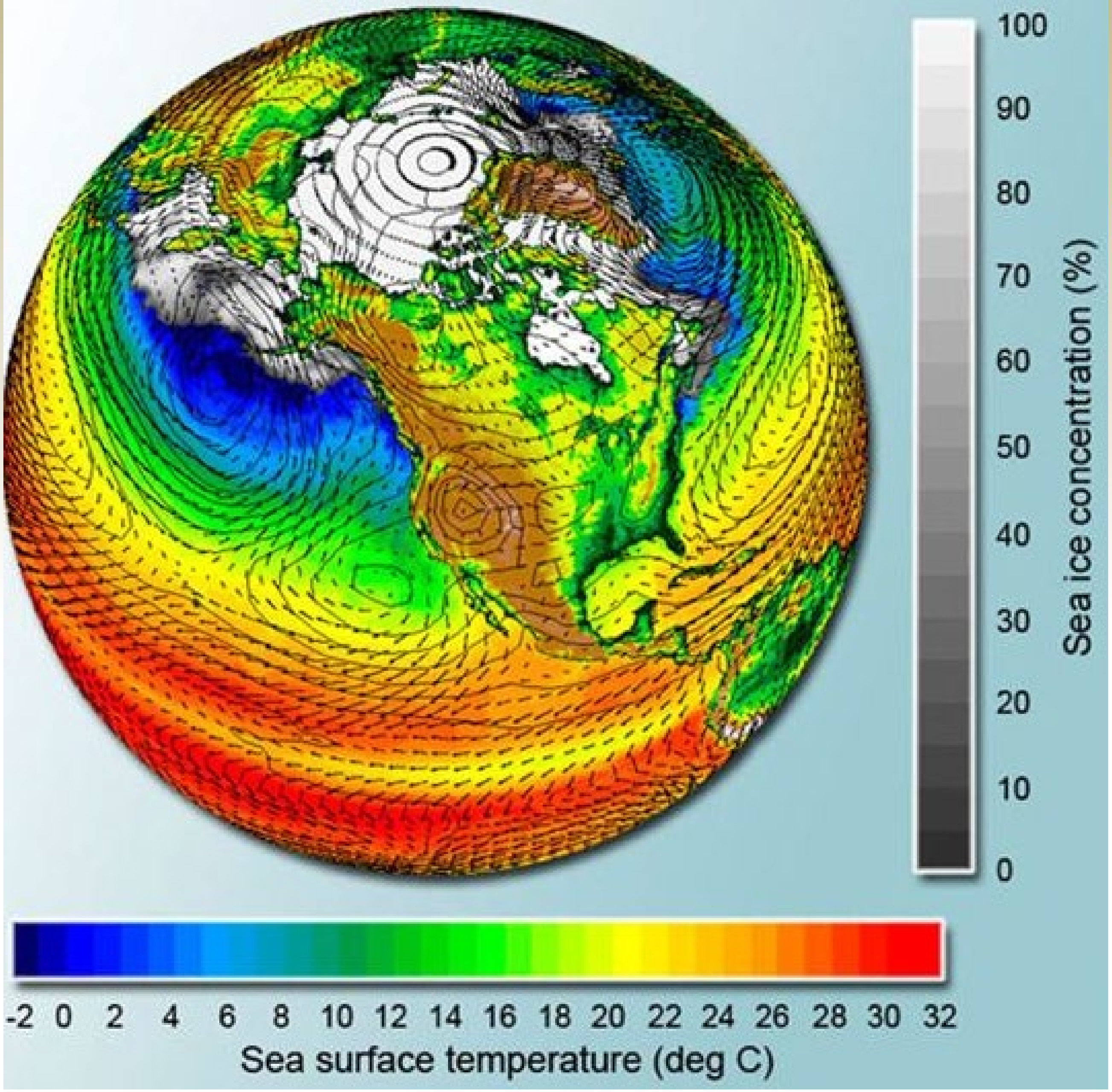
CLIMATE MODELS



PREDICTION IS DIFFICULT PARTICULARLY IN THE FUTURE.

NIELS BOHR

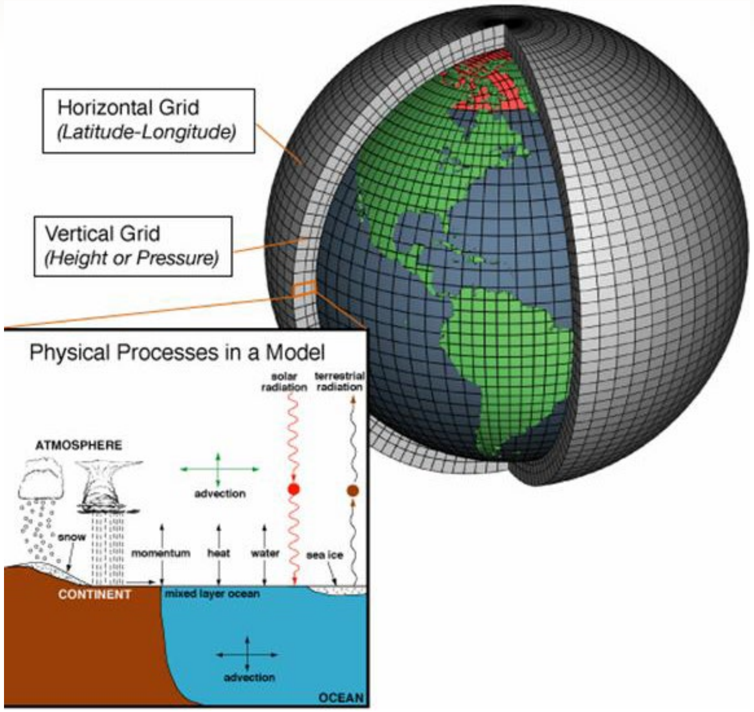
Source images: Ruddiman, 2007

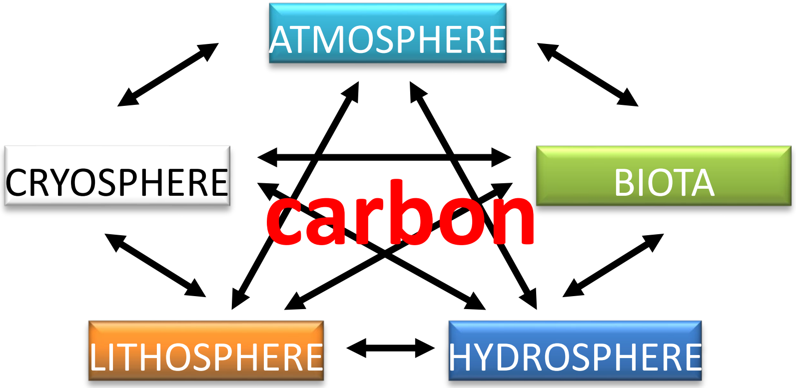
CLIMATE MODELS

Climate scientists use two types of models:

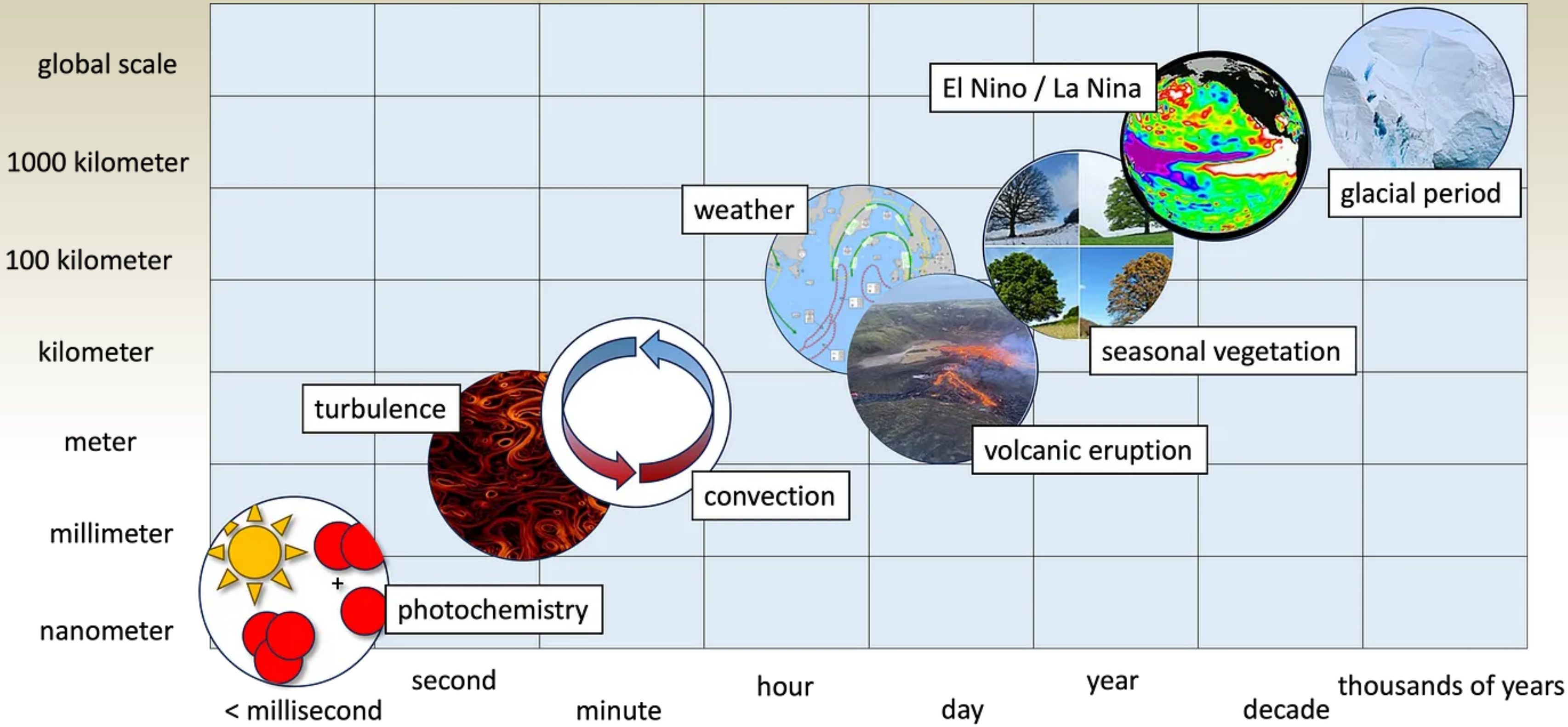
Physical Climate Models:
They are mathematical representation of physical processes in the atmosphere, ocean, land surface, biosphere and cryosphere across various spatial and temporal scales.

•**Geochemical Climate Models**:
They model the movement of specific chemical tracers within climate system components.





CLIMATE MODELS



Schematic of the time scale across which different Earth system processes act.

https://www.climatechangeinaustralia.gov.au/en/learning-support/climate-models/theory-and-physics

BUILDING A CLIMATE MODEL

The physical laws and relationships required to model the climate system are translated into **equations**:

- **Empirical equations:** Derived from observed **real-world relationships**, where the link between elements in sets X and Y is obtained **through experimental measurements** (e.g., Clausius-Clapeyron relation, often used to describe the relationship between temperature and the saturation vapor pressure of water in the atmosphere).

- **Primitive equations:** Represent **theoretical relationships**, where the link between elements in sets X and Y is obtained through a mathematical formula (e.g., the equation of motion used to simulate atmospheric circulation, describing how air masses move and interact under pressure, gravity, and other forces).

- Combinations of both.

Equations solved using finite methods must account for spatial-temporal resolution, or the step size used.

HOW TO SIMPLIFY THE CLIMATE SYSTEM

All models simplify the complex climate system due to:

- Limited understanding of the climate system
- Technical (computational) constraints

Climate system simplification can be achieved by:

- Concentrate on key variables (e.g. CO_2 levels, and ocean circulation)
- Using Conceptual Models to simplify processes into basic concepts
- Applying Empirical Relationships to streamline complex processes
- Reducing Temporal and Spatial Resolution
- Focusing on Major Components (e.g. atmosphere, oceans, and ice, and key interactions)

PHYSICAL CLIMATE MODELS

Most physical models are built to simulate the current functioning of the climate system.

The simulation of the current climate is called the **CONTROL CASE**.

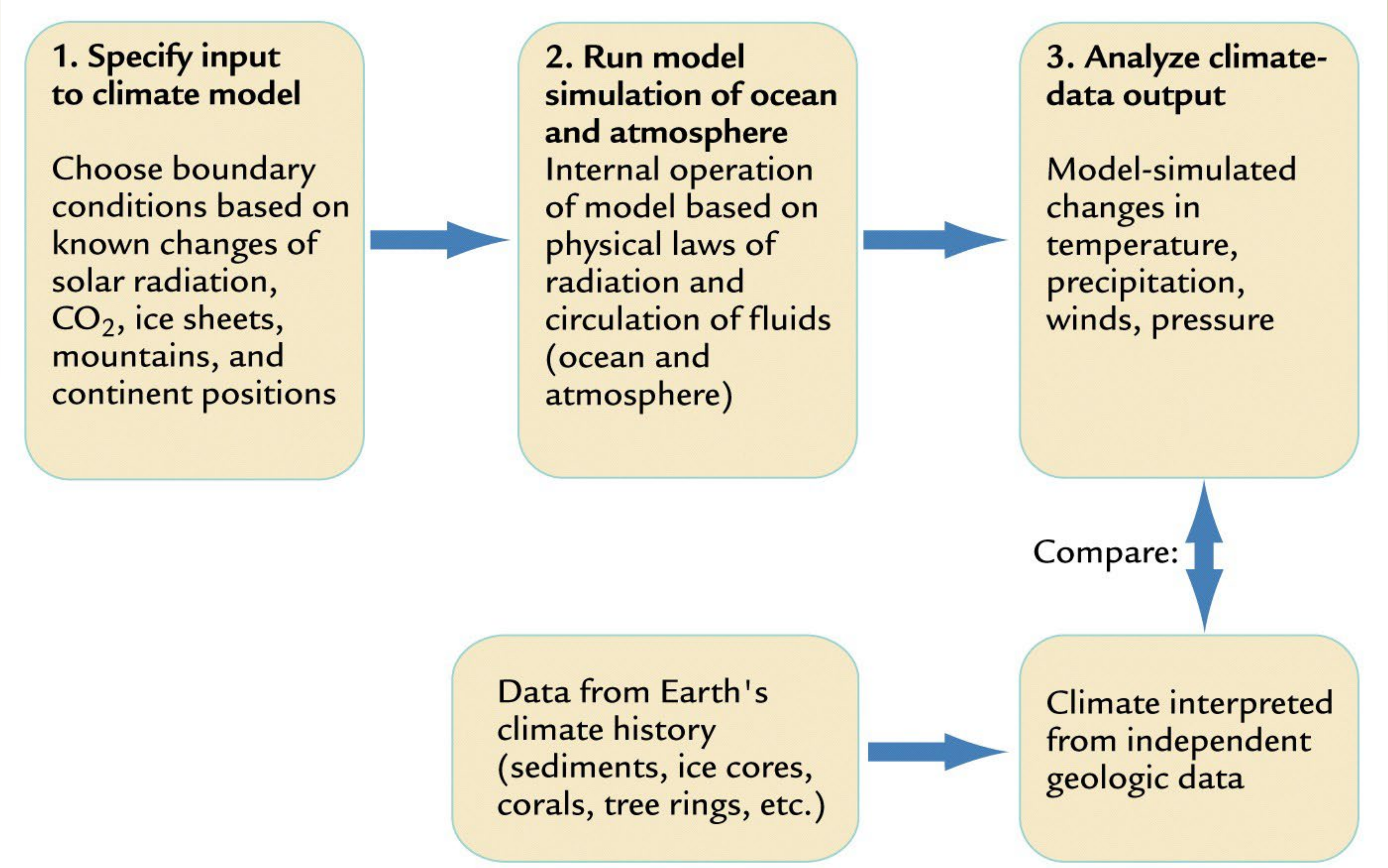
Simulating past climates involves three steps:

1. **Choose the experiment**: One or more parameters (e.g., CO_2 levels) are adjusted from present conditions to simulate past climates. These modified features are known as **BOUNDARY CONDITIONS**.

2. **Model operation**: Physical laws are applied to describe energy flow in Earth's climate system.

3. **Analyze CLIMATE DATA OUTPUT**: Did changes in boundary conditions lead to climate variations consistent with the initial hypothesis?

HOW A MODEL WORKS



ATMOSPHERIC MODELS

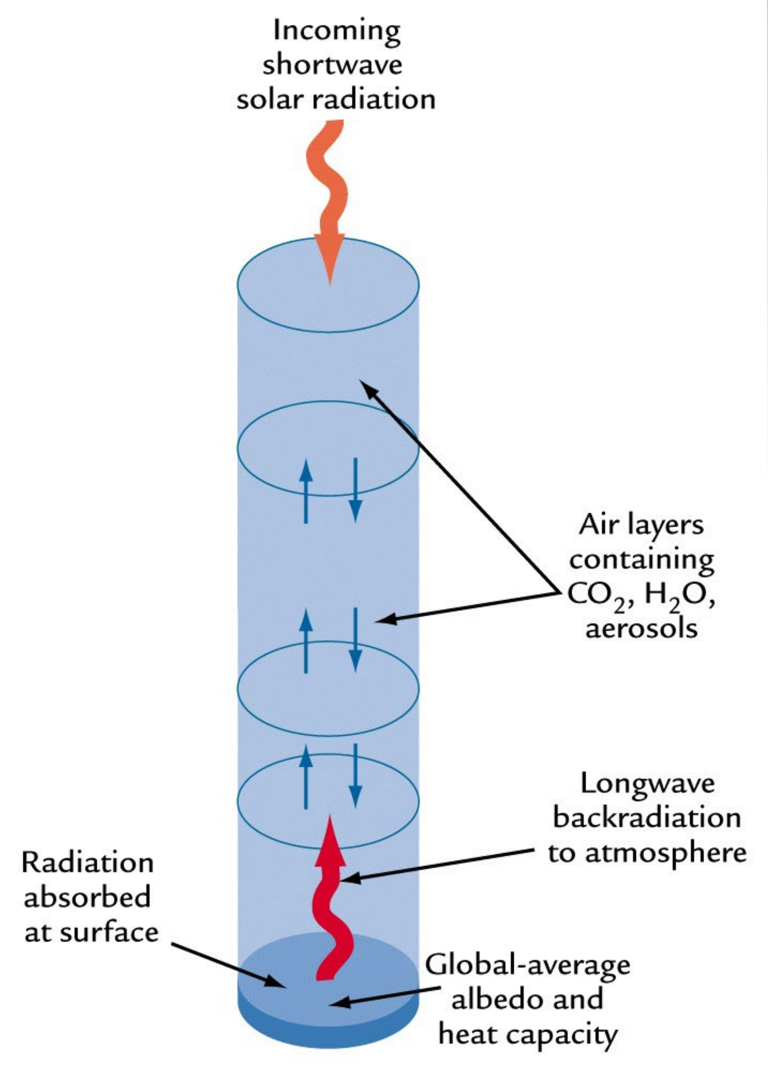
One-dimensional "column" 1-D models are the simplest models.

They simulate a single vertical air column representing the average atmospheric structure of the entire planet.

This column is divided into layers, each containing key constituents (greenhouse gases, dust).

The Earth's surface is represented by a global average value with the mean properties of water, land, and ice.

1-D models help to understand the climate effects of greenhouse gases and aerosols (volcanic ash and dust).

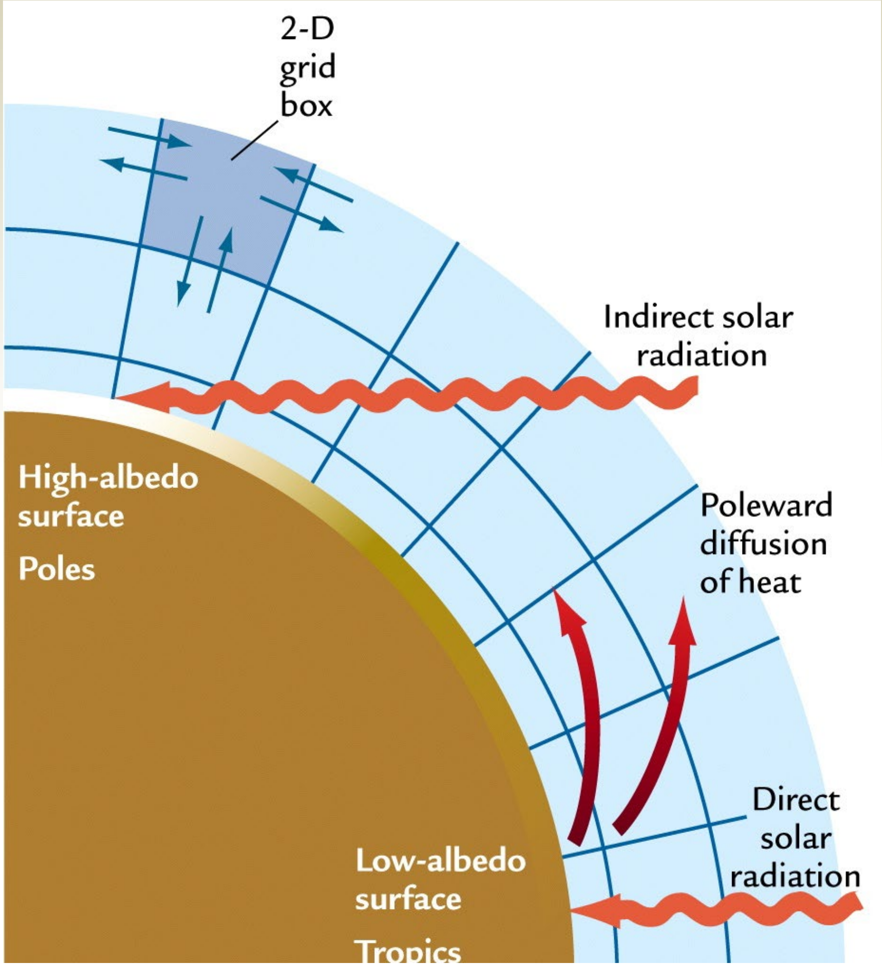


Two-dimensional 2-D models

Two-dimensional (2-D) models are more complex and provide a fuller view of the climate system.

One type includes a multi-layered atmosphere, with the second dimension representing the Earth's average physical properties by latitude.

This model can simulate processes that vary with latitude (e.g., albedo, solar angle, heat capacity) and can easily cover long time periods.
It is often used to explore long-term interactions between the ocean surface, sea ice, and land surface.



Two-dimensional 2-D models

- **Advantages**
  Simulates long time intervals quickly and cost-effectively.

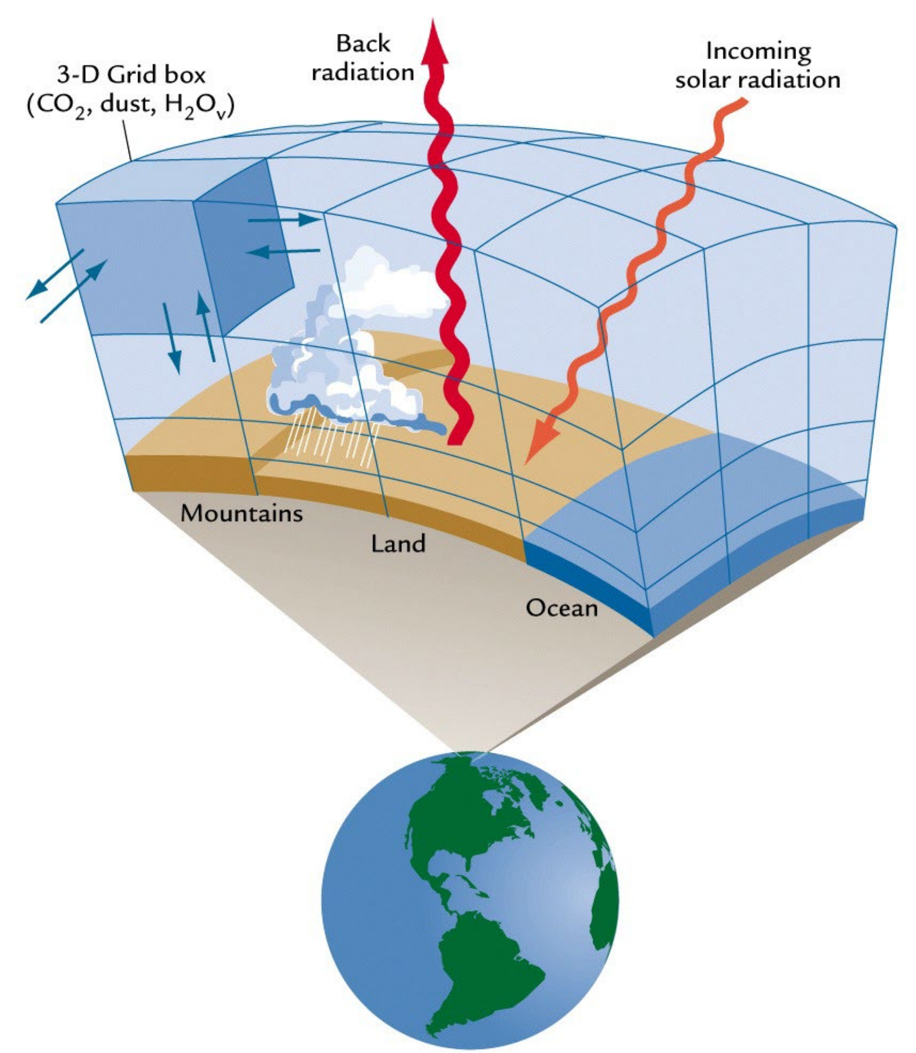
- **Disadvantages**
  Not sensitive to climate processes that depend on the geographic location of continents and oceans.

Three-dimensional 3-D models

Three-dimensional 3-D Atmospheric General Circulation Models (A-GCMs)

These models can represent the distribution of land, water, and ice; mountain and ice cap elevation; the amount and vertical distribution of greenhouse gases; and seasonal variations in insolation.

They require at least 20 years of simulation (15+5).



Three-dimensional 3-D models

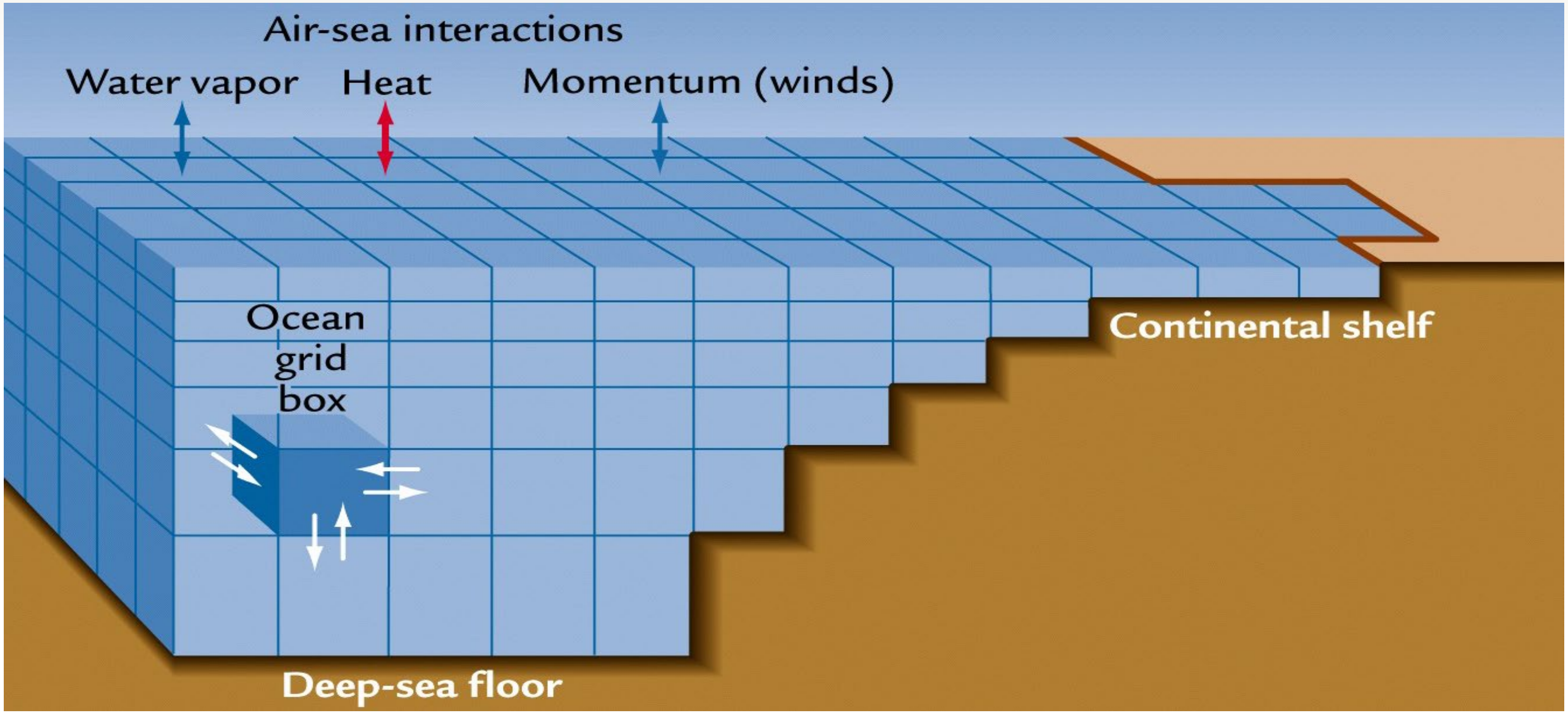
Sensitivity test: Modify only one boundary condition and compare with the control case. The difference reflects the impact of the changed boundary condition.

However, real reconstructions require adjusting multiple boundary conditions, which are often unknown (except for the last glacial-interglacial period).

The current resolution is about 2° latitude and 3° longitude, allowing features like New Zealand and Italy to be visible.

Three-dimensional 3-D Oceanic (O-GCMs)

- Similar to A-GCM construction, these models are more basic than atmospheric ones due to limited knowledge of ocean circulation mechanisms.
- Vertical layers are denser near the surface, where exchanges are more dynamic.
- Typical outputs include temperature, salinity, ice extent, and gas content.



Three-dimensional 3-D Oceanic (O-GCMs)

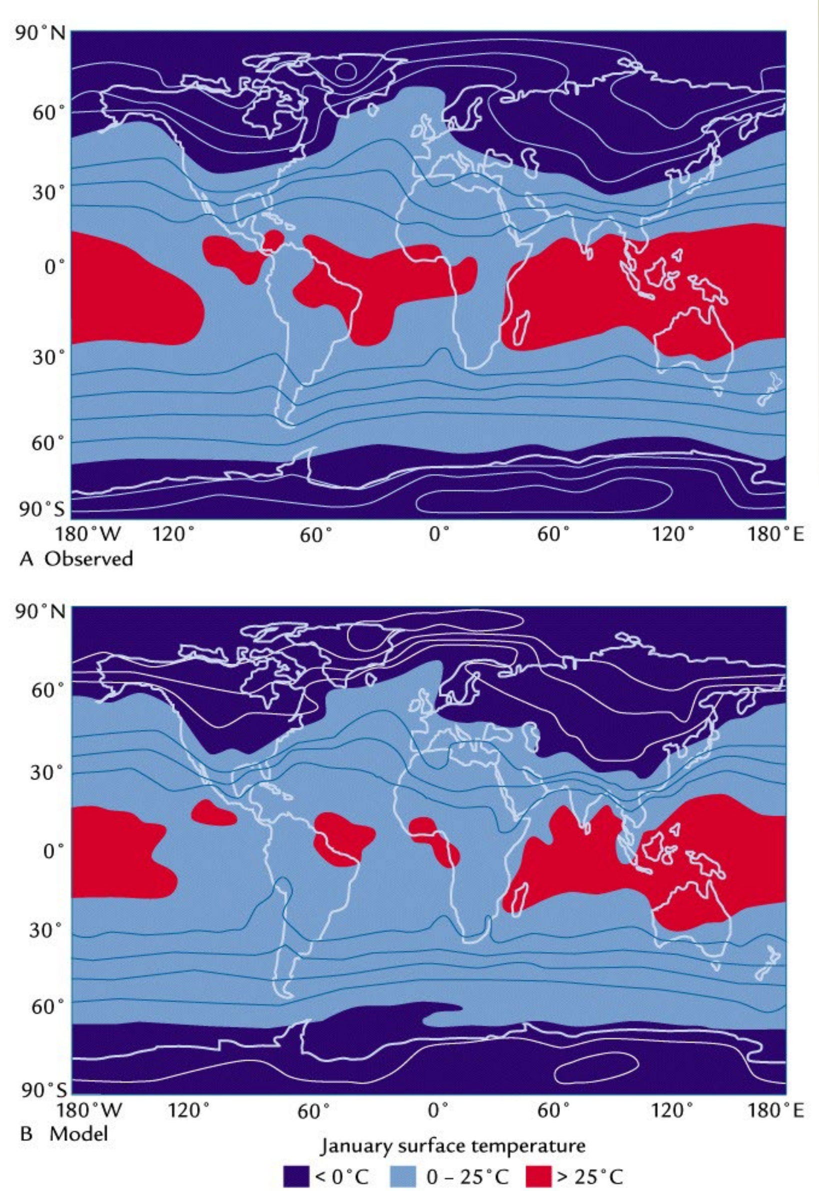
ADVANTAGES

- These models can ignore very short-term interactions, unlike atmospheric models.

DISADVANTAGES

- The main limitation remains resolution (GRID BOX volume).

- Different exchange times create asynchrony that must be resolved when ocean and atmosphere models interact (**asynchronous coupling**).



Ice Sheet Models and Vegetation Models

Ice Sheet Models (2-D and 3-D)

These models are primarily 2-D and operate over long time scales, unlike A-GMCs, which work on much shorter scales.

They can be combined with 2-D atmospheric models to simulate interactions between ice, atmosphere, and land.

Some 3-D models simulate ice accumulation in specific regions (e.g., Antarctica).

Vegetation Models

Vegetation is a key part of the climate system.

In modern models, vegetation is interactive.

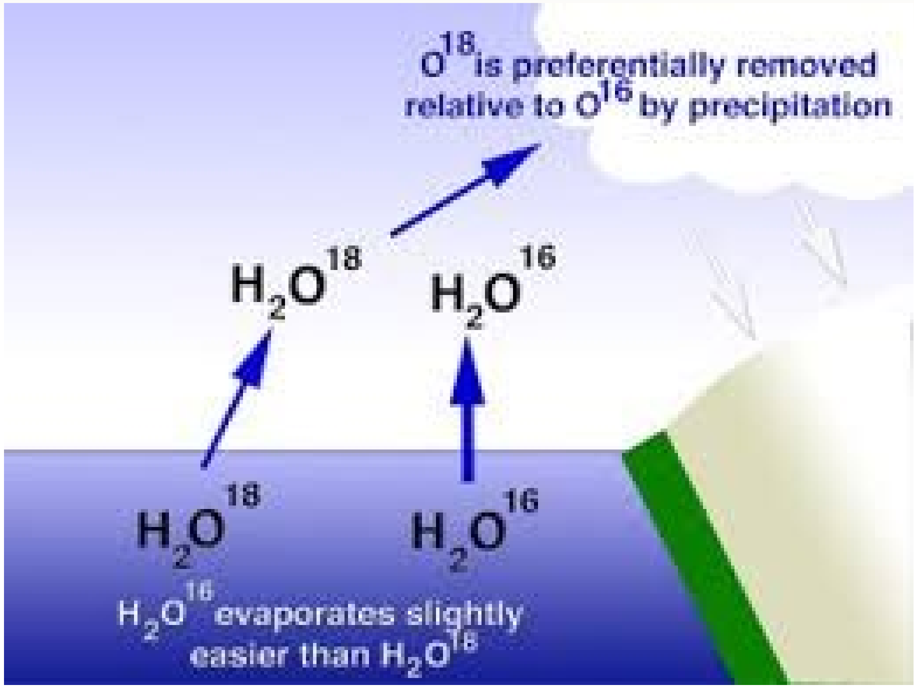
Data from experiments with temperature and precipitation changes (GCMs) serve as input, allowing the vegetation model to simulate results, which are then used as input in other GCMs. It’s a complex process.

GEOCHEMICAL MODELS

In paleoclimatology, geochemical models are tools used to simulate and **track the movement** and distribution of chemical/physical elements and isotopic tracers within the climate system.

These models help identify sources, transfer rates, and deposition pathways of materials like **sediments from physical weathering and ions from chemical weathering.**

By analyzing these geochemical flows, scientists can reconstruct past climate conditions and understand processes like ocean circulation, carbon cycling, and atmospheric composition over geological timescales

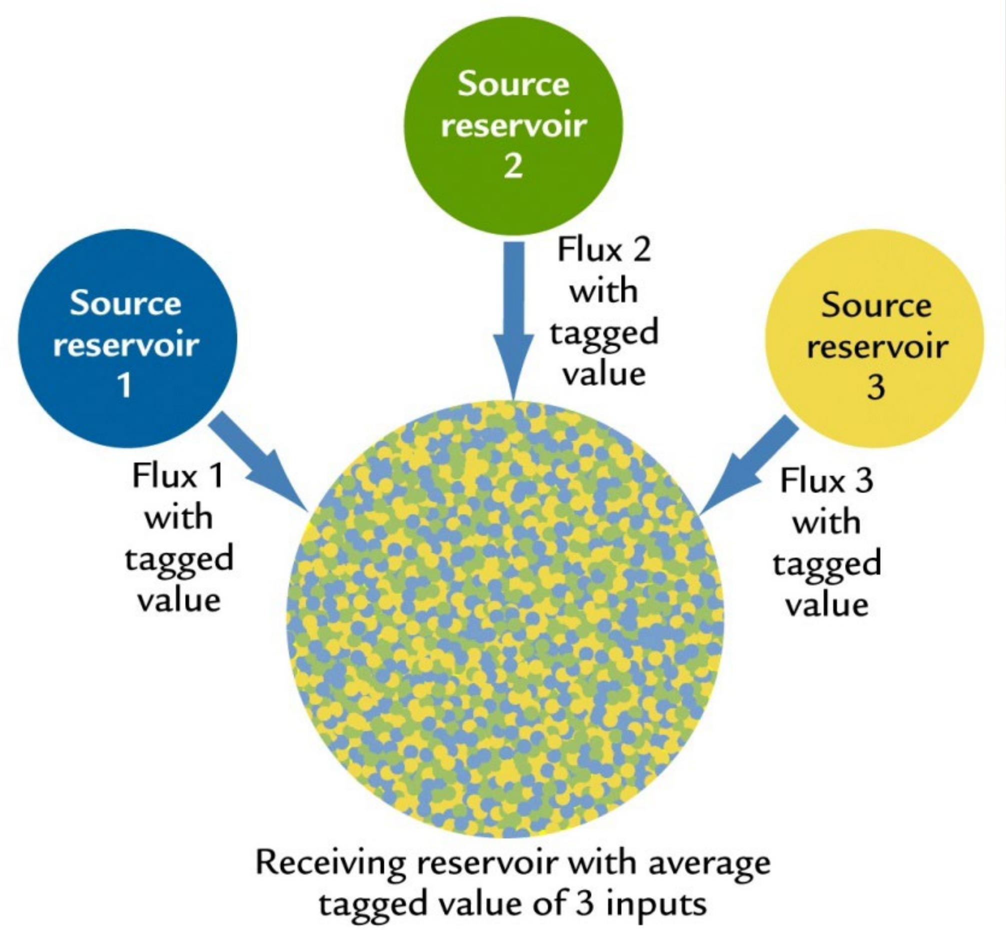


GEOCHEMICAL MODELS

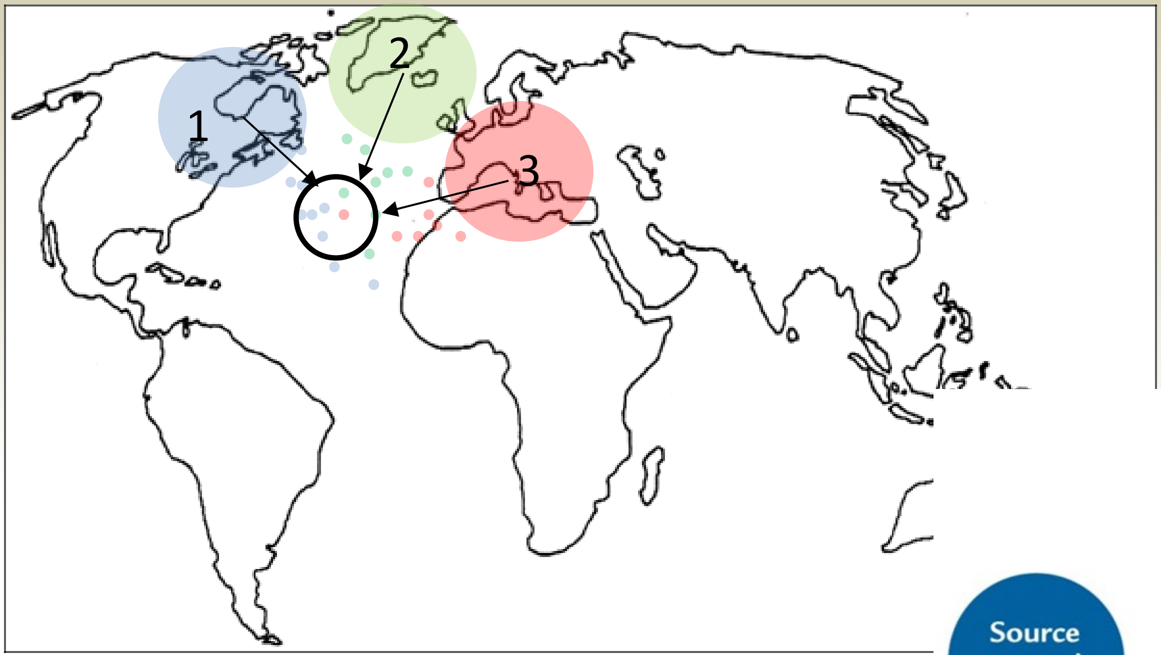
ONE-WAY TRANFER MODEL

One-Way Transfer Model is a model that simulates the one-directional transfer of materials or elements from a source to a final reservoir, without feedback or return cycles.

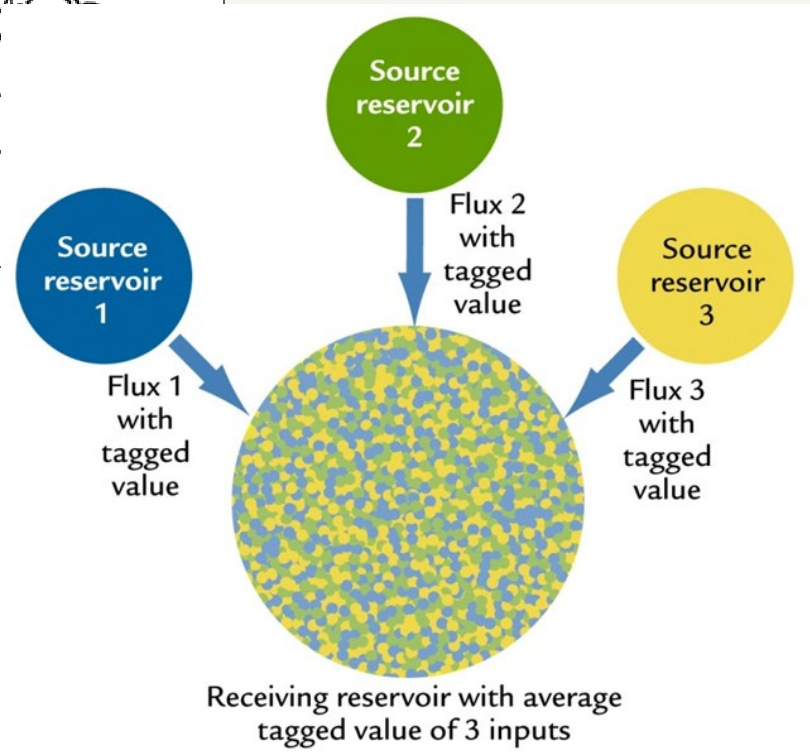
In paleoclimatology, these models are used to trace the flow of materials, such as ice-rafted debris, quantifying climate-related processes like iceberg production or continental erosion.



GEOCHEMICAL MODELS



ONE-WAY TRANFER MODEL



Example:
quantifying the amount of ice-rafted debris involves extracting sands from sediment and separating minerals from fossils.
This analysis quantifies processes—such as changes in iceberg production and flow—that are climate-related.
Further in-depth investigations can also be conducted

GEOCHEMICAL MODELS

To develop geochemical models, **mass balance equations are often used**. These equations allow tracking the input, output, and accumulation of elements or chemical compounds within various reservoirs (such as oceans, atmosphere, sediments), helping to understand and quantify geochemical flows and their variations over time.

- Simple mass balance

  $F_{total} = F_1 + F_2 + F_3$

- Tracer mass balance

  $T_R = (F_1T_1 + F_2T_2 + F_3T_3)/(F_1 + F_2 + F_3)$

  dove

  T_1, T_2, T_3 *= valore iniziale dei singoli componenti presi in considerazione*

  T_R *è il valore medio degli elementi presi in considerazione*

- Mass balance of two components in the system

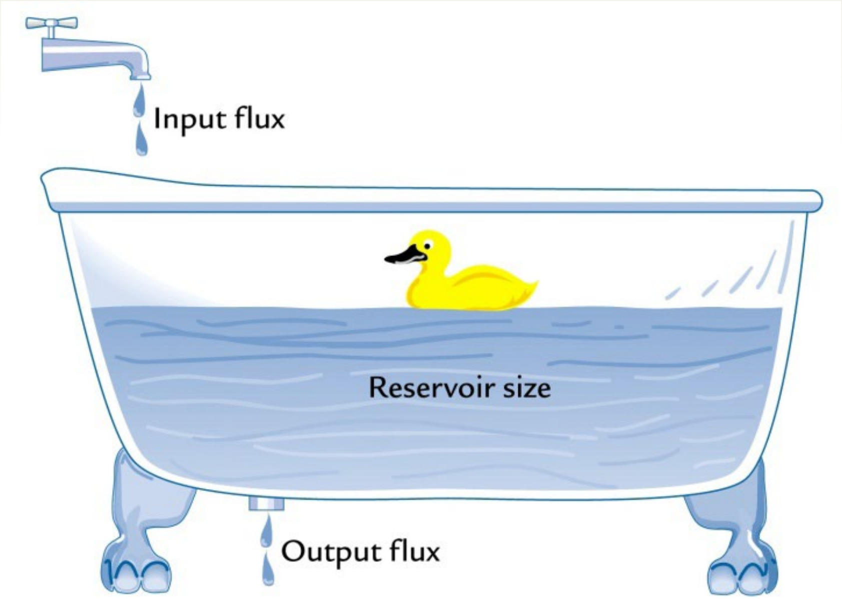
  Tracer entering = tracer leaving

  $T_R = f_{in}T_{in} + (1 - f_{out})T_{out}$

GEOCHEMICAL MODELS

CHEMICAL RESERVOIR –EXCHANGE MODELS

For geochemical tracers transported as dissolved ions, a different modeling approach is used. Mass balance models divide Earth's system into reservoirs (atmosphere, ocean, ice, vegetation, sediments). The ocean is crucial, as it receives erosion products, interacts with other **reservoirs**, and allows tracer deposition/sequestration.



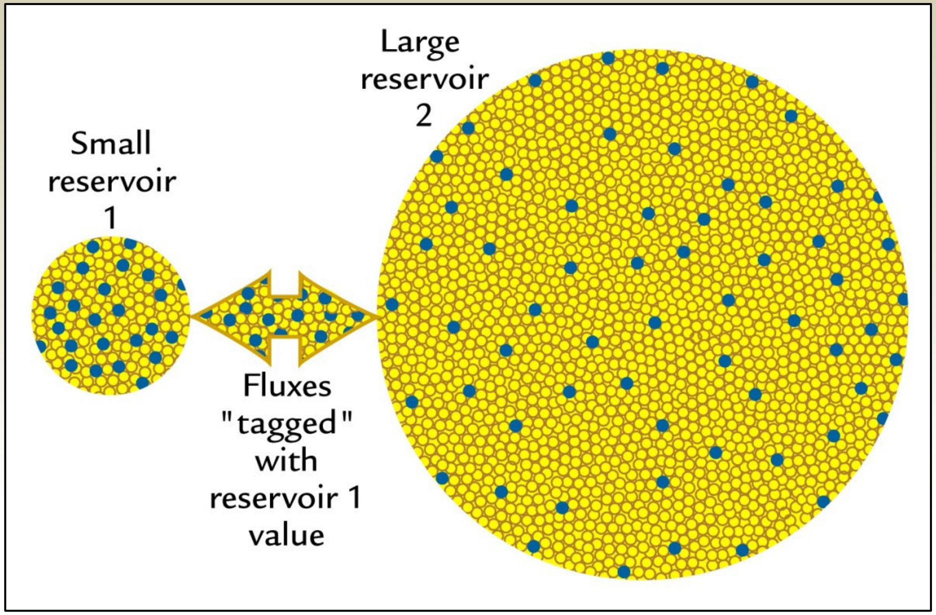
At steady state:
INPUT FLUX = OUTPUT FLUX

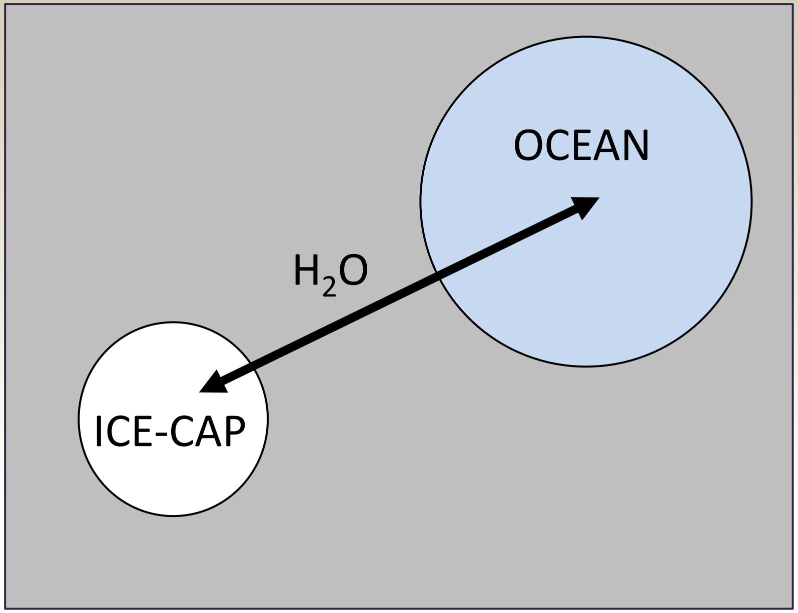
RESIDENCE TIME =
RESERVOIR SIZE / FLUX RATE (in or out)

Residence time is the time a tracer takes to pass through a reservoir.

The bathtub example is a simple version of this model because tracers can move between two or more reservoirs and in all directions.

RESERVOIR - EXCHANGE MODELS





In paleoclimatology, these flux variations are particularly interesting.

Examples:

- H_2O flux between the ocean and ice sheets, with cycles tied to the periodicity of orbital parameters (through isotopic studies).
- Carbon flux between terrestrial vegetation and the marine carbon reservoir (through isotopic studies).