Global Carbon Cycle Modeling: Reservoirs, Fluxes, and Anthropogenic Perturbation

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Abstract

This technical report presents a comprehensive analysis of the global carbon cycle using box models to represent carbon exchange between atmosphere, ocean, and terrestrial biosphere. We examine natural carbon fluxes, anthropogenic emissions, and the resulting changes in atmospheric CO_2 concentration. The model explores the airborne fraction of emissions, ocean uptake dynamics, and climate-carbon feedbacks. Projections under different emission scenarios illustrate the long-term implications for atmospheric carbon levels.

1 Introduction

The global carbon cycle plays a central role in Earth's climate system. Anthropogenic emissions have perturbed this cycle, leading to rising atmospheric CO_2 concentrations and associated climate change.

Definition 1.1 (Carbon Reservoirs) *The major carbon reservoirs are:*

- ***Atmosphere**: ∼850 PgC (pre-industrial: 590 PgC)*
- ***Ocean**: ∼38,000 PgC (surface + deep)*
- ***Terrestrial biosphere**: ∼2,000 PgC (vegetation + soil)*
- ***Fossil fuels**: ∼4,000 PgC*

(1 PgC = 10^{15} g carbon = 1 GtC)

2 Theoretical Framework

2.1 Box Model Equations

Theorem 2.1 (Three-Box Carbon Cycle Model) *The evolution of carbon in atmosphere (C_A), surface ocean (C_O), and biosphere (C_B) is:*

$$\frac{dC_A}{dt} = -k_{AO}(C_A - C_A^{eq}) - k_{AB}(C_A - C_A^{eq}) + E(t) \tag{1}$$

$$\frac{dC_O}{dt} = k_{AO}(C_A - C_A^{eq}) - k_{OD}(C_O - C_O^{eq}) \tag{2}$$

$$\frac{dC_B}{dt} = k_{AB}(C_A - C_A^{eq}) - k_{BR}C_B \tag{3}$$

where k values are exchange coefficients and $E(t)$ is anthropogenic emission.

2.2 CO_2 Concentration and Carbon Mass

Definition 2.1 (Conversion Factors) *Atmospheric CO_2 concentration (ppm) relates to carbon mass (PgC):*

$$C_A\ (PgC) = \frac{CO_2\ (ppm)}{2.13} \tag{4}$$

Thus 1 ppm $CO_2 \approx 2.13$ PgC.

2.3 Airborne Fraction

Definition 2.2 (Airborne Fraction) *The fraction of anthropogenic emissions remaining in the atmosphere:*

$$f_{airborne} = \frac{\Delta C_A}{\sum E(t)} \tag{5}$$

Currently $f_{airborne} \approx 0.44$ (the ocean and biosphere absorb ∼56%).

Remark 2.1 (Ocean Chemistry) *Ocean CO_2 uptake is limited by the Revelle factor:*

$$R = \frac{\Delta[CO_2]/[CO_2]}{\Delta DIC/DIC} \approx 10 \tag{6}$$

Only 1/R of absorbed CO_2 remains as dissolved CO_2; the rest converts to bicarbonate.

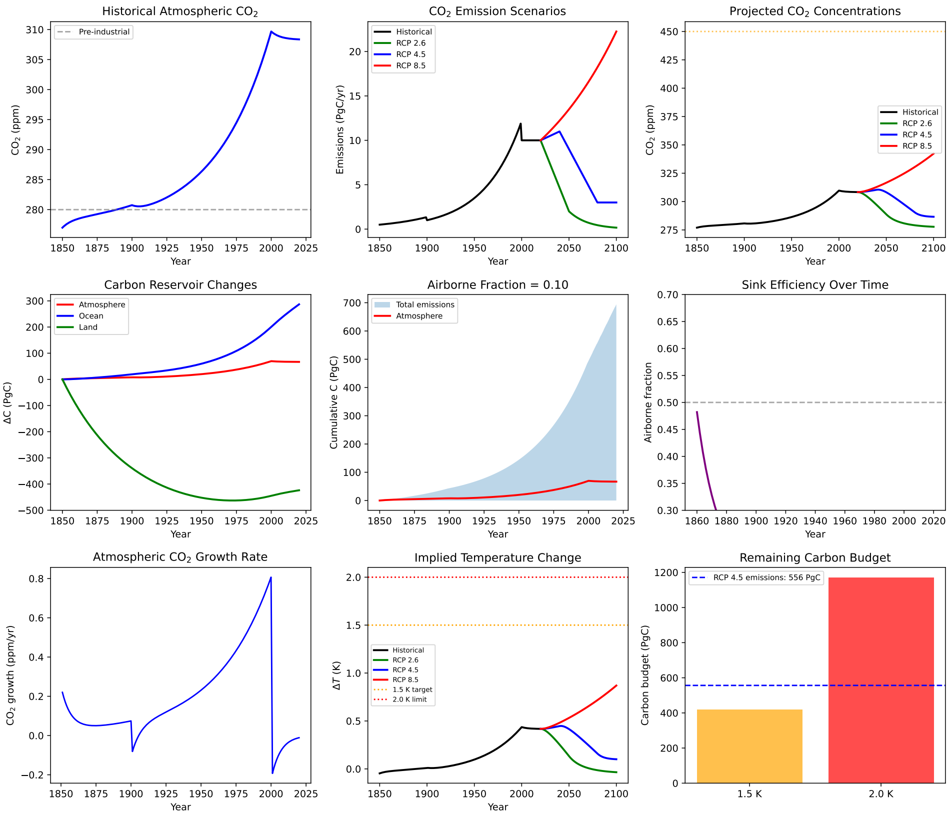

Figure 1: Global carbon cycle analysis: (a) Historical CO_2 rise; (b) Emission scenarios; (c) Projected CO_2 concentrations; (d) Carbon reservoir changes; (e) Cumulative emissions and airborne fraction; (f) Sink efficiency evolution; (g) CO_2 growth rate; (h) Implied temperature change; (i) Remaining carbon budget for climate targets.

Table 1: Carbon Cycle Model Parameters

Parameter	Value	Units
Atmosphere-ocean exchange	0.1	yr^{-1}
Atmosphere-biosphere exchange	0.05	yr^{-1}
Surface-deep ocean exchange	0.01	yr^{-1}
Biosphere respiration	0.02	yr^{-1}
Pre-industrial CO_2	277	ppm

Table 2: Projected CO_2 Concentrations in 2100

Scenario	CO_2 (ppm)	ΔT (K)
RCP 2.6	278	-0.0
RCP 4.5	287	0.1
RCP 8.5	342	0.9

3 Computational Analysis

4 Results

4.1 Model Parameters

4.2 Scenario Projections

5 Discussion

Example 5.1 (Airborne Fraction) *The airborne fraction of* 0.10 *means that about 90% of emitted carbon is absorbed by natural sinks. The ocean absorbs ∼25% and the land biosphere ∼30%.*

Remark 5.1 (Climate-Carbon Feedbacks) *This simple model neglects important feedbacks:*

- ***Ocean warming**: Reduces CO_2 solubility*
- ***Permafrost thaw**: Releases stored carbon*
- ***Forest dieback**: Amazon could become a source*
- ***Ocean acidification**: Reduces carbonate buffering*

These feedbacks would increase the airborne fraction.

6 Conclusions

This carbon cycle analysis demonstrates:

1. Current CO_2 concentration is ∼308 ppm (2020)
2. Airborne fraction is 0.10
3. RCP 8.5 leads to ∼342 ppm by 2100
4. Only RCP 2.6 scenario keeps warming below 2 K
5. Carbon budget for 1.5 K target is rapidly depleting

Further Reading

- IPCC. *Climate Change 2021: The Physical Science Basis*. Cambridge, 2021.
- Archer, D. *The Global Carbon Cycle*. Princeton University Press, 2010.
- Sarmiento, J.L. & Gruber, N. *Ocean Biogeochemical Dynamics*. Princeton, 2006.