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An Introduction to Simple Climate Models

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Module 1: Introduction

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the core objectives of simple climate models (SCMs) in the context of policy and scientific analysis.
- **Evaluate** the trade-offs between model complexity, computational efficiency, and spatial resolution.
- **Apply** the concept of falsifiability to assess the credibility of climate model projections.

Executive Summary: Climate models are essential tools for predicting anthropogenic impacts across the chain of causality from emissions to physical consequences. While highly detailed Atmosphere-Ocean General Circulation Models (AOGCMs) provide high-resolution simulations, their extreme computational demands necessitate the use of Simple Climate Models (SCMs) for extensive scenario analysis and long-term stabilization projections.

Aims

This Technical Paper serves as a primer on the climate system and SCMs, focusing on two primary objectives:

- **Methodology:** Explaining SCM mechanics, their included processes, and their relative strengths and weaknesses compared to complex models.
- **Documentation:** Detailing the procedures and assumptions used to generate projections for trace gas concentration, global mean temperature change, and global mean sea level rise.

Climate Models as Tools for Scientific and Policy Analysis

The prospect of human activities altering atmospheric composition has stimulated the development of climate system models to provide credible tools for policy analysis before the climate itself changes.

The Modeling Hierarchy

Climate modeling utilizes a **hierarchy of models** with differing levels of complexity, dimensionality, and spatial resolution.

- **Optimization:** No level is inherently better; the choice depends on the specific analytical context.
- **Efficiency:** Modellers avoid coupling detailed sub-models of minor system components with crude models of dominant processes to save computer resources.
- **Simplicity:** The guiding principle is to keep models "as simple as possible, but no simpler".

Complex vs. Simple Models

The most general models are **coupled AOGCMs**, which solve equations by breaking domains into volumetric grids (boxes).

- **Spatial Resolution:** This refers to the size of the grid box; smaller boxes represent higher resolution.
- **Sub-Grid Processes:** Computing limitations prevent AOGCMs from resolving important processes smaller than the grid scale, such as:
  - Cloud formation and radiation interactions.
  - Sulphate aerosol dynamics and ocean plumes.
  - Terrestrial and marine biosphere dynamics.

⚠️ **Safety Constraint:** All climate system models must use **parametrizations**—empirical or semi-empirical relations—to approximate the net effects of sub-grid processes.

The Role of Simple Climate Models

SCMs are utilized when AOGCMs are too time-consuming to run for a wide range of emission scenarios.

- **Ocean Representation:** A standard SCM paradigm is the **one-dimensional upwelling-diffusion ocean**.
- **Mechanics:** The 3D ocean is replaced by a single horizontally-averaged column where temperature and carbon vary only with depth.
- **Heat/Mass Transfer:** The column exchanges energy at the top with a well-mixed surface layer and is fed by cold water from a downwelling polar sea at the bottom.

💡 **Design Tip:** While SCMs typically deal with global averages, they can be used in integrated assessments by scaling regional temperature and precipitation distributions (produced by AOGCMs) to the global mean temperature change.

Model Credibility and Falsifiability

Scientific methodology recognizes that no model can be proven "true" in an absolute sense; instead, the test is whether a model can be proven **false**.

- **Confidence:** The more independent challenges a model passes, the more confidence it earns.
- **Climate Sensitivity:** This is the equilibrium temperature change for a CO2 doubling. SAR WGI estimates this range to be 1.5 to 4.5°C.
- **Estimation Methods:** Four independent methods support this range:

1. 3D AGCM simulations.
2. Observations of radiative damping processes.
3. Reconstructions of ancient (palaeo-) climates.
4. Comparisons of model runs with historical temperature records.

🧮 **Calculation Note:** In simple models, climate sensitivity is directly specified as an input parameter, whereas it is a computed result in AGCMs. The rate at which heat penetrates the thermocline (roughly the first kilometer of ocean depth) is a primary control on realized global warming.

Checkpoint Quiz

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1. **Which technical challenge necessitates the use of "parametrization" in climate models?**
   a) The inability to solve physical laws based on conservation of mass.
   b) The mismatch between important sub-grid processes (like clouds) and realizable grid scales.
   c) The requirement to use only empirical correlations from social sciences.
   d) The inability to use three-dimensional grids in AOGCMs.

Answer: (b). Even complex AOGCMs have resolutions of hundreds of kilometers, which are too coarse to resolve small-scale phenomena like cloud formation.

2. **Why is a one-dimensional upwelling-diffusion model preferred over a single well-mixed box for ocean modeling?**
   a) A well-mixed box requires significantly more computational resources.
   b) A well-mixed box cannot account for the long mixing time of the oceans relative to forcing rates.
   c) The 1D model is the only way to calculate regional precipitation.
   d) Only 1D models can incorporate the concept of falsifiability.

Answer: (b). Mixing times in the ocean are long; a well-mixed box would result in incorrect rates of heat and mass uptake over time.

3. **In the context of the "falsifiability rule," how is confidence in the 1.5 to 4.5°C climate sensitivity range established?**
   a) By proving it is the only possible physical explanation for warming.
   b) By its consistency across multiple, independent methods of estimation.
   c) By ensuring the model resolution is small enough to be "no simpler."
   d) By scaling regional variations to global averages.

Answer: (b). Confidence is gained because independent methods—including AGCM simulations, palaeo-climate data, and historical records—all yield consistent results

Module 2: Climate and the Climate System

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the major components of the climate system and their primary interactions.
- **Evaluate** the role of radiative forcing and feedback mechanisms in determining climate sensitivity.
- **Distinguish** between the climate effects of well-mixed greenhouse gases and spatially heterogeneous aerosols.

Executive Summary: The climate system is a complex network comprising the atmosphere, oceans, biospheres, cryosphere, and land surface. These components are powered by solar energy and interact through various energy and chemical flows to determine the Earth's surface climate. Human-induced perturbations to atmospheric composition alter the radiative balance, triggering "fast" and "slow" feedbacks that ultimately define climate sensitivity.

The Components of the Climate System

Climate is defined as the statistical description of weather in terms of the mean and variability of relevant quantities over periods typically spanning three decades. The climate system consists of five primary interacting components:

- **The Atmosphere**: The gaseous envelope surrounding the Earth.
- **The Oceans**: Major storehouses for heat and carbon.
- **The Terrestrial and Marine Biospheres**: Living organisms on land and in the sea.
- **The Cryosphere**: Includes sea ice, seasonal snow cover, mountain glaciers, and ice sheets.
- **The Land Surface**: The physical characteristics of the Earth’s continents.

These components interact via flows of energy, water, and trace gases like carbon dioxide (**CO2**) and methane (**CH4**). In its natural state, these flows remain closely balanced over decades.

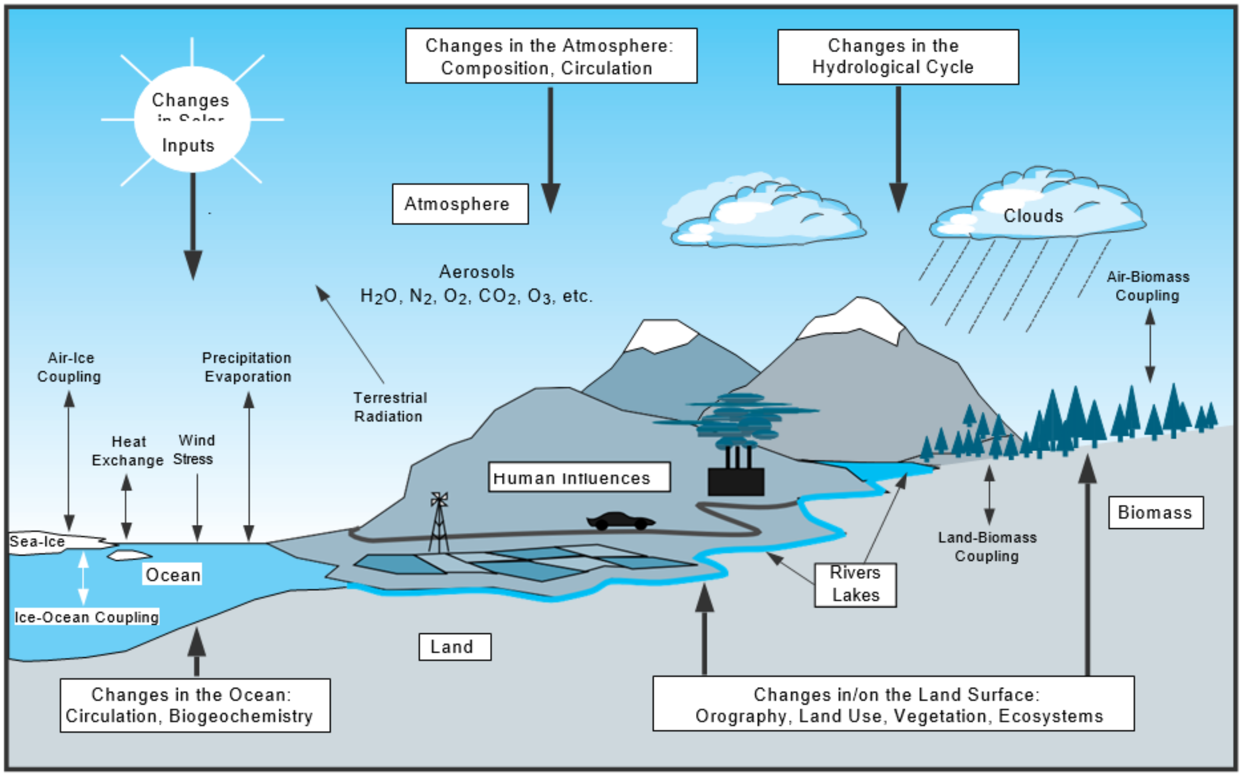

Figure 1. Schematic overview of the components of the global climate system that are relevant to climatic changes on the century time-scale (bold), their processes and interactions (thin arrows) and some elements that may change (bold arrows) (reproduced from SAR WGI, Figure 1.1).

Human Perturbations to the Atmosphere

Greenhouse Gases

Greenhouse gases (**GHGs**) reduce the loss of infrared heat to space, warming the surface.

- **Naturally Occurring GHGs**: These include water vapour (**H2O**), carbon dioxide (**CO2**), ozone (**O3**), methane (**CH4**), and nitrous oxide (**N2O**).
- **Anthropogenic GHGs**: Purely human-made gases include halocarbons (**CFCs**, **HCFCs**, **HFCs**) and sulphur hexafluoride (**SF6**).
- **Mixing Characteristics**: With the exception of ozone, these gases are **well-mixed** in the atmosphere, meaning their concentration is consistent globally regardless of where emissions occur.