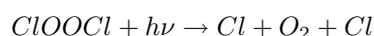


Stratospheric Ozone Depletion

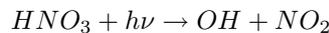
- An ozone hole is observed over Antarctica.
 - Particularly prominent at the polar sunrise.
- Ozone thinning is also observed over the Arctic.
- The Antarctic region can be characterized by:
 - Large land mass
 - Stable long-lived air circulation pattern
- The Arctic region can be characterized by:
 - Water and islands
 - Unstable air circulation.
- The mechanism of ozone depletion over Antarctica is currently understood to involve the following factors.
 - In the winter, a polar vortex develops.
 - This vortex is stable and the air in it is relatively isolated from the rest of the stratosphere.
 - Therefore photochemically active products build up over the winter.
 - During the winter, in the absence of sunlight, the gases in the stratosphere cool radiatively. This means that they sink to below about 30 km altitude.
 - This part of the stratosphere contains about 5 ppm water.
 - The water freezes into polar stratospheric clouds (PSC) as the winter progresses.
 - In addition, other species such as HCl, HNO₃, H₂SO₄ and other reservoir species also freeze out or stick to the surface of ice crystals.
 - The stability of the PSC's is enhanced by the stability of the polar vortex over the land mass.
 - In the late winter the clouds are at their coldest.
 - Crystals of HNO₃·3H₂O form at -70°C and water crystals form at -85°C.
 - The crystals in the PSC's provide sites for heterogenous catalysis later.
- Recall that in the dark, the Chapman Cycle has halted because no photons are available.
 - No ozone is formed over the winter, but collisional depletion of ozone continues.
 - Depletion of ozone enhanced by the catalytic breakdown of ozone depleting reservoir species.
- In the late winter and early spring, ClONO₂ and HCl are broken down on crystals in the polar stratospheric clouds to form Cl₂ and HOCl, both of which can be photolyzed by visible and near-visible ultraviolet light.
 - This results in chlorine which can catalytic destroy ozone.
- As soon as the photons are available, ClOOCl photolyzes, producing two Cl atoms.



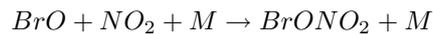
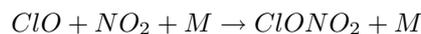
- In the early polar sunrise, the rate of ozone destruction increases, but photons with enough energy to run the Chapman cycle are not yet available.
- Later in the spring, more photons are available and the rate of ozone formation increases.

Arctic Ozone Depletion

- In the Arctic, polar stratospheric clouds are not as long lived.
 - Average winter temperatures are not as cold.
 - When PSC's do form, unstable weather patterns break them up.
- The Arctic polar vortex is less isolated from external air, so there is more mixing of the air.
 - Photochemically active species do not accumulate.
 - Arctic depletion is not as extensive because there it is offset by tropospheric injection of ozone into the stratosphere over the winter.
- Because PSC's are not as common, HNO₃ stays in the gas phase.
 - It can photolyze generating NO₂:



- NO₂ can react with ClO and BrO to form the corresponding nitrates



In these forms they cannot contribute to O₃ depletion.

- Br from Halons is implicated in Arctic ozone depletion.
- Observed Arctic ozone depletion is of the order of 10-30%.

Consequences of Ozone Depletion

- Greater penetration of UV into the troposphere.
 - UV-A (320-400 nm) increased over natural tropospheric levels.
 - UV-B (290-320) increased over natural tropospheric levels.
 - UV-C (< 290) does not naturally penetrate to the troposphere, but as a consequence of O₃ thinning is now getting through.
- UV-C can damage the DNA repair mechanism.
 - Can cause mutations.
 - Can lead to skin cancer.
 - Can cause death of microorganisms and plankton.

Global Cycles

- Your package includes diagrams from:
 - Brasseur
 - Manahan
 - Safe (unpublished)
- Will consider global cycles for:
 - Energy
 - Water (Hydrologic cycle)

- Carbon
- Nitrogen
- Oxygen
- Phosphorous
- Sulphur
- All these cycles are coupled:
 - To each other
 - To anthropogenic impacts
 - To climatic impacts

Energy Cycle

- The two main sources of energy are:
 - The Sun
 - The Earth
- Each of these may be treated as a blackbody radiator:

$$\rho(\lambda; T)d\lambda = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} d\lambda$$

- This integrates to:

$$\int_0^\infty \rho(\lambda; T)d\lambda = \frac{8\pi^5 (kT^4)}{15 (hc)^3} = \eta T^4$$

- Radiation from the sun that reaches the earth is insolation and is expressed as radiative flux in units of W m^{-2} where $1 \text{ W} = 1 \text{ J s}^{-1}$
 - Energy flux intercepted by the earth is 1370 W m^{-2}
 - Energy flux captured by the earth is 342 W m^{-2}
- The energy cycle is coupled to the hydrologic cycle by the thermal properties of water.
 - Water requires energy to undergo phase transitions.

$$\Delta H_{fus} = 6.008 \text{ kJ mol}^{-1}$$

$$\frac{C_p(l)}{R} = 12.16 - 1.943 \times 10^{-2}T + 3.042 \times 10^{-5}T^2$$

$$\Delta H_{vap} = 40.66 \text{ kJ mol}^{-1}$$

$$C_p(g) = 33.59 \text{ J mol}^{-1} \text{ K}^{-1}$$

- The energy cycle is coupled to the carbon cycle by:
 - Photosynthesis (which is also essential for nitrogen and phosphorous fixation.
 - Burning of fossil fuels.
- Sources of energy are well-defined
 - Sun and earth
- Sinks of energy include:

- Photosynthesis
- Thermal absorption
- Chemical

- Mechanical
- Reflection
- Scattering
- The atmosphere has a significant role in the energy cycle because it is where absorption and scattering occur.

Water Cycle (or Hydrologic cycle)

- In the energy cycle we have already discussed the thermodynamic properties of water.
 - Because of these thermodynamic properties, water acts as a thermal buffer, especially at temperatures near the freezing point.
- Examination of a phase diagram for water indicates the temperature and pressure for coexistence of phases.
 - It is from this diagram that relative humidity, dew point and frost point may be determined.
 - For a given T , the relative humidity is:

$$\frac{P_{actual}(H_2O)}{P_{equilibrium}(H_2O)}$$

- The dew point or the frost point is the temperature at which the ambient $P(H_2O)$ becomes the $P_{equilibrium}(H_2O)$
- As a saturated air mass cools it must lose water by precipitation.
- Reservoirs and fluxes for the hydrologic cycle include:

Reservoir	10^6 km^3	Fluxes
Ground water	8	precipitation
Surface water	0.1 (Lakes) 0.1 (Salt lakes) 0.001 (Rivers)	evaporation
Snow & Ice		transpiration.
Clouds & Vapour	0.013	cloud momentum
Oceans	1350	run off
Glaciers & icecaps	29	movement of moist air
Soil Moisture	0.07	

- The hydrosphere is defined as where water is found.
- The lithosphere is defined as the portion of the geosphere that is accessible to water.
- Water is a significant factor in human history.
 - Denial of access to water is a tool of war, siege, and oppression.
 - Movement of nomadic peoples often correlated with the availability of water.
 - Presence of water is a significant factor in human settlement patterns.
 - Increasing important issue in international trade.
- Water is an economic factor for:
 - Transport
 - Coolant
 - Raw Material
- Anthropogenic impacts on water include:
 - Contamination
 - Warming
 - Salinization

Impact of Water Usage

- For the United States of America
 - Precipitation is 1.48×10^{13} L day⁻¹
 - Evaporation is 1.02×10^{13} L day⁻¹
 - which leaves 4.6×10^{12} L day⁻¹
- Daily usage in the USA has evolved with time:

Usage	L day ⁻¹	L day ⁻¹ capita ⁻¹ (Domestic Use)
2002		1200
1990	1.6×10^{12}	600
1900	1.7×10^{11}	40

- This usage breaks down as:
 - 46 % agricultural
 - 46% industrial
 - 8% municipal
- The impact of this usage has caused:
 - The depletion of the Ogallala aquifer
 - Salinization of irrigated soils
 - Desertification

- Deterioration of water quality
- Precipitation is irregularly distributed.
 - Linked to terrain and energy transfer.
- The likelihood of precipitation is linked to the thermal lapse rate.

$$\text{Lapse Rate} = \frac{\Delta T}{\Delta h}$$

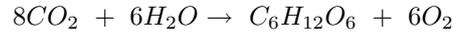
where h is altitude.

- Warm air rises and cools.
- For dry air undergoing an adiabatic expansion, the lapse rate is 10° C/km .
- For moist air undergoing an adiabatic expansion, the lapse rate is 6° C/km .
- The difference is due to the heat capacity of water.
- The difference in lapse rates can contribute to the forming of thermal inversion as wet air moves over dry air.
- Inversions occur when warm air rest on top of cooler air.
 - Traps vertical circulation patterns.
 - Decreases mixing volumes for ground level emissions.
- Inversions can also be caused by the difference in the heat capacity of air and ground.
 - These are radiation inversions.
- Another type of inversion is a subsidence inversion when high air drops, compresses, and warms.
- Marine inversions are due to the difference in heat capacity of the ocean and land.
 - Land warms more rapidly than ocean.
 - Cool air from the ocean moves under the warmer air originally over the land mass.

The Carbon Cycle

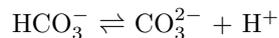
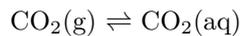
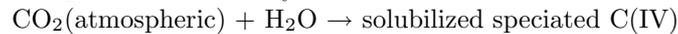
- Consider the oxidation states of carbon.
 - The range of oxidation states is determined by the ground state electronic configuration of the C atom, $1s^2 2s^2 2p^2$.
 - Carbon must either gain four electrons or lose four electrons to have a closed shell configuration.
 - Range of oxidation states is therefore +4 to -4.
- Some examples of oxidation state of carbon:
 - CO_2 is in oxidation state +4.
 - CO is in oxidation state +2.
 - HCO is in oxidation state +1.
 - H_2CO , $\text{C}(\text{graphite})$, $\text{C}(\text{diamond})$ are in oxidation state 0.
 - C_2H_2 is in oxidation state -1.
 - C_2H_4 is oxidation state -2.
 - CH_3 is in oxidation state -3.

- CH₄ is in oxidation state -4.
- Carbon fixation puts carbon into biologically available forms.
 - Photosynthesis uses 8 photons to drive the reaction:



which requires 2801.3 kJ per mole of glucose (467 kJ per mole of carbon).

- Photosynthesis is coupled to the energy cycle by the phosphorous cycle.
- The CO₂ cycle is coupled to the hydrologic and energy cycle.
 - Before 1800, the level of atmospheric CO₂ was about 280 ppm.
 - The 1800's saw the beginning of the industrial revolution and increased use of fossil fuel.
 - In 1994, atmospheric CO₂ was observed to be 358 ppm.
- The global budget of CO₂ has not been fully determined.



- CO₃²⁻ precipitates and is incorporated into shells of aquatic animals such as coral.
- Organic carbon comprises oxidation states 0 to -4.
 - Living organic carbon may be represented as {CH₂O}
 - Fossil organic carbon is reduced and may be represented as (CH₂)_nH₂ and is produced by biogeochemical processes.
- Reservoirs of organic carbon include:
 - Oceans with 5.8 × 10¹⁴ moles of carbon in biomass, 5 × 10¹⁵ moles C as suspended {CH₂O} particles, 5.8 × 10¹⁶ moles C as dissolved organic carbon.
 - By comparison, oceans contain 3.2 × 10¹⁸ moles of C as C(IV).
 - On land, 4 × 10¹⁶ moles C is found in living biomass with a residence time of 16 years.
 - On land, living and dead biomass combined account for 1 × 10¹⁷ moles of C with a residence time of 40 years.
- The atmosphere provides a reservoir for a number of carbon containing species.

ppm	Species	mol C	τ
1.7	CH ₄	5.2 × 10 ¹⁴	3.6 yrs
0.1	CO	1.9 × 10 ¹³	0.1 yr
360	CO ₂	5 × 10 ¹⁶	4 yr

- In addition the atmosphere contains smog (smoky fog) and carbon containing particulates (such as soot) which account for 2.9 × 10¹⁴ mol of C.

- The atmospheric reservoirs are coupled to the biomass cycle.
- Recent sediments under the ocean are also significant reservoirs for carbon.
 - 50.8×10^{20} mol of C as CO_3^{2-}
 - 10.4×10^{20} mol of C as $\{\text{CH}_2\text{O}\}$
 - Both of these have a lifetime 342 years.
- Sources for recent sediments are in the form of:
 - 6.1×10^{12} mol C yr^{-1} as $\{\text{CH}_2\text{O}\}$
 - 11.8×10^{12} mol C yr^{-1} as CO_3^{2-}
- Sinks for recent sediments consist of transfer to old sediments (burial):
 - 2.5×10^{12} mol C yr^{-1} as $\{\text{CH}_2\text{O}\}$
 - 15.4×10^{12} mol C yr^{-1} as CO_3^{2-} in the form of CaCO_3 and MgCO_3
 - These sinks are balanced by transfer from old to recent sediments.
- Anthropogenic activity extracts 3.88×10^{12} mol C yr^{-1} as fossil fuel.
 - This is a net loss.

Nitrogen Cycle

- Consider the oxidation states of nitrogen.
 - The range of oxidation states is determined by the ground state electronic configuration of the N atom, $1s^2 2s^2 2p^3$.
 - Nitrogen must either gain three electrons or lose five electrons to have a closed shell configuration.
 - Range of oxidation states is therefore +5 to -3.
- Some examples of oxidation state of nitrogen:
 - NO_3^- and N_2O_5 are in oxidation state +5.
 - NO_2 is in oxidation state +4.
 - N_2 is in oxidation state 0.
 - NH_3 and NH_4^+ are in oxidation state -3.
- Nitrogen is essential to amino acids.
- The atmosphere is the main reservoir of nitrogen:
 - Contains 3.9×10^{18} N
 - 78% of the atmosphere
 - $\tau \sim 10^7$ years
- In order to be biologically available, N must be fixed.
 - 2×10^{11} kg N fixed a year.
 - Anthropogenic fixation accounts for 5×10^{10} kg N y^{-1} .
- Biological fixation of nitrogen is coupled to the carbon cycle.



- If the pH is sufficiently high, NH_3 is released.
- Fixation of nitrogen may be considered from a redox perspective:

$$\text{N}_2 + 8\text{H}^+ + 6\text{e}^- \rightarrow 2\text{NH}_4^+$$

$$\{\text{CH}_2\text{O}\} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{e}^-$$
- Biological fixation occurs with
 - Aquatic organism such as Azobacter, Clostridium, and Cyanobacter (formerly known as bluegreen algae).
 - Terrestrial organism Rhizobium in symbiosis with legumes (peas, beans, peanuts). The Rhizobium infect root hairs to draw on the legumes organic carbon from photosynthesis.
- Not enough nitrogen is fixed annually to satisfy the current biomass requirements.
- Anthropogenic fixation occurs by the Haber Process:

$$\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$$
 - The process is catalyzed by Fe, K_2O , and Al_2O_3
 - The process is endothermic with $\Delta H = 92.6 \text{ kJ mol}^{-1} \text{ N}_2$.
 - Used to form NH_4NO_3 for fertilizer and explosives.
- Organically bound N occurs in humus ($\text{N}/\text{C} \approx 1/10$) and can be released on a time scale similar to that of plant growth.
- Nitrification is the process of transforming N(-3) to N(+5):
 - From a redox perspective:

$$\text{NH}_4^+ + 3 \text{H}_2\text{O} \rightarrow \text{NO}_3^- + 10 \text{H}^+ + 8 \text{e}^-$$

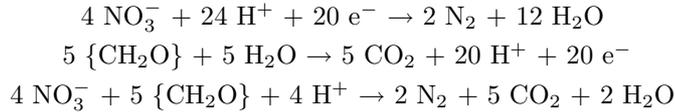
$$4 \text{H}^+ + 4 \text{e}^- + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}$$

$$\text{NH}_4^+ + 2 \text{O}_2 \rightarrow \text{NO}_3^- + \text{H}_2\text{O} + 2 \text{H}^+$$
 - Nitrification is a thermodynamically favoured process with $K = 10^{60.72} = 5.25 \times 10^{60}$.
- NO_3^- may be absorbed by plants.
- Nitrification can occur naturally as a two step process mediated by bacteria:
 - $\text{NH}_4^+ \rightarrow \text{NO}_2^-$ is mediated by nitrosomonas.
 - $\text{NO}_2^- \rightarrow \text{NO}_3^-$ is mediated by nitrobacter.
 - Both are obligate aerobes that require O_2 for the oxidation process.
 - This is why aeration of soil is important.
- NO_3^- may act as an oxygen source for anaerobes.
 - Do not want nitrification to occur during sewage treatment because of subsequent denitrification.
- Thunderstorms may contribute to the production of NO_3^- .

$$\text{N}_2 + \text{O}_2 \rightarrow 2\text{NO}$$

$$\text{NO} \rightarrow \dots \rightarrow \text{HNO}_3$$
 - HNO_3 is scavenged efficiently by cloud droplets.
- Decay of biomass leads to the mineralization of nitrogen in the form of NO_2^- and NO_3^- .
- Denitrification is the removal of nitrogen from the biologically available forms.
 - Returns N_2 to the atmosphere.

- Involves the reduction of NO_3^- and the oxidation of NH_3 .
- Reduction of NO_3^- produces N_2O and NO , both of which are greenhouse gases.
- If reduction of NO_3^- occurs during sewage treatment, it is undesirable.
- Denitrification can also occur during sewage treatment:



- N_2 and CO_2 bubbles are formed and prevent settling.

Phosphorous Cycle

- Consider the oxidation states of phosphorous.
 - The range of oxidation states is determined by the ground state electronic configuration of the P atom, $1s^2 2s^2 2p^6 3s^2 3p^3$.
 - Phosphorous must either gain three electrons or lose five electrons to have a closed shell configuration.
 - $3d$ orbitals available for contribution expanded octet configurations.
 - Range of oxidation states is therefore +5 to -3.
- Some examples of oxidation state of phosphorous:
 - PH_3 is in oxidation state +3
 - PO_4^{3-} , HPO_4^{2-} , H_2PO_4^- , H_3PO_4 and associated polyphosphates are in oxidation state +5.
- In many cases, P is the limiting element in biological uptake.
 - C:N:P are taken up in the ratio 100:15:1
 - P is essential to ADP and ATP in organisms.
- The primary reservoir is the geosphere as various forms of phosphate.
 - There is no gas phase reservoir for P.
 - The solubility of phosphates is strongly pH dependent.
- Phosphates in the geosphere include insoluble mineral forms of phosphate:
 - Hydroxyapatite is very insoluble ($K_{sp} = 10^{-59} \text{ M}^9$)

$$\text{Ca}_5(\text{PO}_4)_3\text{OH} \rightleftharpoons 5 \text{Ca}^{2+} + 3 \text{PO}_4^{3-} + \text{OH}^-$$
 - Hydroxyapatite is also found in tooth enamel.
- Occluded phosphorous is not biologically available.
 - Soil contains Fe_2O_3 and Al_2O_3 and aluminosilicates.
 - The associated hydrates form an amorphous matrix, with orthophosphate (monophosphate) contained within the matrix.
- Non-occluded phosphorous is primarily in the form of orthophosphate bound to surface silicate (SiO_2) or CaCO_3 .
 - Depending on pH, this is more soluble than occluded phosphorous

- Anthropogenic environmental impact of phosphorous compounds is of most concern in aquatic reservoirs.
 - Soluble forms of phosphate include orthophosphate, linear polyphosphate ($P_3O_{10}^{5-}$) and cyclic polyphosphates ($P_3O_9^{3-}$)
- Solubility of phosphates are closely connected to their speciation.
 - Consider rock phosphate, $Ca_3(PO_4)_2$, which has a $K_{sp} = 10^{-24} M^5$

$$Ca_3(PO_4)_2 \rightleftharpoons 3 Ca^{2+} + 2 PO_4^{2-}$$
 - This equilibrates with HPO_4^{2-} and $H_2PO_4^-$ in according with pH, the above K_{sp} and K_{a1} , K_{a2} , and K_{a3} .

$$H_3PO_4 \rightleftharpoons H_2PO_4^- + H^+; K_{a1} = 7.5 \times 10^{-3} M$$

$$H_2PO_4^- \rightleftharpoons HPO_4^{2-} + H^+; K_{a2} = 6.2 \times 10^{-8} M$$

$$HPO_4^- \rightleftharpoons PO_4^{3-} + H^+; K_{a3} = 4.8 \times 10^{-13} M$$
 - Solubility of $CaHPO_4$ and $Ca(H_2PO_4)_2$ can be calculated from the above reactions.
 - It is the protonated forms that are effective for biological uptake.
 - Phosphate for fertilizer is prepared by mixing sulphuric acid with rock phosphate.
- Anthropogenic impact on P levels is due to:
 - Phosphate fertilizers
 - sewage
 - detergents
- Phosphate in detergents was primarily in the form of sodium tripolyphosphate or STP, $Na_3H_2P_3O_{10}$.
 - STP was added as a “builder”, or a source of hydroxide ion, but does not precipitate Ca^{2+}
 - This keeps the pH high enough that the detergent molecules are in their ionic form.
 - The ionic form of a detergent or soap is active as a surfactant.
 - In addition to detergent (or soap) and a builder, laundry detergent products may contain bleach, zeolites, non-ionic surfactants, and bluing or brightening agents.
 - Use of STP in detergents has been restricted since the late 1970's. In Canada and Europe the sodium salt of nitrilotriacetic acid (NTA) is used as a builder instead of STP.
- Discharge of phosphates can lead to algal blooms in lakes and can promote eutrophication.
 - Treatment of sewage removes phosphates by precipitation with Ca^{2+} at high pH.
- Biologically, phosphate is found in:
 - Nucleic acids
 - ADP/ATP
 - bones and teeth
- Phosphorothionate and phosphorodithionate pesticides do not bioaccumulate.

Oxygen Cycle

- Electronic configuration of oxygen is $1s^2 2s^2 2p^4$.
 - Oxidation states are 0, -1, and -2.
- Some examples of oxidation states of oxygen are:

- Oxidation state 0: O₂
- Oxidation state -1: OH radical, peroxides HOOH, ROOH.
- Oxidation state -2: H₂O, oxides, and organic compounds.
- Coupled to the energy cycle and the carbon cycle by photosynthesis.
 - All atmospheric O₂ comes from photosynthesis.
- Primary reservoir is the atmosphere.
 - O, O₂, and O₃ are involved in the Chapman Cycle and are found in the mesosphere, stratosphere, and troposphere.
- Many oxygen containing species in the atmosphere.
 - Nitrogen oxide species NO_x and NO_y include NO, NO₂, NO₃, and N₂O.
 - Sulphur containing species SO_x refers to SO₂ which can be further oxidized.
 - Hydrogen containing species HO_x refers to OH and HO₂, which are important free radicals in atmospheric chemistry.
 - Oxygen is also found in atmospheric organic compounds, known as VOCs or volatile organic carbon
- Sinks for oxygen include weathering and the formation of metal oxides.
 - These processes are exothermic and spontaneous.
 - In contrast, the smelting of metals (reducing the oxide to the pure metal) is endothermic.
- Properties and reactivity of atmospheric oxygen have their origins in the electronic structure with unpaired electrons in both the atom and diatom.
 - Two common electronic states of the atom are the ground state (³P) and the excited state (¹D).
 - Two common electronic states of the molecule are the ground state (³Π) and the excited state (¹Δ).
 - The main source of atmospheric OH is:

$$\text{O}({}^1\text{D}) + \text{H}_2\text{O} \rightarrow 2\text{OH}$$
 - The source of O(¹D) is the photolysis of ozone:

$$\text{O}_3 + h\nu \rightarrow \text{O}({}^1\text{D}) + \text{O}_2({}^1\Delta)$$
 - Ozone also photolyzes to the ground states:

$$\text{O}_3 + h\nu \rightarrow \text{O}({}^3\text{P}) + \text{O}_2({}^3\Pi)$$
 - Photons of wavelength 310 nm or shorter required.

Sulphur Cycle

- Electronic configuration of sulphur is $1s^2 2s^2 2p^6 3s^2 3p^4$.
 - Oxidation states range from +6 to -2.
- Some examples of the oxidation states of sulphur:
 - SO₃, H₂SO₄, HSO₄⁻, and SO₄²⁻ are in oxidation state +6.
 - SO₂, H₂SO₃, HSO₃⁻, and SO₃²⁻ are in oxidation state +4.
 - S₈ is in oxidation state 0.
 - S₂²⁻ and FeS₂ (pyrite) are in oxidation state -1.

- H_2S and Fe_2S_3 contain S in oxidation state -2.
- The S cycle is coupled to the O cycle.
- The geosphere is an important reservoir with S found in:
 - Sulphate salts
 - Sulphite salts
 - metal disulfide ores
 - metal sulphide ores.
 - Since proteins contain S, fossil fuels will contain S.
- Anthropogenic impacts are most significant in the atmospheric reservoir.
- Atmospheric species include:
 - Sulphur dioxide, SO_2
 - Dimethyl sulphide or DMS, CH_3SCH_3
 - Dimethyl disulphide or DMDS, CH_3SSCH_3
 - Carbonyl sulphide or OCS, $\text{O}=\text{C}=\text{S}$
 - Carbon disulphide, $\text{S}=\text{C}=\text{S}$
 - Hydrogen sulphide or (H_2S)
- Anthropogenic emissions are three times natural emissions.
 - Most anthropogenic emissions are as SO_2 from smelting of metals and combustion of fossil fuels.
 - In contrast, most natural emissions are reduced forms of sulphur since anaerobic organisms use S(VI) as a source of oxygen.
 - Natural emissions include DMS, CS_2 , and OCS from the reduction of amino acids.
 - With the exception of OCS, the reduced species can be oxidized in the troposphere.
 - OCS is transported to the stratosphere where it is photolyzed.
- Volcanic emissions include SO_2 , H_2S , and OCS.
 - May be injected directly into the stratosphere.
- Atmospheric oxidation of H_2S proceeds by the sequence:

$$\begin{aligned}\text{H}_2\text{S} + \text{OH} &\rightarrow \text{HS} + \text{H}_2\text{O} \\ \text{HS} + \text{O}_2 &\rightarrow \text{OH} + \text{SO} \\ \text{SO} + \text{O}_2 &\rightarrow \text{SO}_2 + \text{O}\end{aligned}$$
- Atmospheric oxidation of SO_2 proceeds by several routes.
 - Direct gas phase oxidation is too slow to be significant.

$$\text{SO}_2 + \text{O}_2 \rightarrow \text{SO}_3 + \text{O}$$
 - Gas phase oxidation can occur with photochemical oxidants formed in photochemical smog by nonmethane hydrocarbons (NMHC). These oxidants includes OH, HO_2 , O, O_3 , NO_3 , N_2O_5 , ROO, and RO.
- Aqueous phase oxidation inside cloud droplets is the dominant route.
 - SO_2 is effectively scavenged by cloud droplets as are oxidants such as O_2 , O_3 , HO, H_2O_2 , ROOH, CH_3OOH , and $\text{CH}_3(\text{CO})\text{OOH}$ (peroxyacetic acid or PAA).
 - Aqueous phase oxidation with O_2 is catalyzed by Fe^{2+} , Mn^{2+} and C.

- Aqueous phase oxidation with O_3 , OH , and H_2O_2 is pH sensitive and is connected with the S(IV) speciation. HSO_3^- is more easily oxidized than other species of S(IV).
- A major anthropogenic source of SO_2 is the roasting of metal ores. For example:

