Climate Model Development and Simulation Report

Introduction

Climate change is driven by a complex interplay of radiative forcing, feedback mechanisms, and natural variability. While global circulation models (GCMs) provide detailed simulations, simplified models are invaluable for exploring fundamental processes and long-term trends. This report presents the development of a two-layer climate model in Julia, designed to capture both rapid atmospheric responses and slower deep-ocean dynamics. By integrating multiple forcing agents and feedbacks, the model provides a realistic yet computationally efficient framework for studying climate sensitivity and variability.

Model Framework

The model is structured as an **energy balance system** with two reservoirs:

- **Atmosphere/Mixed Layer Ocean:** responds quickly to changes in forcing.
- **Deep Ocean:** acts as a thermal buffer, absorbing excess heat over centuries.

Heat exchange between these reservoirs is governed by a coupling constant, representing vertical mixing and ocean circulation.

Parameters

Key physical parameters include:

- **Solar constant (S_0):** 1361 W/m^2
- **Planetary albedo (α):** dynamic, influenced by ice–albedo feedback
- **Heat capacities:**
  - Atmosphere/mixed layer: 1.0×10^8 J/(m^2·K)
  - Deep ocean: 1.0×10^{10} J/(m^2·K)
- **Outgoing longwave radiation (OLR):**
  - Intercept A = –337.825 W/m^2

- Slope B_0 = 2.0 W/(m^2·K)

- **Coupling constant (k):** 1.0×10^7 W/(m^2·K)
- **Radiative forcing (Fmax):** 3.7 W/m^2, representing CO_2 doubling

Forcing and Feedbacks

The model integrates multiple processes to reflect real-world climate dynamics:

- **Ramp forcing:** gradual CO_2 increase over 200 years.
- **Volcanic eruptions:** cooling pulses at years 100–105 and 600–605.
- **Solar variability:** 11-year cycle, ±0.5 W/m^2.
- **Seasonal cycle:** annual oscillation in solar input (±2%).
- **Stochastic variability:** Gaussian noise to mimic unpredictable natural fluctuations.
- **Feedbacks:**
- Ice–albedo: warming reduces ice cover, lowering albedo and amplifying absorption.
- Water vapor: warming increases atmospheric water vapor, reducing OLR slope.
- Cloud feedback: modifies OLR intercept, influencing both cooling and warming.
- Lapse rate feedback: changes in vertical temperature gradients affect radiative balance.

Results

Simulations over 1000 years reveal several key behaviors:

- **Atmospheric warming:** rapid increase in surface temperature due to ramp forcing.
- **Volcanic cooling:** short-term dips in temperature, followed by recovery.
- **Seasonal oscillations:** annual cycles superimposed on long-term warming.
- **Ocean inertia:** deep ocean warms slowly, lagging behind atmospheric changes.
- **Nonlinear amplification:** feedbacks increase effective climate sensitivity beyond linear expectations.

The equilibrium climate sensitivity (ECS) is calculated as:

ECS = Fmax / B_0 ≈ 1.85 K per CO_2 doubling

This baseline value is consistent with simplified models, though feedbacks raise effective sensitivity over time.

Discussion

The model demonstrates how multiple processes interact to shape climate trajectories. Volcanic eruptions provide temporary cooling, but long-term forcing dominates. Solar cycles add variability, while stochastic noise introduces unpredictability. Feedbacks amplify warming, highlighting the importance of nonlinear processes. The two-layer framework captures both short-term atmospheric responses and long-term ocean heat uptake, making it a powerful tool for exploring climate sensitivity.

Conclusion

The Julia two-layer climate model integrates radiative forcing, feedbacks, volcanic eruptions, solar variability, and stochastic noise into a coherent framework. It successfully reproduces both smooth long-term warming and abrupt short-term events. This balance of realism and simplicity makes it suitable for educational purposes, sensitivity experiments, and scenario testing.