength of the zonal (i.e., east-west) circulation in the Southern Ocean. They attributed this trend to changes in the ocean's thermal structure, rather than changes in wind.

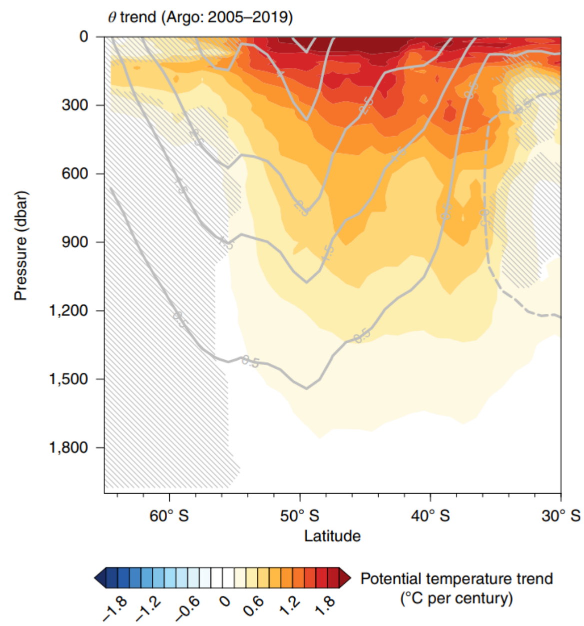


Figure 3b: zonally-averaged potential temperature trend in the Southern Ocean. Disregard the gray contours.

Is the Southern Ocean zonal circulation accelerating or decelerating? (*Hint: how might the spatially-varying temperature forcing shown above lead to a trend in zonal flow?*)

Solution: A geostrophic zonal flow is driven by a meridional pressure gradient. We see that there is a north-south gradient in the temperature trend at about 54 deg S, with strong warming to the north and little to no warming to the south. Across this interface, there is an increasing density gradient (with denser waters to the south), and hence an increasing southward pressure gradient (with higher pressures to the north). This reinforces the existing meridional pressure gradient (as seen in figure 3a); the zonal circulation is accelerating.

3. (3 points) In addition to horizontal circulation, the Southern Ocean also features significant vertical circulation.

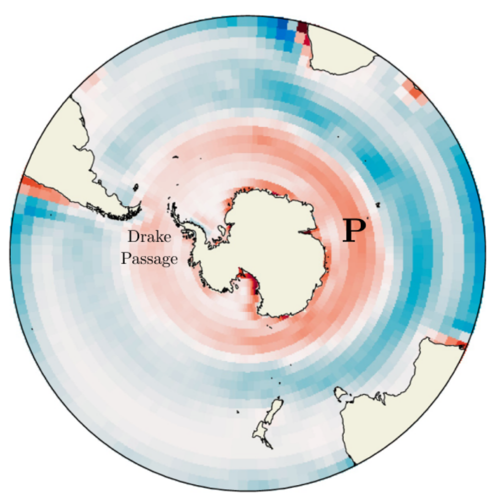


Figure 3c: climatological (1980 to 2017) annual-mean vertical velocities.

Are areas colored red (e.g., at point P) regions of downwelling or upwelling? Justify your answer.

Solution: Red regions are upwelling. The strong polar westerlies, in addition to generating strong zonal flow, also drive a northward Ekman transport. Since the strength of northward Ekman transport drops off near the coast, there is a net Ekman divergence of surface water and upwelling must compensate.

4. The Southern Ocean is also where various water masses are formed.

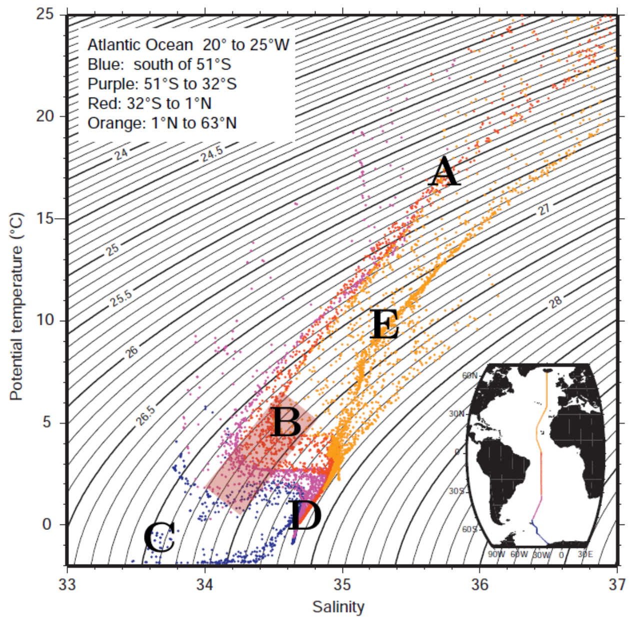


Figure 3d: T-S diagram of water samples (at various depths) along the transect shown in the bottom right.

(a) (1 point) Antarctic Bottom Water (AABW), is a water mass formed in the Southern Ocean. Its formation can be represented as a transformation from an initial water mass. Which two letter sequence best represents AABW formation? (e.g., A $\longrightarrow$ B)

Solution: C $\longrightarrow$ D.

(b) (2 points) Briefly explain how AABW is formed.

Solution: The subfreezing atmosphere and brine rejection from sea-ice formation causes Antarctic surface waters (specifically, in polynyas along the continent) to be exceptionally dense. This water sinks and forms AABW.

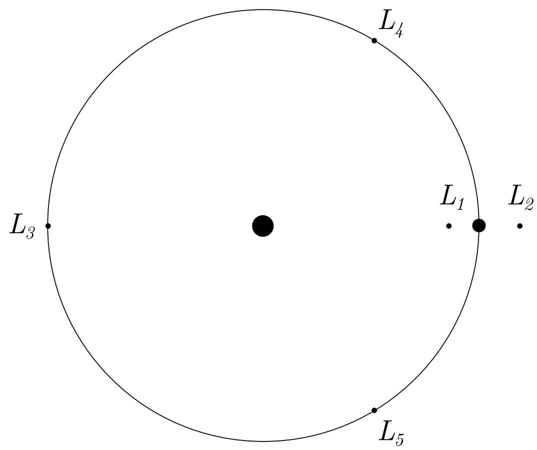
(c) (2 points) In the blue, purple, and red transects, there is a clear salinity minimum (see shaded area). However, it disappears further north in the orange transect. Briefly explain why this is the case.

Solution: The salinity minimum is associated with a single water mass that forms in the Southern Ocean and travels northward in the Atlantic. Further extension is impeded by a warmer, saltier water mass.

Problem 4

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

Lagrange points are five equilibrium points for a small mass in a two-body system (shown below). The Jupiter trojans are a group of asteroids that share Jupiter's orbit around the Sun. The trojans librate around Jupiter's Lagrange points L_4 and L_5, 60 degrees ahead and behind the planet's orbit, respectively.



1. (2 points) Trojans have a wide range of possible diameters, the largest observed being 203 km. For those within 4.4 to 40 km, their size distribution is similar to the size distribution of the asteroid belt. What is a likely explanation of how these smaller trojans formed?

Solution: Given a similar size distribution, trojans likely formed similarly to main-belt asteroids—namely, collisions between larger asteroids.

2. (2 points) For this question, we will assume that Jupiter trojans do not librate around their Lagrange point; rather, they are stationary relative to L_4 and L_5. Which of the following is true about the planetary phase of Jupiter when viewed from trojan asteroids?

   A. Jupiter is gibbous as seen from L_4 trojans and crescent as seen from L_5 trojans

   B. Jupiter is crescent as seen from L_4 trojans and gibbous as seen from L_5 trojans

   C. Jupiter is gibbous as seen from both L_4 and L_5 trojans

   D. Jupiter is crescent as seen from both L_4 and L_5 trojans

   E. Jupiter's phase seen from the trojans is time-varying

Solution: The position of L_4 and L_5 remain constant relative to Jupiter throughout its orbit. Seen from both L_4 and L_5, about 67% of Jupiter is lit by the Sun, so it is gibbous.

3. It is exceptionally difficult to observe Jupiter trojans due to their small size and low albedo. Consider a hypothetical trojan T located at L_4 with an albedo of 0.05 and a radius of 5.0 km.

Apparent magnitude of Sun ($m_\odot$)	-26.74
Semi-major axis of Jupiter (a_J)	5.2 AU
1 AU	1.496×10^8 km

(a) (1 point) Describe the orbital configuration in which T will be the brightest (i.e., minimum apparent magnitude) as observed from Earth.

Solution: T is brightest when the Earth is between T and the Sun (opposition), such that the distance between Earth and T is minimized.

(b) (4 points) Calculate the minimum apparent magnitude of T as seen from Earth. (Hint: $m - n = 2.5\log(f_n/f_m)$, where m and n are two apparent magnitudes and f_m and f_n are their respective fluxes). **Show your work**.

Solution: We need to find the radiative flux of T, f_T, as seen from Earth. Qualitatively, f_T is the luminosity of T (which itself is due to reflection of sunlight) divided by the surface area over which T radiates (which is the surface area of a sphere with radius spanning from T to Earth). Expressing this mathematically, we have:

$$f_T = \alpha \pi r^2 \frac{L_\odot}{4\pi a_J^2} \left(\frac{1}{4\pi (a_J - a_\oplus)^2} \right)$$

Where $L_\odot$ is the solar luminosity, α is the albedo, and r is the radius of T. Since the magnitude scale is relative, we need the Sun for reference. The radiative flux of the Sun as seen from Earth is:

$$f_\odot = \frac{L_\odot}{4\pi a_\oplus^2}$$

Hence,

$$m_T = 2.5 \log \left(\frac{f_\odot}{f_T} \right) + m_\odot = 2.5 \log \left(\frac{4 a_J^2 (a_J - a_\oplus)^2}{\alpha r^2 a_\oplus^2} \right) + m_\odot$$

Plugging in numbers we get $\boxed{m_T = +22.1}$.

4. (2 points) Similarly, Mars has trojan asteroids that congregate around L_4 and L_5 of its system with the Sun. A new study hypothesizes that Mars' trojans are Martian ejecta; thus, the asteroids are likely:

   A. Rich in olivine

   B. Smoothly shaped

   C. Relatively young

   D. Slow-spinning

Solution: Much of Mars is covered with remnants of volcanic activity and impacts. Olivine is very rarely found in asteroids but common in Martian impact basins, suggesting that the trojans were once part of the planet. Past volcanic activity indicates that the asteroids must be quite old for olivine to crystallize within them. Due to their age, solar heating has significantly spun up the asteroids, increasing their rotation rates.

5. (4 points) Satellites are also uniquely positioned in order to have certain orbital characteristics with their main bodies. What *elevation* above Earth's surface would a 1,000 kg satellite orbit in order to have a geosynchronous orbit? The mass and radius of the Earth are $M_\oplus = 6.0 \times 10^{24}$ kg and $R_\oplus = 6.4 \times 10^3$ km, respectively. The gravitational constant $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. **Show your work.**

Solution: Since the period of a geosynchronous orbit is 24 hours, we can use Kepler's third law to find the elevation.

$$\frac{a^3}{T^2} = \frac{GM_\oplus}{4\pi^2}$$

Rearranging, the semi-major axis is:

$$a = \sqrt[3]{\frac{GM_\oplus T^2}{4\pi^2}}$$

Plugging in numbers (note that we need to convert 24 hours to seconds), we get that the semi-major axis $a = 4.2 \times 10^4$ km. The elevation h is $a - R_\oplus$. We find that the elevation of geosynchronous orbit is about $\boxed{3.6 \times 10^4 \text{ km}}$.