

1. Greenhouse Gases (50 pts: 10, 10, 20, 10)

a) What are the two greenhouse gases with the highest atmospheric concentration? Give the type of radiation that they absorb.

H_2O , CO_2 . A greenhouse gas absorbs infrared radiation.

b) What is the albedo of the Earth? Give a description and an approximate value. Give an example of a man-made change to the cloud albedo.

The albedo is the amount of incoming solar radiation that is reflected by the Earth, including by clouds, aerosol and surface. The current value is estimated to be 31%. An example of a man-made change to cloud albedo is ship tracks.

c) For the albedo estimated in (b), and neglecting greenhouse gases, what is the estimated temperature of the Earth? State your assumptions.

If we assume the Earth acts as a blackbody, the atmosphere is in radiative equilibrium, the albedo reflects 31% of incoming solar radiation, and the atmosphere is transparent to incoming solar radiation, then the global mean surface temperature is given by:

$$F_S = F_L$$

$$0.25 * S_0(1 - \alpha_p) = s T_e^4$$

$$T_e = [0.25 * S_0(1 - \alpha_p) / s]^{0.25} \sim 255K$$

d) How will greenhouse gases affect the temperature calculated in (c)?

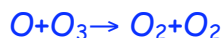
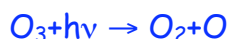
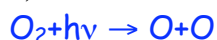
Greenhouse gases absorb infrared radiation emitted by the Earth, and re-emit it to warm the Earth's surface by more than 30K compared to the calculation in (c) without an atmosphere.

2. Stratospheric Ozone (50 pts: 10, 20, 10, 10)

a) What is the name of the set of reactions that control O_3 formation and destruction in the stratosphere?

The Chapman cycle describes the four steps by which O_2 is photolyzed to produce O atoms and O_3 , which can then be photolyzed to recover O_2 .

b) Write the four reactions named in part (a).



c) What three factors are needed to calculate the *rate constants* for the photolysis reactions in part (b)? Which of these factors varies most with altitude? Why?

Photolysis rate constants are calculated from quantum yield, absorption cross-section, and photon flux. Photon flux varies most with altitude because light absorbed higher in the atmosphere does not penetrate to lower levels of the atmosphere, e.g. UV light is higher above the ozone layer.

d) What is the typical concentration of ozone in the ozone layer?

Ozone has a concentration of up to 5-10 ppmv in the ozone layer.

3. Ozone Hole (60 pts: 10, 20, 10, 20)

a) What anthropogenic emissions cause the formation of the ozone hole?

The ozone hole describes the depletion of the stratospheric ozone layer at the Arctic and Antarctic poles by CFCs.

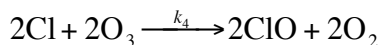
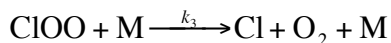
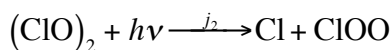
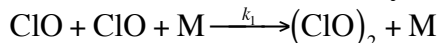
b) Describe the five steps required for the formation of the ozone hole.

1. Polar vortex transports HCl, ClO and ClONO₂ produced by photolysis at 25km.
2. Stratospheric ice (<-80°C) forms PSCs.
3. HCl and ClONO₂ make Cl₂ on PSC particles.
4. Cl₂ + sunlight makes Cl.
5. Cl, ClO catalyzes O₃ destruction to O₂.

c) Write the mechanism responsible for 25% of ozone loss in the ozone hole. Name the catalyst.



d) State the net reaction for the cycle below. What role does it play in the ozone hole?



Assuming that the concentrations of Cl, ClOO, and (ClO)₂ are in steady state, write an expression for the concentration of Cl in terms of the concentrations of ClO, O₃, and M and the constants k₁ and k₄.

$$[\text{Cl}] = (2k_1[\text{M}][\text{ClO}]^2) / (k_4[\text{O}_3])$$

4. Atmospheric Composition and Sources (40 pts: 10, 10, 10, 10)

a) Name the five most abundant components of the atmosphere.

N₂, O₂, Ar, H₂O, CO₂.

b) Give the volumetric percentage of the top two most abundant components.

78% N₂, 21% O₂.

c) Which of the five major components has the most variable composition? Describe the difference in its concentration in the troposphere and stratosphere.

H₂O is the most variable. The stratosphere is very dry and has <1% H₂O. The troposphere has up to 4% H₂O.

d) Which of the seven types of processes (biogenic, anthropogenic, volcanic, sea salt, radiogenic, lightning/meteorological, photochemical) produce emissions from biological sources of (i) N₂O; (ii) CO₂; (iii) CFCs? Name *at most* two of these process types that have the largest contributions for each compound.

(i) anthropogenic and biogenic; (ii) biogenic and anthropogenic; (iii) anthropogenic only.