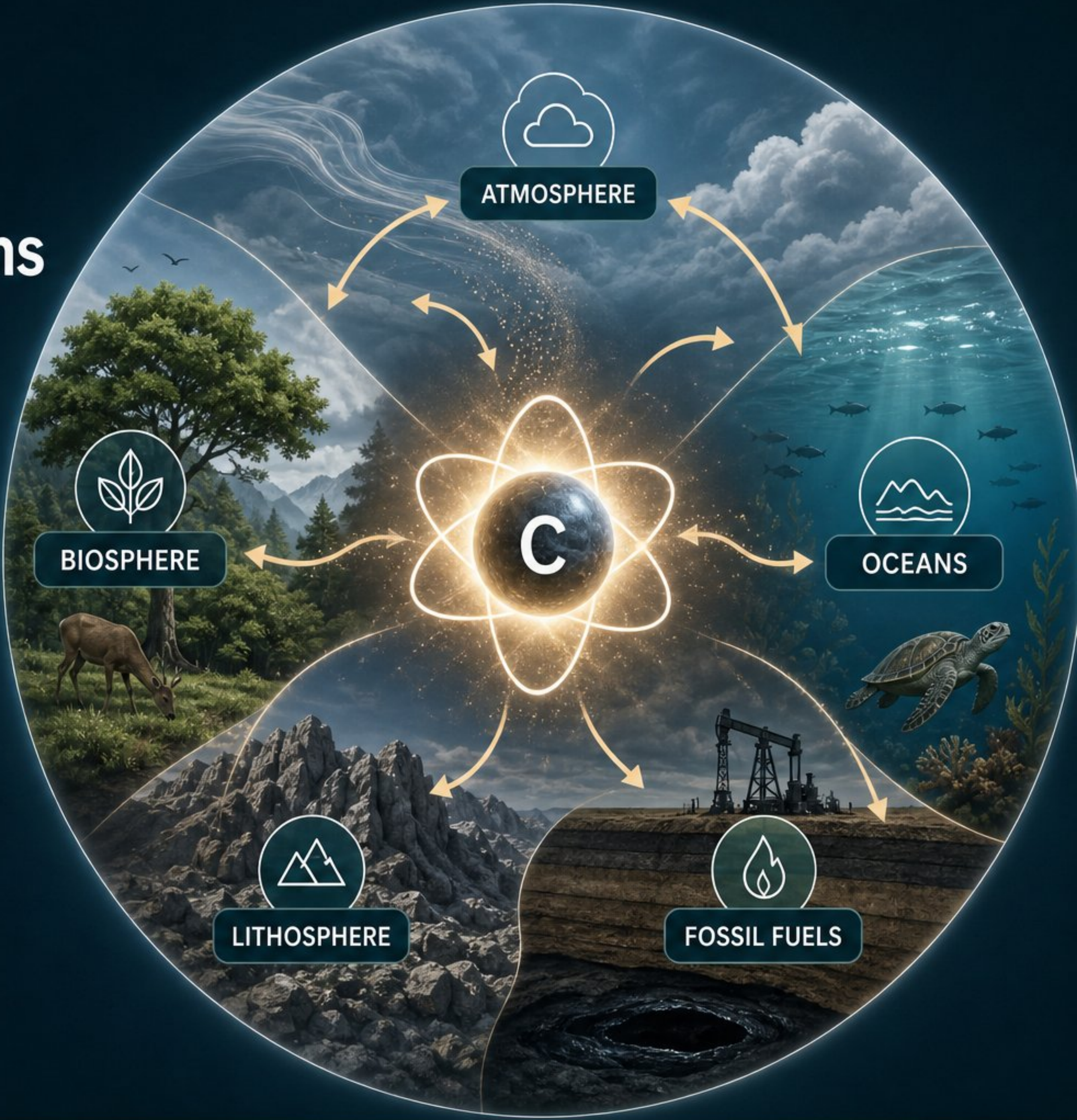
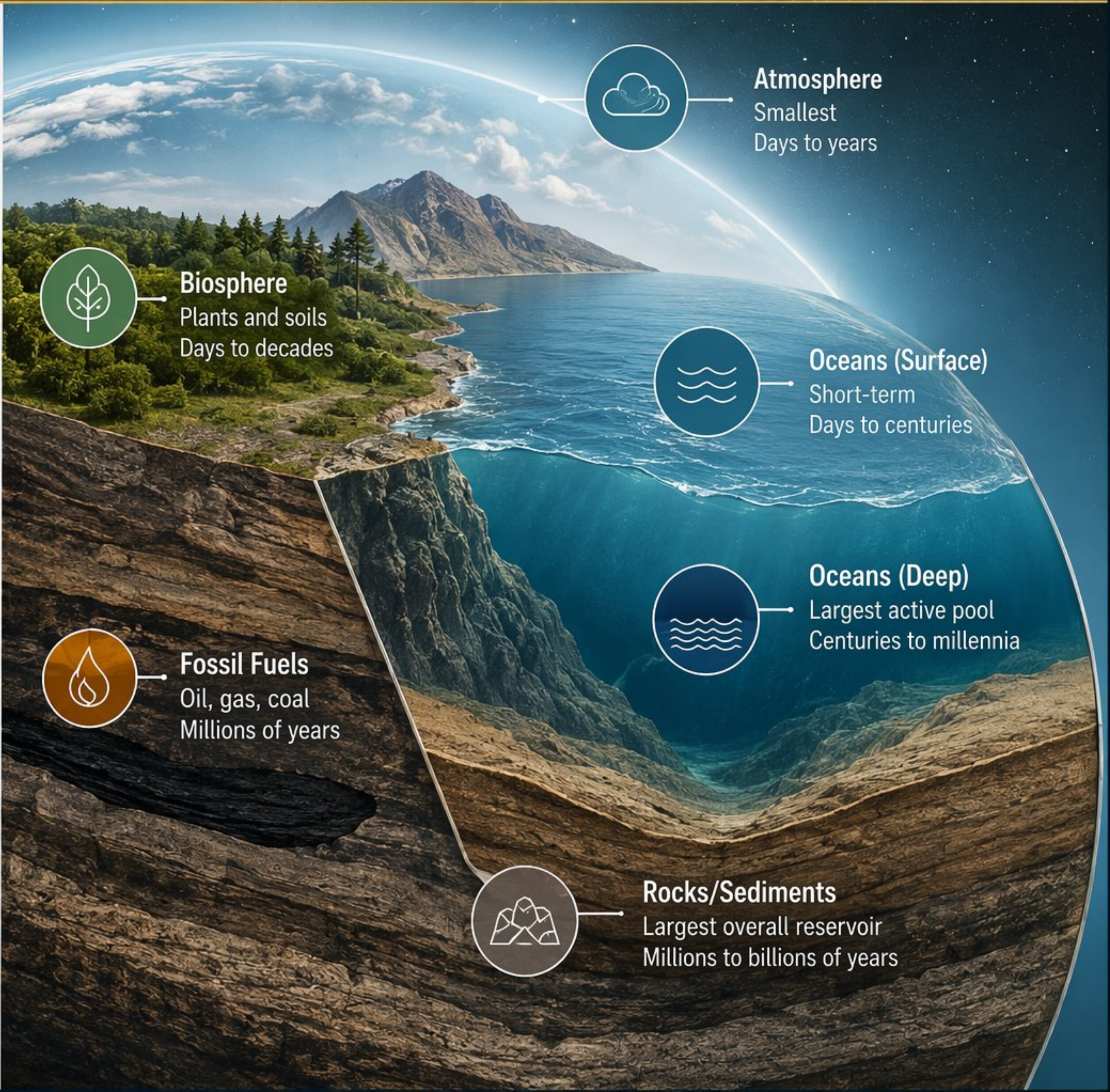
The Carbon Cycle: Matter Moving Through Earth Systems

- **Carbon cycle:** continuous movement of carbon atoms through air, land, water, organisms, and rocks
- Carbon is the backbone of life, a key climate regulator, and an energy carrier
- Major reservoirs: atmosphere, biosphere, oceans, lithosphere, and fossil fuels
- Processes like photosynthesis, respiration, and weathering move carbon between reservoirs
- By the end, you'll explain how carbon flows, where it's stored, and how humans disrupt the balance



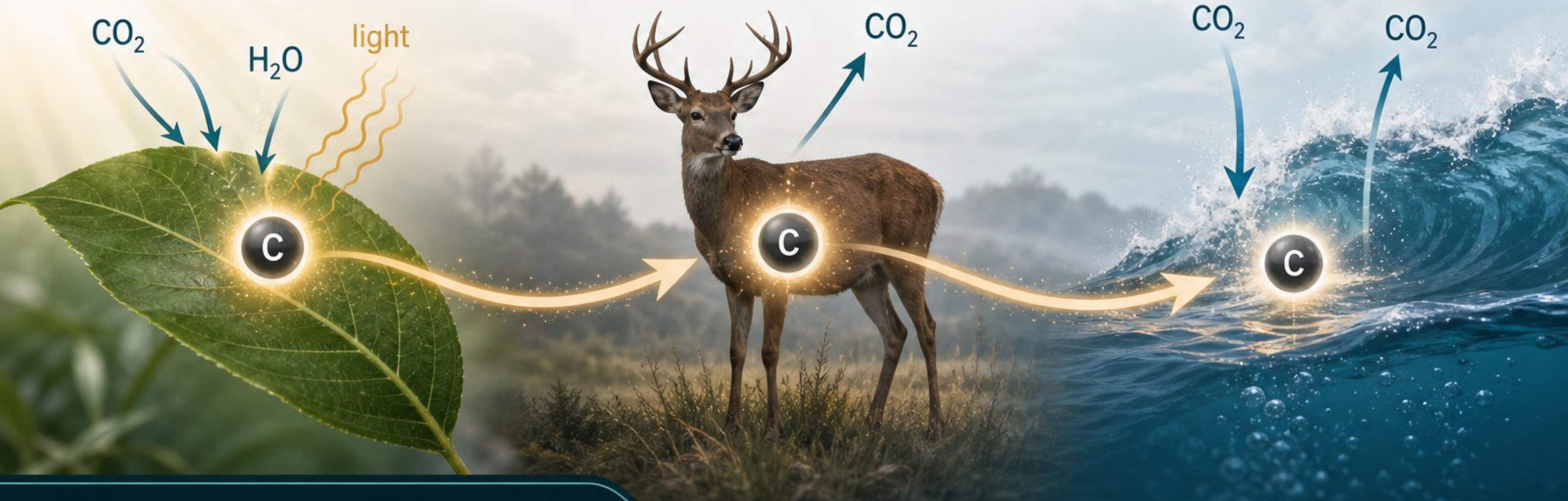
Earth's Carbon Reservoirs: Where the Carbon Is

- The five major reservoirs: atmosphere, biosphere, oceans, fossil fuels, and rocks/sediments
- Short-term (surface) vs. long-term (deep ocean, rocks, fossil fuels) reservoirs
- Sediments and rocks dominate; the deep ocean is the largest active pool; the atmosphere is the smallest
- Residence time: days in the atmosphere, millions of years in rocks



The Fast Carbon Cycle:
Photosynthesis, Respiration, and Air-Sea Exchange

- **Photosynthesis:** $6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$
- **Respiration returns CO_2:** $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
- **Air-sea exchange:** CO_2 dissolves in and outgasses from ocean surface
- **Timescale:** days to centuries, driving seasonal planetary 'breathing'



Reading the Planet's Breath:
The Keeling Curve and the Seasonal Cycle

- **The Keeling Curve:** continuous atmospheric CO_2 record at Mauna Loa since 1958
- **Sawtooth pattern: ~6 ppm** seasonal cycle overlaid on a steady annual rise
- **NH land plants drive the cycle:** CO_2 falls in summer, rises in winter
- Seasonal amplitude is increasing in northern high latitudes due to amplified plant productivity

The Slow Carbon Cycle: Earth's Geological Thermostat

- Carbon moves between rocks, atmosphere, and ocean over millions of years
- Silicate weathering: CO_2 + rainwater → carbonic acid dissolves rocks → bicarbonate ions carried to ocean
- Marine organisms build $CaCO_3$ shells; shells sink, accumulate, and form limestone
- Subduction + volcanism return CO_2 to atmosphere, closing the inorganic cycle
- Fossil fuels form separately: buried organic matter transformed under heat and pressure

The Ocean Carbon Pumps: How the Ocean Locks Away Carbon

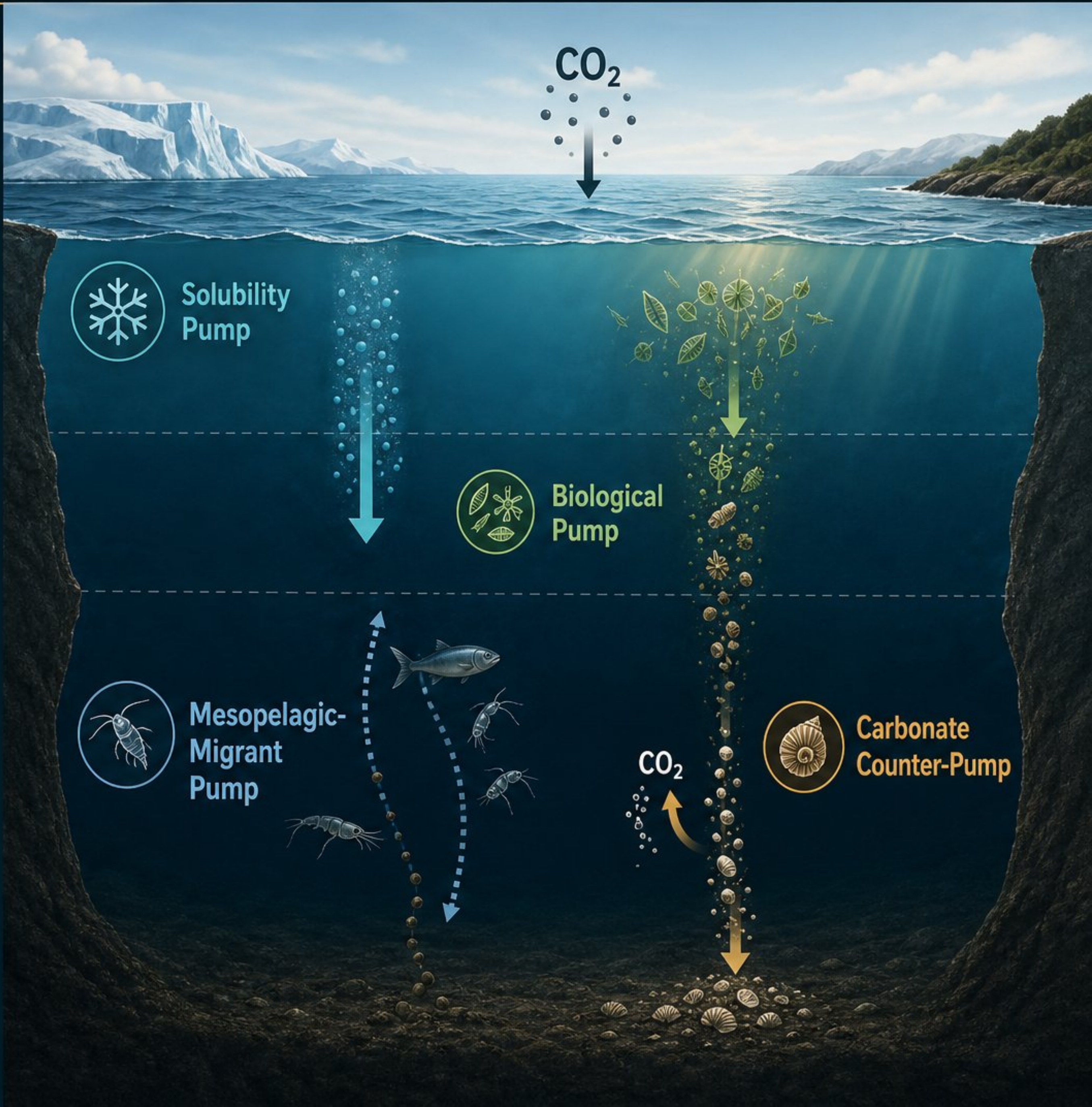
- Ocean is the largest active carbon sink, driven by three interconnected pumps

Solubility Pump: Cold, dense high-latitude water dissolves CO_2 and sinks, storing it for centuries

Biological Pump: Phytoplankton fix CO_2; sinking remains transfer carbon to the deep sea

Carbonate Counter-Pump: Shell formation releases CO_2, but burial in sediments locks carbon away

Mesopelagic-Migrant Pump: Zooplankton and fish actively inject carbon into the deep ocean daily



Human Interference, Part 1:
Fossil Fuels, Land Use, and the Emission Surge

- **Fossil fuel and cement emissions:** 10.3 GtC in 2024, projected 10.4 GtC in 2025
- **Land-use change (deforestation)** adds a net flux of 1.3 GtC per year
- **Total anthropogenic emissions:** approximately 11.6 GtC/yr in 2024
- **Natural sinks absorb only about** half of what we emit annually
- **Atmospheric CO_2 surged** from 278 ppm to 425.6 ppm, unprecedented in 800,000 years

Human Interference, Part 2:

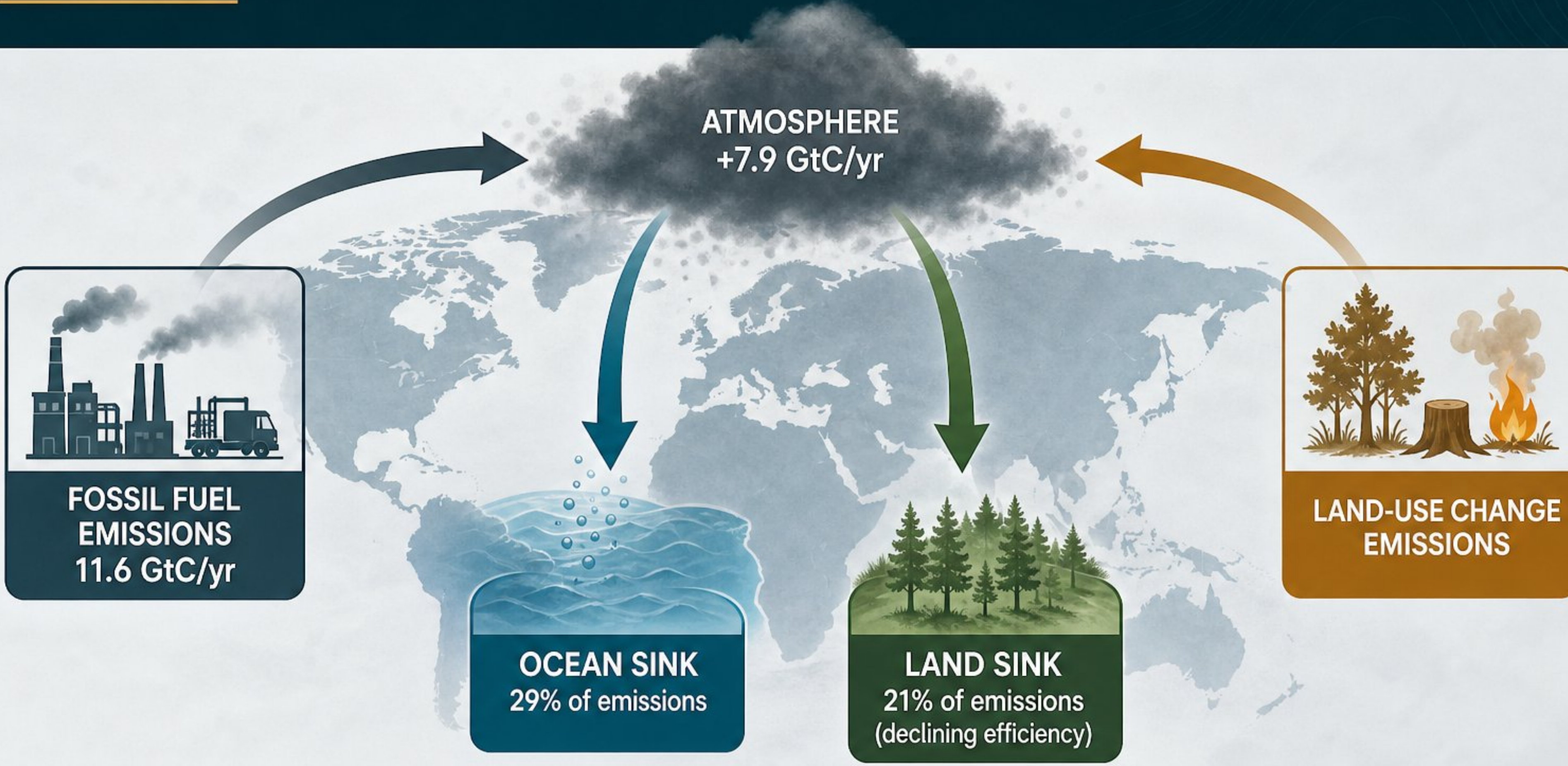
The Enhanced Greenhouse Effect and Climate Feedbacks

- Added CO_2 traps outgoing infrared radiation, directly warming the planet
- June 2026: Mauna Loa CO_2 reached 431.44 ppm, growing 2.6 ppm/yr
- Positive feedbacks: permafrost thaw, weaker ocean uptake, forest dieback
- Negative feedbacks: CO_2 fertilization boosts plant growth; rock weathering
- Feedbacks can accelerate warming, making climate change more severe

The Permafrost Feedback:
A Ticking Carbon Time Bomb

- Permafrost stores ~1,460-1,600 PgC, twice the atmospheric amount
- Warming thaws permafrost, microbes release ancient CO_2 and methane
- Thaw and fire emissions cut the 1.5°C carbon budget by 25% ± 12%
- Released carbon is irreversible, locking in long-term warming

The Global Carbon Budget: Tracking Sources and Sinks



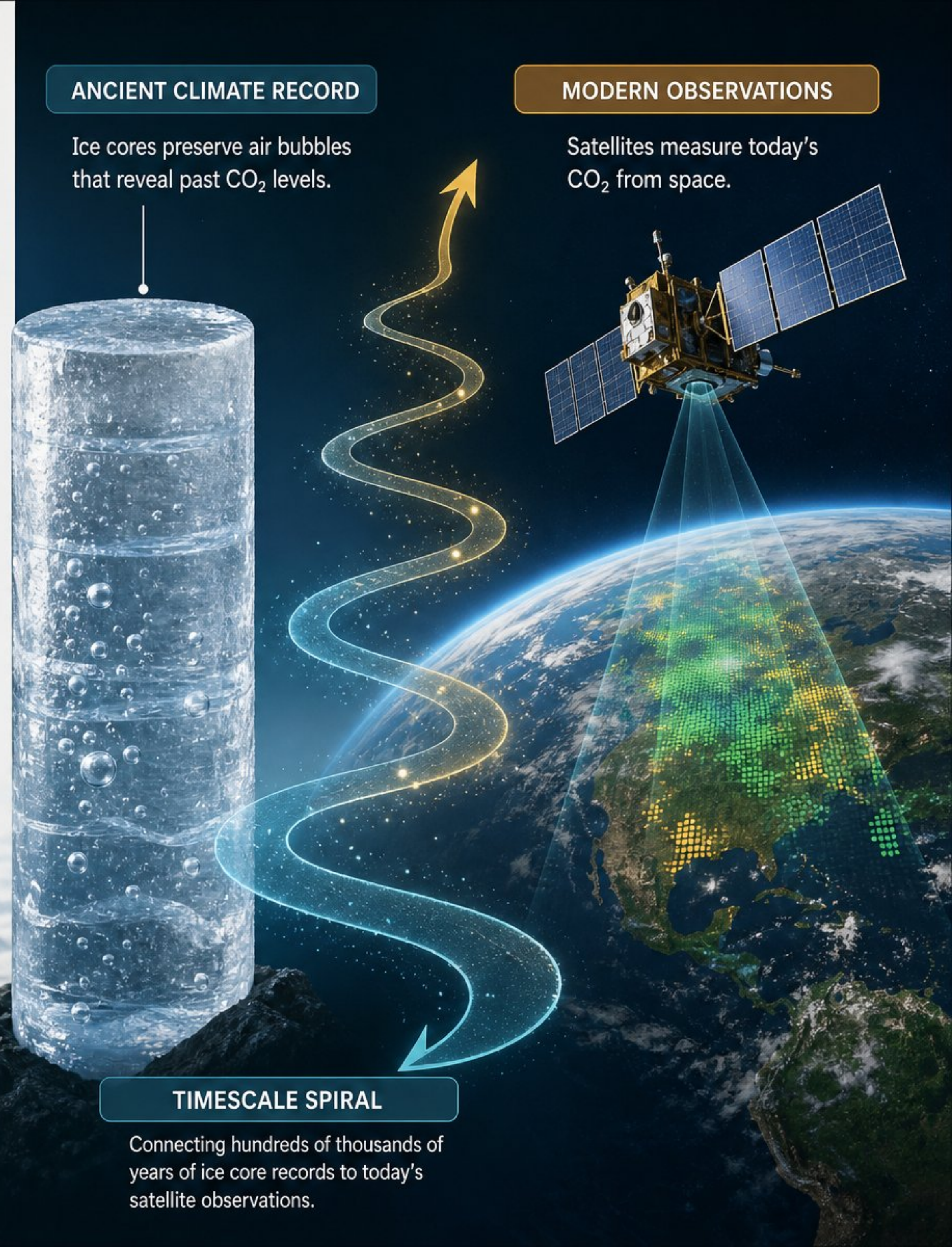
- Annual scientific assessment of CO_2 emissions and sinks
- 2024 total emissions: 11.6 GtC, record atmospheric growth of 7.9 GtC/yr
- Ocean sink: 29% of emissions; Land sink: 21% (declining efficiency)
- 1.5°C budget nearly exhausted: 170 $GtCO_2$ (~4 years of current emissions)

How We Know: Atmospheric Monitoring and the Keeling Legacy

- Mauna Loa Observatory: continuous, high-precision CO_2 records since 1958
- Global flask-sampling network tracks planetary-scale CO_2 trends and regional fluxes
- Weekly, monthly, and annual data capture long-term rise and seasonal cycle
- The gold-standard dataset for calculating global growth rates and validating models

How We Know: Ice Cores, Satellites, and the View from Space

- Ice cores trap ancient air bubbles, revealing CO_2 levels 800,000 years back
- OCO-2 and GOSAT satellites measure column-averaged CO_2 globally
- OCO-2 v11.1 data shows biases under 0.2 ppm vs. ground-based TCCON
- Solar-induced chlorophyll fluorescence (SIF) tracks plant photosynthesis and drought stress
- OCO-2's growth rate was adopted by the Global Carbon Project in 2025



How We Know: Modeling the Carbon Cycle in a Computer

- Earth System Models (ESMs) simulate carbon–climate interactions
- DGVMs estimate land carbon fluxes and vegetation responses
- Models integrate satellite, inversion, and ground-based data
- Validation with airborne and ocean tracer data reveals biases
- Key uncertainties: permafrost carbon, tropical land sink, climate variability

Your Role in the Carbon Cycle:

Personal and Systemic Actions

- Personal footprint vs. systemic carbon flows: both are critical
- Daily choices link directly to carbon reservoirs and emission surges
- Reforestation, soil carbon, and wetlands absorb atmospheric CO_2
- Direct Air Capture: <1 $MtCO_2$/yr capacity, costs \$600–\$800/tCO_2

The Carbon Cycle as a Single Connected System

The Carbon Atom's Journey

- Same carbon atoms move through air, life, water, and rocks over different timescales
- A closed system, but flow rates govern climate on human timescales
- Human emissions outpace natural sinks, causing ~5-6 GtC annual atmospheric accumulation
- Systems-thinking is essential to grasp interconnected climate impacts and evaluate solutions

Applying Carbon Knowledge: Science, Policy, and Personal Decisions

- Carbon literacy enables critical evaluation of climate models and emission reports
- Understanding the carbon budget (170 $GtCO_2$ remaining for 1.5°C) drives evidence-based policy
- Permafrost feedback reduces remaining budgets by 25% for 1.5°C, demanding urgent targets
- Personal action means championing systemic change, not just individual footprint reduction
- DAC remains nascent (<1 $MtCO_2$/yr, \$600–\$800/t); nature-based solutions are ready now

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