Midterm I: Summary

- Everybody did a great job
- Direct answers (Q8, “the top of Earth’s atmosphere”)
- Points distribution (e.g., Q3)
- Clarifications with me if the Qs are not clear to you.
- Keep the Qs sheet with your answers.

Item Statistics: Midterm Exam I

Class Statistics   User Statistics

View By: User   Apply

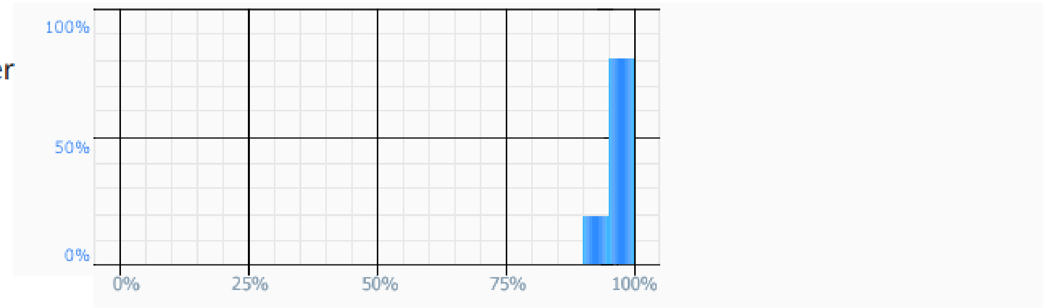
Midterm Exam I Class Statistics

Number of submitted grades: 16 / 16

Minimum:	91 %
Maximum:	100 %
Average:	96.75 %
Mode:	100 %
Median:	97 %
Standard Deviation:	2.59 %

Grade Distribution

Number of Users (%)



Grade Received (%)

Chapter 5: The Carbon Cycle: Feb 23 & 25, 2026

5.1. Greenhouse Gases and Our Atmosphere’s Composition
5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange
5.3. Atmosphere-Rock Exchange
5.4. How Are Humans Perturbing the Carbon Cycle?
5.5. Some Commonly Asked Questions about the Carbon Cycle
5.6. The Long-term Fate of Carbon Dioxide
5.7. Methane
5.8. Other Greenhouse Gases
Terms
Problems

Introduction

1) In **Eqn. 4.5** planet T determined by number of atmospheric layers (n), albedo (α), and solar constant (S).

2) Carbon dioxide (CO_2) = primary greenhouse gas (GHG) emitted by human activity.

3) Policies to control climate change frequently focus on CO_2.

4) Must understand carbon cycle between Earth's air-land-water system.

5.1. Greenhouse Gases & Atmosphere Composition

1) Greenhouse effects: two concepts (buffering and absorbing)
2) Dry atmosphere: ~78 % diatomic nitrogen (N_2), ~21 % diatomic oxygen (O_2), and ~1 % Argon (Ar).
3) Wet atmosphere: dry air + water vapor (H_2O)

- Most abundant GHG on Earth - mostly from ocean evaporation.
- Abundance decreases by latitude: tropics (~4 %) to polar regions (~0 %).
- Abundance decreases by altitude: Removed by raindrop (condensation) or ice-crystal (deposition) formation.
- As Earth T increases, H_2O abundance increases.
- Human contribution minimal.

5.1. Greenhouse Gases & Atmosphere Composition

1) **CO_2**: 0.0412% in 2020 (second-most abundant GHG)

- Most important GHG that humans directly influence.
- Unit: parts per million (ppm), how many molecules out of 1 million? Contrast with per cent = "out of 100."
- 0.0412% = 412 ppm (412 molecules of CO_2 in every 1 million molecules of air).
- CO_2 abundance currently rising ~2 ppm/yr.

5.1. Greenhouse Gases & Atmosphere Composition

2) **Methane** (CH_4): 1.87 ppm in 2020

   Sources: decomposition, digestion, natural gas.

3) **Nitrous oxide** (N_2O): 0.32 ppm in 2020; GHG.

   Sources: nitrogen-based fertilizer, industrial processes, and natural sources.

5.1. Greenhouse Gases & Atmosphere Composition

4) **Ozone** (O_3) = varies widely in atmosphere, can reach ~10 ppm in stratosphere.

- Absorbs ultraviolet photons from Sun, which cause tissue damage.
- In unpolluted air near surface, abundance varies 10-40 parts per billion (ppb).
- Component of photochemical smog near ground.
- Thus, O_3 above ground = “good,” but near ground = “bad.”

5.1. Greenhouse Gases & Atmosphere Composition

5) **Halocarbons**, including chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HFCs):

- Synthetic industrial chemicals used as refrigerants.
- Powerful GHG.
- Abundance (few ppb).
- Destroy O_3.

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

5.2.1. Atmosphere-Land Biosphere Exchange

Directly monitor CO_2 abundance since mid-1900s (Fig. 5.1):

- **Keeling Curve**: after Charles Keeling who initiated measurements in 1957.
- Long-term upward trend: number of layers (n) increasing (Eqn. 4.5).
- "Sawtooth" annual cycle: maximum (May), minimum (Sept.) w/ range ~6 ppm.
- Depicts annual cycle of plant growth/decay.

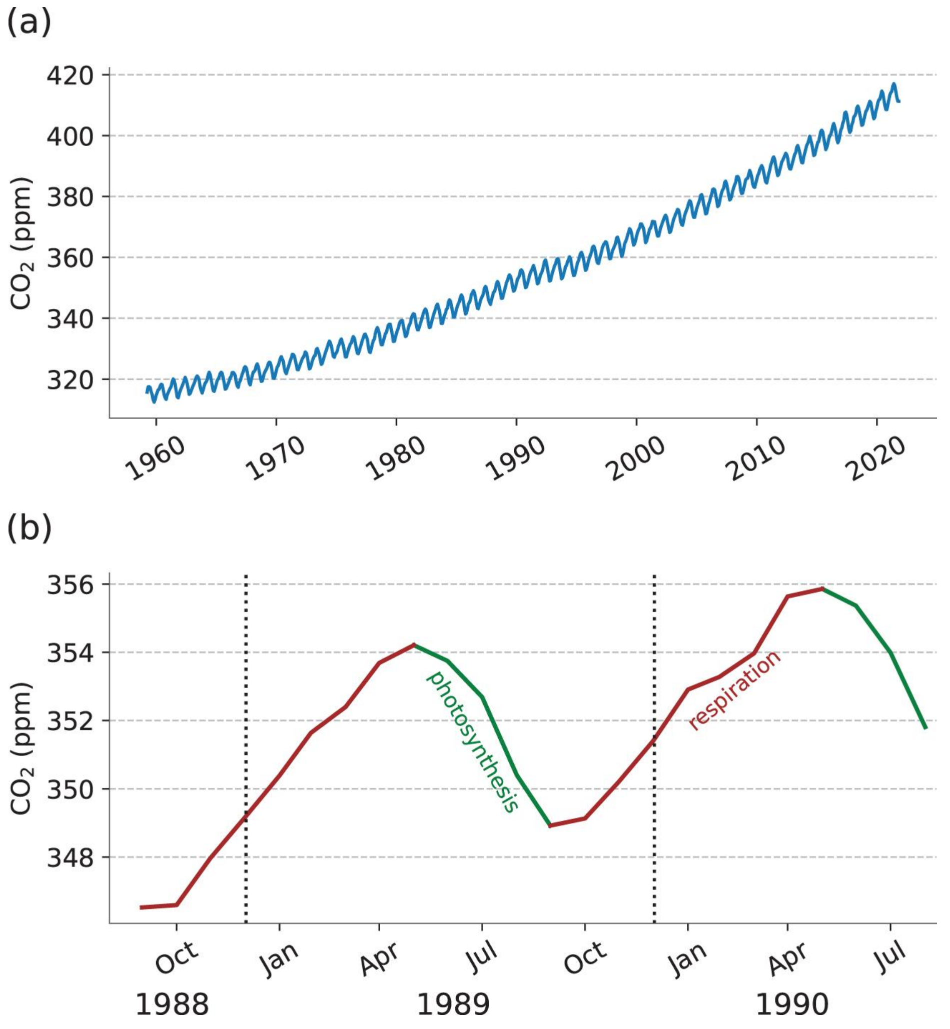
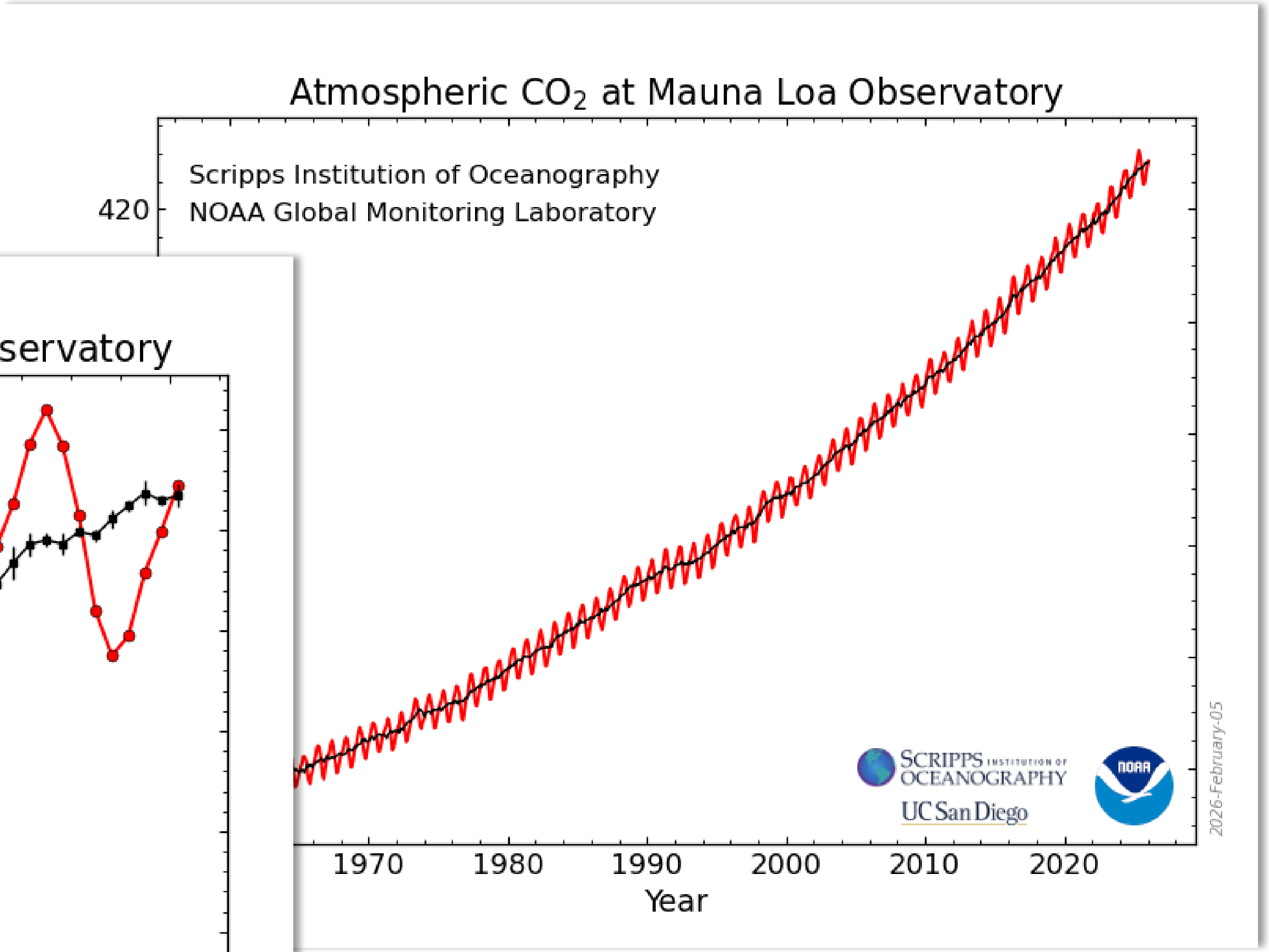
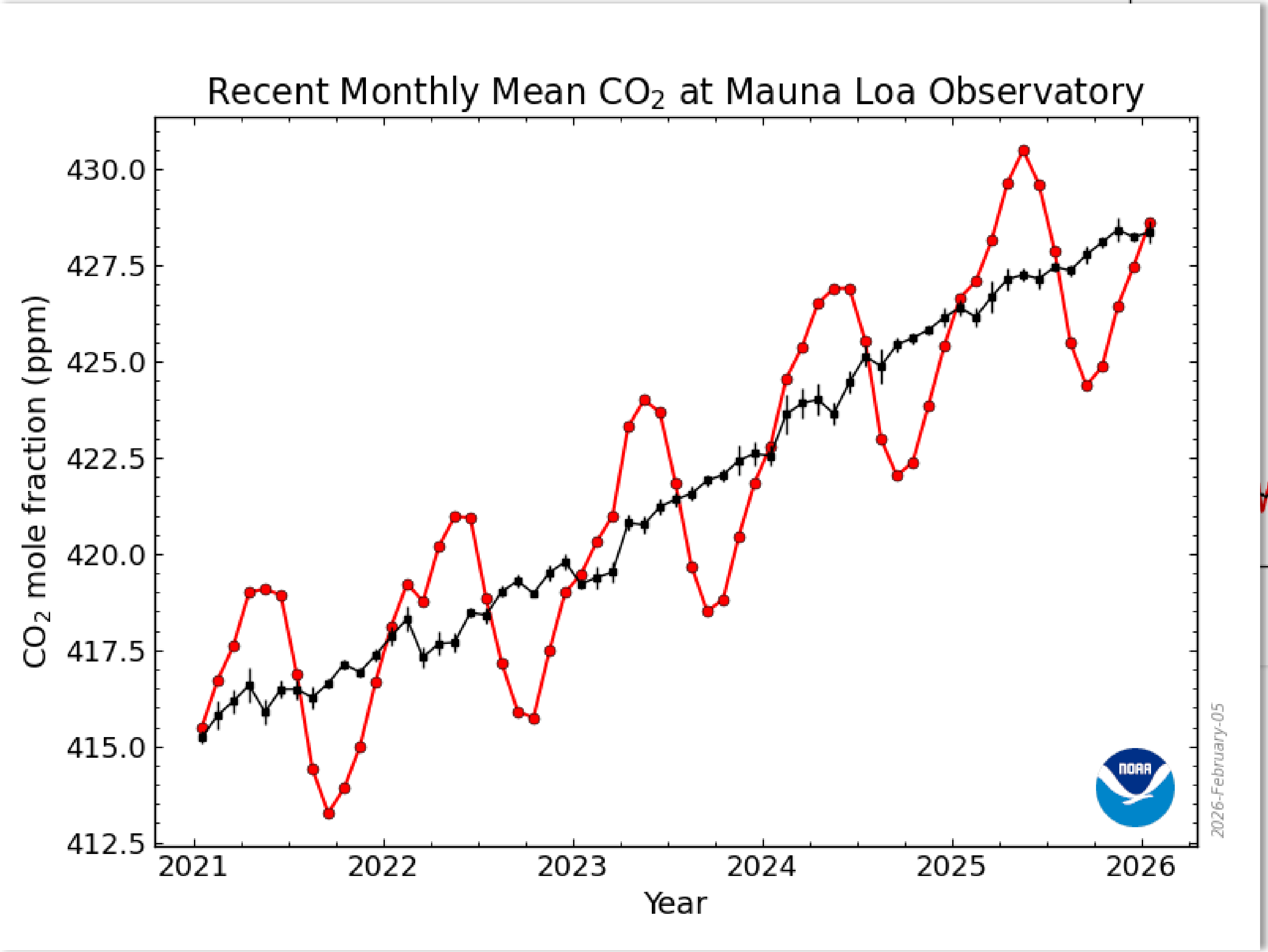


Fig. 5.1: (a) Record of atmospheric carbon dioxide since mid-1900s. (b) Close-up of two years: fall 1988 through fall 1990. Periods dominated by photosynthesis are green and periods dominated by respiration are brown.

Updated diagram (2/22/2026)





https://gml.noaa.gov/ccgg/trends/

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

Two major C exchanges in terrestrial ecosystems

Photosynthesis (Eqn. 5.1)

$$CO_2 + H_2O = CH_2O + O_2$$

CH_2O: plant carbohydrate.

O_2: released to atmosphere as the main source of oxygen in Earth atmosphere!

Respiration (Eqn. 5.2)

$$CH_2O + O_2 = CO_2 + H_2O$$

As organisms consume plant material.

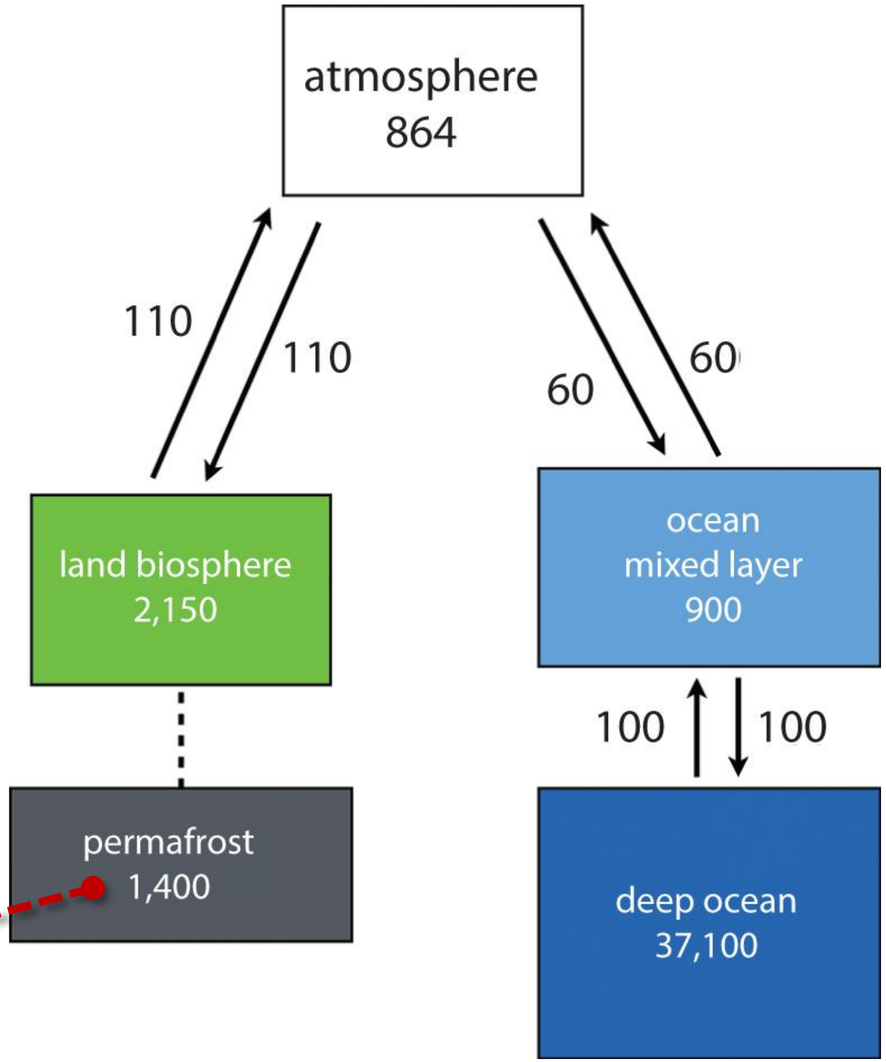
CO_2 released to atmosphere + water vapor + energy to organism.

CH_2O, CO_2, O_2 roughly balance between Eqn. 5.1-5.2.

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

C storage in terrestrial ecosystems

Atmosphere:	~864 GtC
Land-biosphere:	~2150 GtC
Photosynthesis:	~110 GtC
Permafrost:	~1400 GtC



A particular concern

Fig. 5.2: Schematic of exchange between atmosphere, land biosphere, and ocean. Number in boxes represent amount of carbon stored in each reservoir, in GtC. Arrows represent fluxes in GtC/yr.

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

5.2.2. Atmosphere-Ocean Exchange

CO_2 readily dissolves in water creating carbonic acid (H_2CO_3) during reaction *(***Eqn. 5.3)**

- Ocean can absorb huge amounts of CO_2 from atmosphere:

  $$CO_2 + H_2O = H_2CO_3$$

- CO_2 returned to atmosphere by reverse reaction (**Eqn. 5.4)**:

  $$H_2CO_3 = CO_2 + H_2O$$

- C flux: ~60 GtC/yr

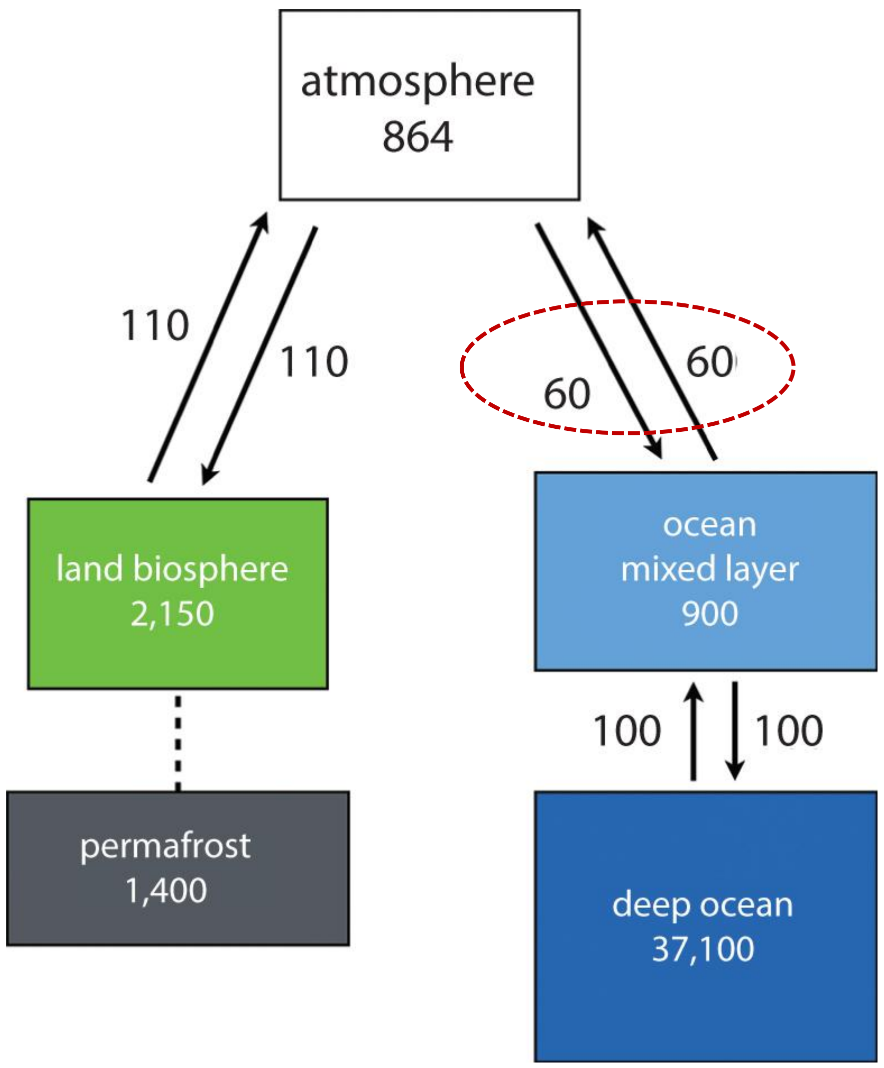


Fig. 5.2: Schematic of exchange between atmosphere, land biosphere, and ocean.

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

5.2.2. Atmosphere-Ocean Exchange

Ocean mixed layer (top ~100 m of ocean) exchanges CO_2 rapidly with atmosphere:

~3 % of ocean mass, ~900 GtC

Deep ocean:

~97 % of ocean mass, ~37,100 GtC (43x more CO_2 than atmosphere!)

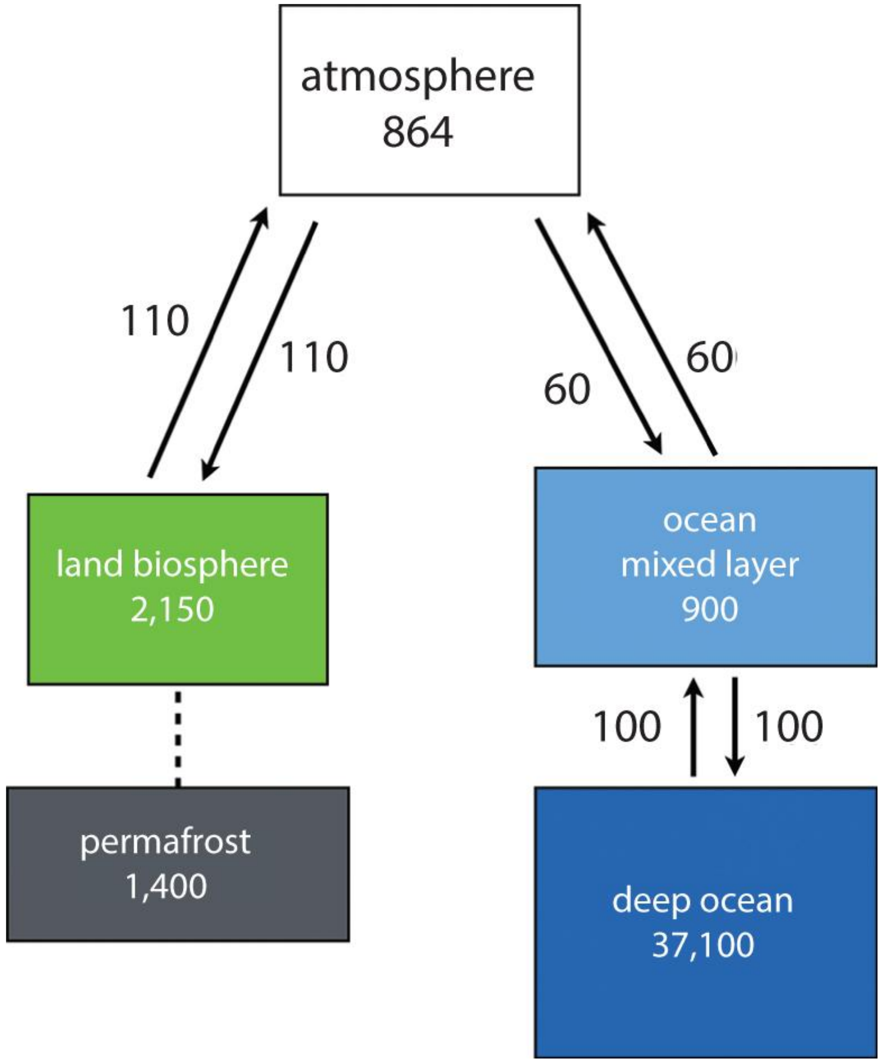


Fig. 5.2: Schematic of exchange between atmosphere, land biosphere, and ocean.

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

5.2.3. The Combined Atmosphere-Land Biosphere-Ocean System

- To understand numbers in Fig. 5.2, useful to calculate how fast carbon flows through reservoirs (**fluxes**).

- **Turnover Time**: how fast C atoms flow through these reservoirs

- Average C turnover time of **atmosphere** reservoir:

  ✓ The size of reservoir (~864 GtC) divided by total flux out of reservoir.
  ✓ ~110 GtC/yr to land-biosphere; ~60 GtC/yr to ocean mixed-layer.
  ✓ (~864 GtC) / (~110 + ~60 GtC/yr) = ~5 yr

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

5.2.3. The Combined Atmosphere-Land Biosphere-Ocean System

- Average C turnover time of **land-biosphere reservoir**:
- Estimated size of reservoir (~2150 GtC) divided by total flux out of reservoir.

✓ ~110 GtC/yr to atmosphere.

✓ ~0 GtC/yr to permafrost.

✓ (~2150 GtC) / (~110 GtC/yr) = **~20 yr**.

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

5.2.3. The Combined Atmosphere-Land Biosphere-Ocean System

- Average C turnover time of **ocean mixed-layer** :

- Estimated size of reservoir (~900 GtC) divided by total flux out of reservoir.

  - ✓ ~60 GtC/yr to atmosphere.

  - ✓ ~100 GtC/yr to deep ocean.

  - ✓ (~900 GtC) / (~60 + ~100 GtC/yr) = **~6 yr**.

5.2. Atmosphere-Land-Biosphere-Ocean Carbon Exchange

5.2.3. The Combined Atmosphere-Land Biosphere-Ocean System

- Average C turnover time of **deep ocean**:

- Estimated size of reservoir (~37,100 GtC) divided by total flux out of reservoir.

  ✓ ~100 GtC/yr to ocean mixed layer.

  ✓ (~37,100 GtC) / (~100 GtC/yr) = **~371** yr.

5.3. Atmosphere-Rock Exchange

- **Rock reservoir** contains many millions of GtC (limestone = $CaCO_3$).

  ✓ Most of Earth carbon stored in rocks.

  ✓ CO_2 transferred **slowly** from rock to atmosphere via volcanic eruptions **(~0.1 GtC/yr**).

  ✓ Flux seems small, but impactful over **millions of years**.

  ✓ Volcanism exchange from rock to atmosphere (~0.1 GtC/yr) balanced by chemical weathering (~0.1 GtC/yr).

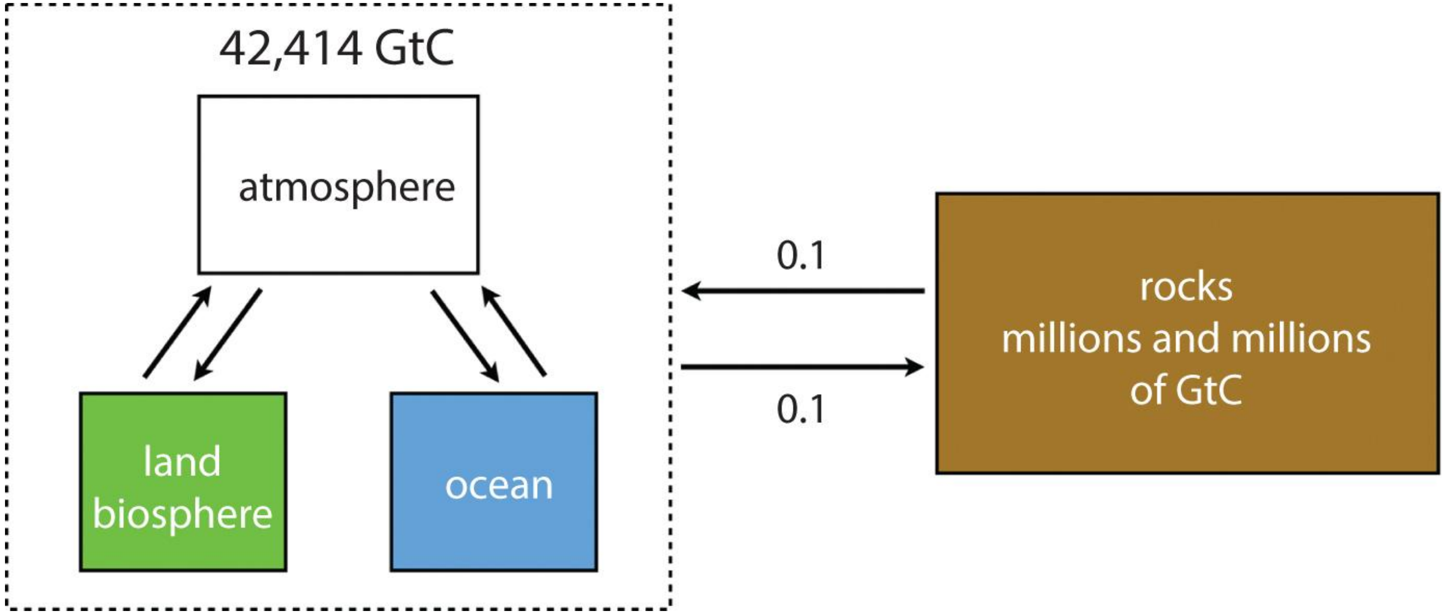


Fig. 5.3: Schematic of exchange between combined atmosphere, land-biosphere, ocean reservoirs, and rock reservoir. Arrows represent fluxes in GtC/yr.

5.3. Atmosphere-Rock Exchange

- Chemical **Weathering**: when precipitation containing carbonic acid (H_2CO_3) strikes rock, impact and reaction breaks down rock (pH = ~5.6):

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$

- CO_2 molecule consumed in reaction from atmosphere, via precipitation, and transferred into molecule of calcium carbonate ($CaCO_3$), eventually running off into ocean (i.e., chalk or limestone).

- Silicon dioxide (SiO_2) primary component of sand, quartz, glass.

5.3. Atmosphere-Rock Exchange

- $CaCO_3$ deposits on sea floor.
- Over millions of years plate tectonics carry it deep within Earth, high T and/or pressure turns it into magma, with volcanism eventually returning it to atmosphere to complete cycle.
- Rapid burial of plant material before decay, followed by high T and/or pressure creates fossil fuel.

C atom remains in atmosphere-land-biosphere-ocean system for

(~42,000 GtC) / (~0.1 GtC/yr) = **~420,000 yr**

before transferred to rock reservoir.

5.3. Atmosphere-Rock Exchange

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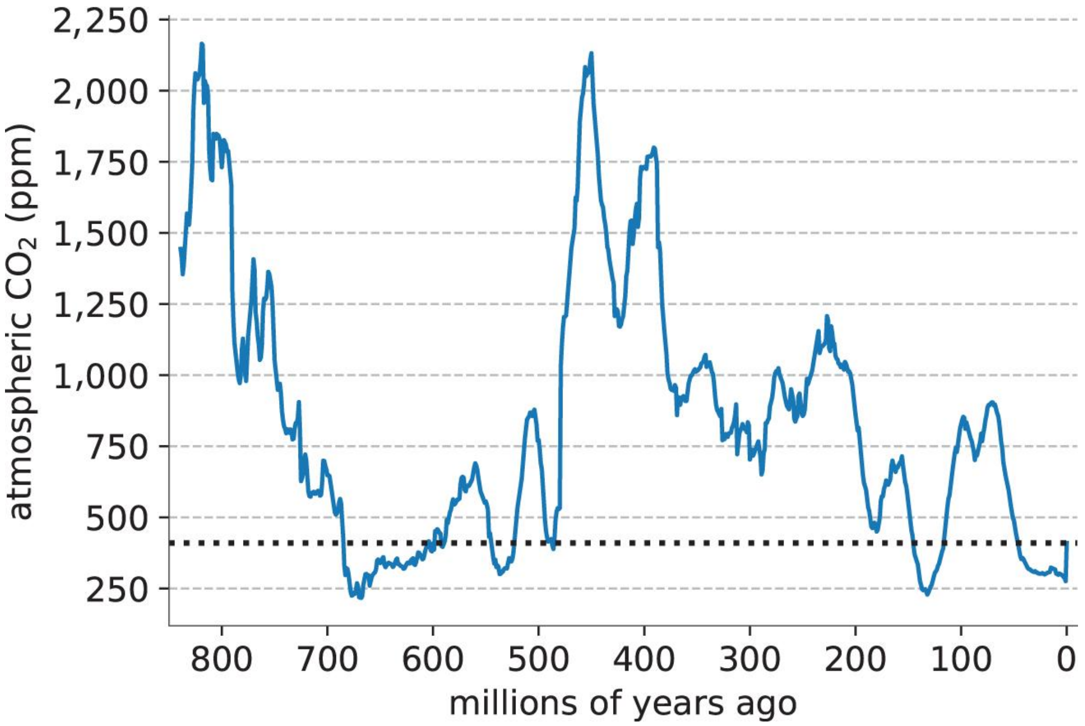

Fig. 5.4: Atmospheric CO_2 over past ~850 million years. Dotted line is atmospheric abundance in 2020, 410 ppm.

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TERMS

Carbon cycle
Carbonic acid
Chemical weathering
Deep ocean
Deforestation
Fossil fuels
Global warming potential
Greenhouse gas
Halocarbons
Isotopes
Keeling curve
Land-use changes
Mixed layer
Ocean acidification
Parts per million
Photosynthesis

Respiration