College of Agriculture & Environmental Sciences

The climate system & models

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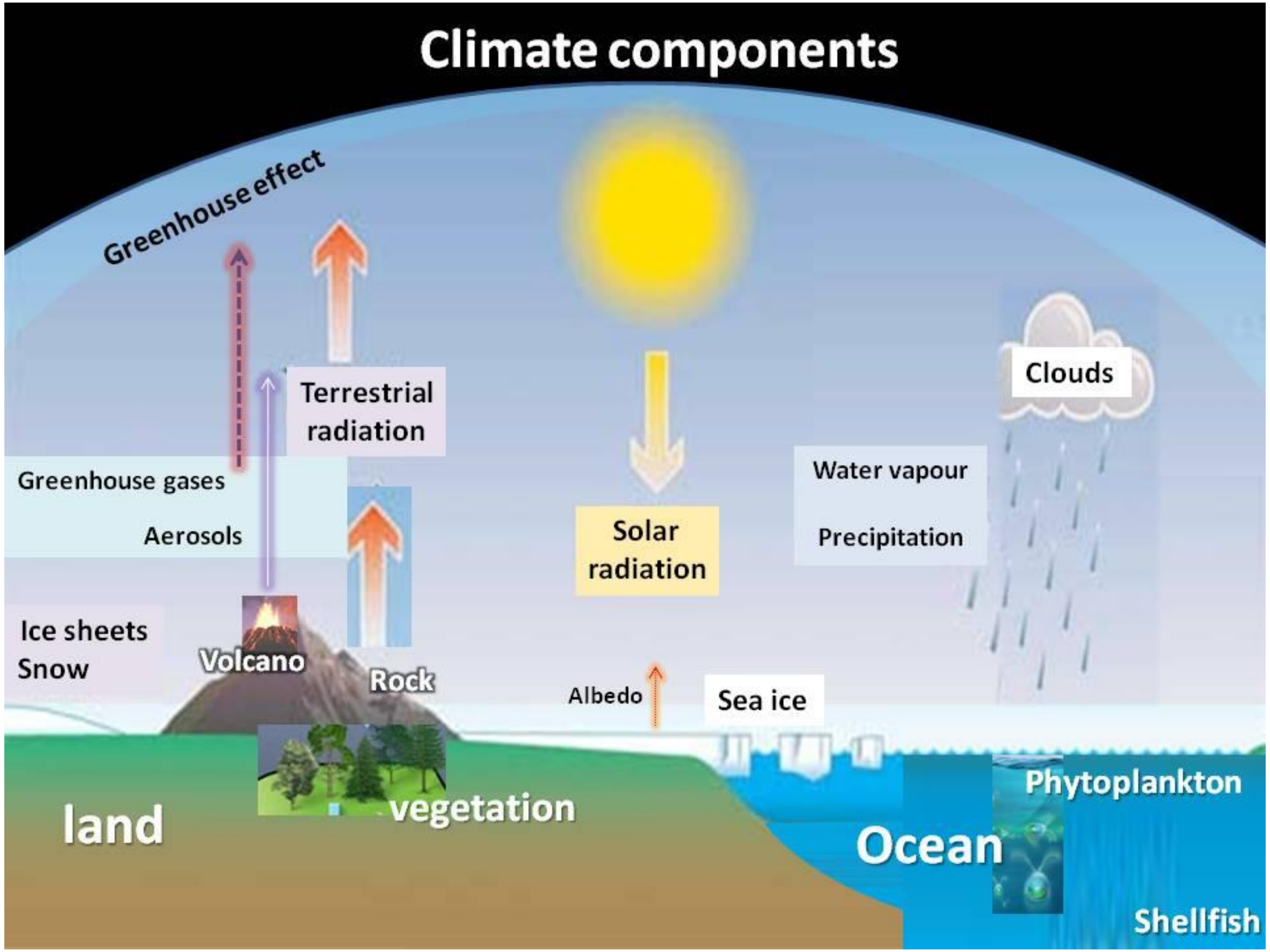
The climate system components

To understand the climate and estimate its evolution and changes, the five components of the climate system should be considered:

- **Atmosphere (**the envelope of gas surrounding the Earth)
- **Hydrosphere** (contains the liquid water of the Earth's surface and underground (e.g., oceans, rivers, lakes)
- **Cryosphere (**contains water in its frozen state (e.g., glaciers, snow, ice…))
- **Lithosphere (**which is the upper layer of solid Earth on land and oceans)
- **Biosphere (**that contains all the living organisms and ecosystems over the land and in the ocean)

The climate system components



Schematic view of the components of the climate system and some of their processes and interactions. *Source: https://www.onlyzerocarbon.org*

The interactions and exchanges of energy and matter between the climate system components influence the climate dynamics, its state, and changes.

- The atmosphere drives weather systems and transports heat and moisture around the globe.

  Their GHG trap outgoing infrared radiation, warming the planet (the natural greenhouse effect).

  Aerosols (tiny particles) can reflect or absorb solar radiation and influence cloud formation.

- The oceans

  store a great part of solar radiation;

  they help distribute heat around the globe

  absorb and store carbon dioxide and play an important role in the water cycle.

- Sea ice cover reduces the intensity of the heat coming from the ocean to warm the air.

  A decrease in snow cover can lead to a decrease in surface albedo which in turn increases the absorbed solar radiation by the surface and leads to increased local air temperature.

- The forests influence climate by affecting the amount of carbon dioxide in the atmosphere (Carbone cycle).

  They remove carbon dioxide from the atmosphere and store it over long periods. They can restore it as they are removed.

- Changes in the biosphere through for example land use can influence surface albedo and then the reflected solar radiation amount by the earth surface.

  Plants release water vapor into the atmosphere (Evapotranspiration). Plants can release volatile organic compounds that can form aerosols.

- Irrigation increases soil moisture and evapotranspiration, which can cool the local area and increase humidity.

- Lithosphere:

  Topography (mountains);

  Surface properties affects albedo;

  Surface roughness influences winds;

  Soil moisture plays an important role in the water cycle and energy balance at the land surface.

Drivers of variability and change

What are the possible causes of climate variability and change?

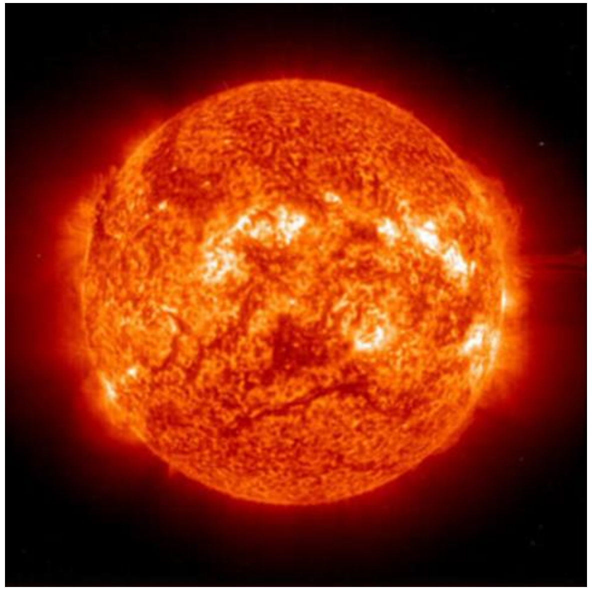
Drivers of variability and change

- Climate may change due to **natural internal processes** to the climate system involving one or more components.

- It can be due to **external natural forcings** such as:

  - Modulations of the solar activity which can for example influence temperatures

  - Large volcanic eruptions may increase the concentration of aerosols. These aerosols reflect solar radiation, leading to a temporary global cooling effect for a few years (typically lasting 1-3 years).



earthobservatory.nasa.gov

www.express.co.uk

➔ **Climate variability**

Refers to natural fluctuations in the climate system that occur on various timescales, from seasons to decades or even centuries, without any long-term trend

Drivers of variability and change

Natural long-term changes:

- Orbital Changes (Milankovitch Cycles):
  - Slow, cyclical changes in Earth's orbit around the Sun that occurs over tens of thousands to hundreds of thousands of years.
  - They alter the amount and distribution of solar radiation reaching Earth's surface ➔ the primary pacemaker of ice ages.
- Eccentricity: Changes in the shape of Earth's orbit (more circular to more elliptical).
- Obliquity (Axial Tilt): Changes in the angle of Earth's axis.
- Precession: Changes in the direction of Earth's axis of rotation.
- Plate Tectonics:
  - The movement of tectonic plates changes (over millions of years) the configuration of continents and ocean basins, influencing ocean currents, affecting atmospheric circulation

Drivers of change

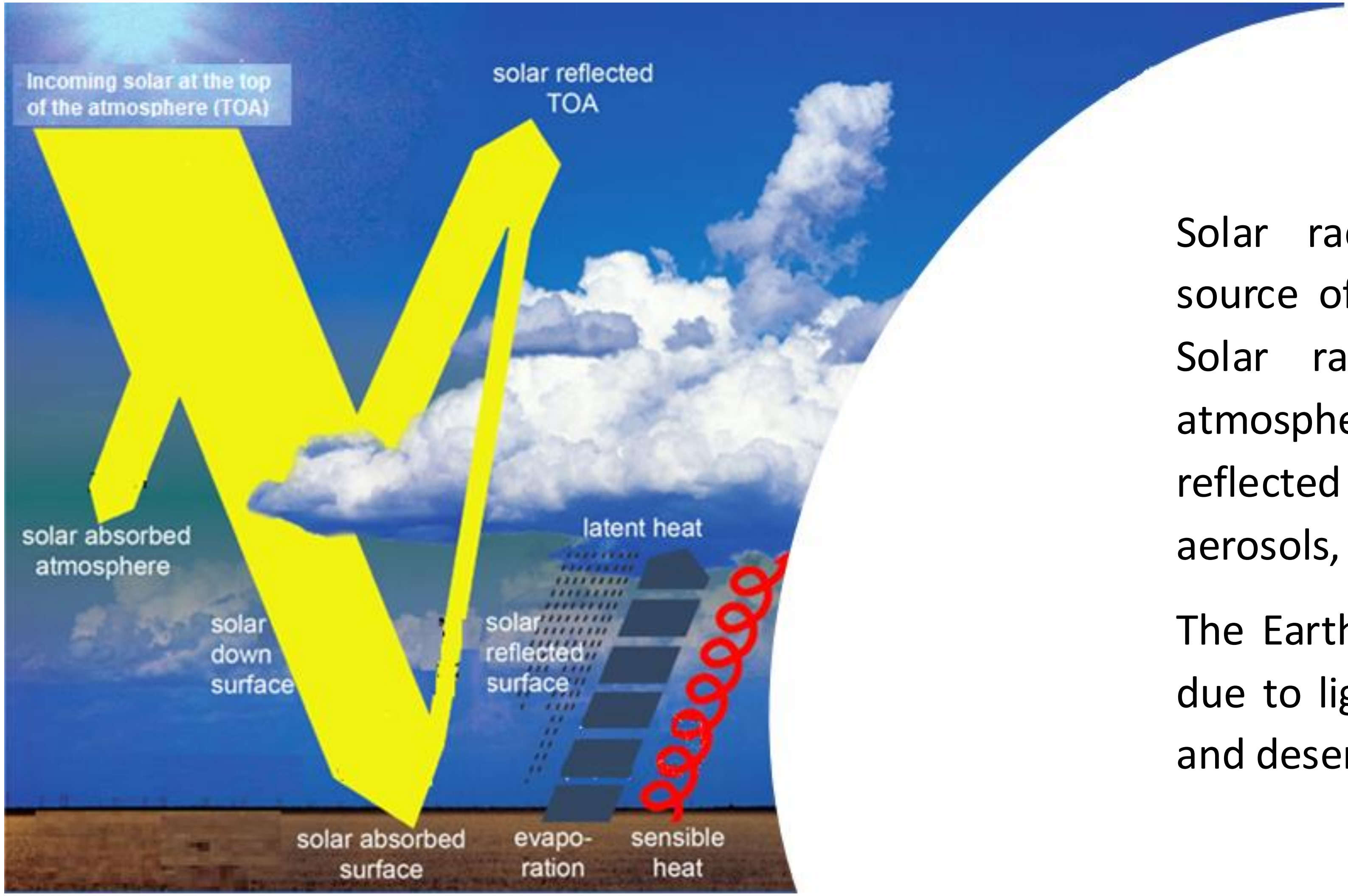
it can result from persistent human induced (anthropogenic) changes in the composition of the atmosphere (e.g. GHGs, Aerosols) or the changes in land use.

UN Photo/Kibae Park

Climate change refers to a significant and persistent change in the statistical properties of the climate system over periods longer than those associated with natural variability (typically decades or longer)

What is the Greenhouse Gas effect on climate?

GHG effect



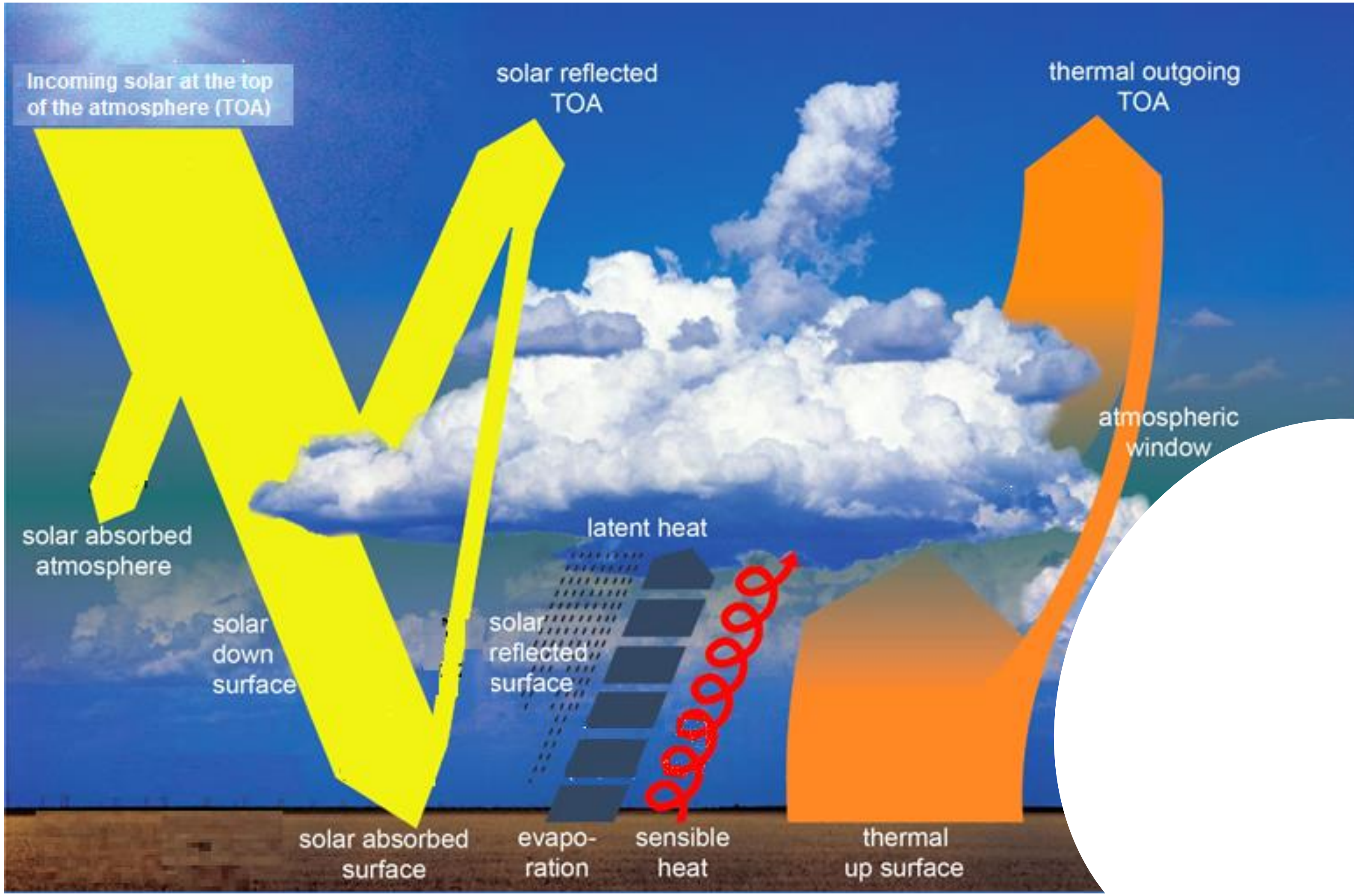
Global mean energy budget under present-day climate conditions

Source: IPCC AR5 (adapted)

Solar radiation represents the main source of energy for the earth. When Solar radiation reaches the earth's atmosphere, a part of it (nearly 30 %) is reflected into space by the clouds, aerosols, and surface earth.

The Earth’s surface reflectivity is mainly due to light-colored areas like snow, ice and deserts.

GHG effect

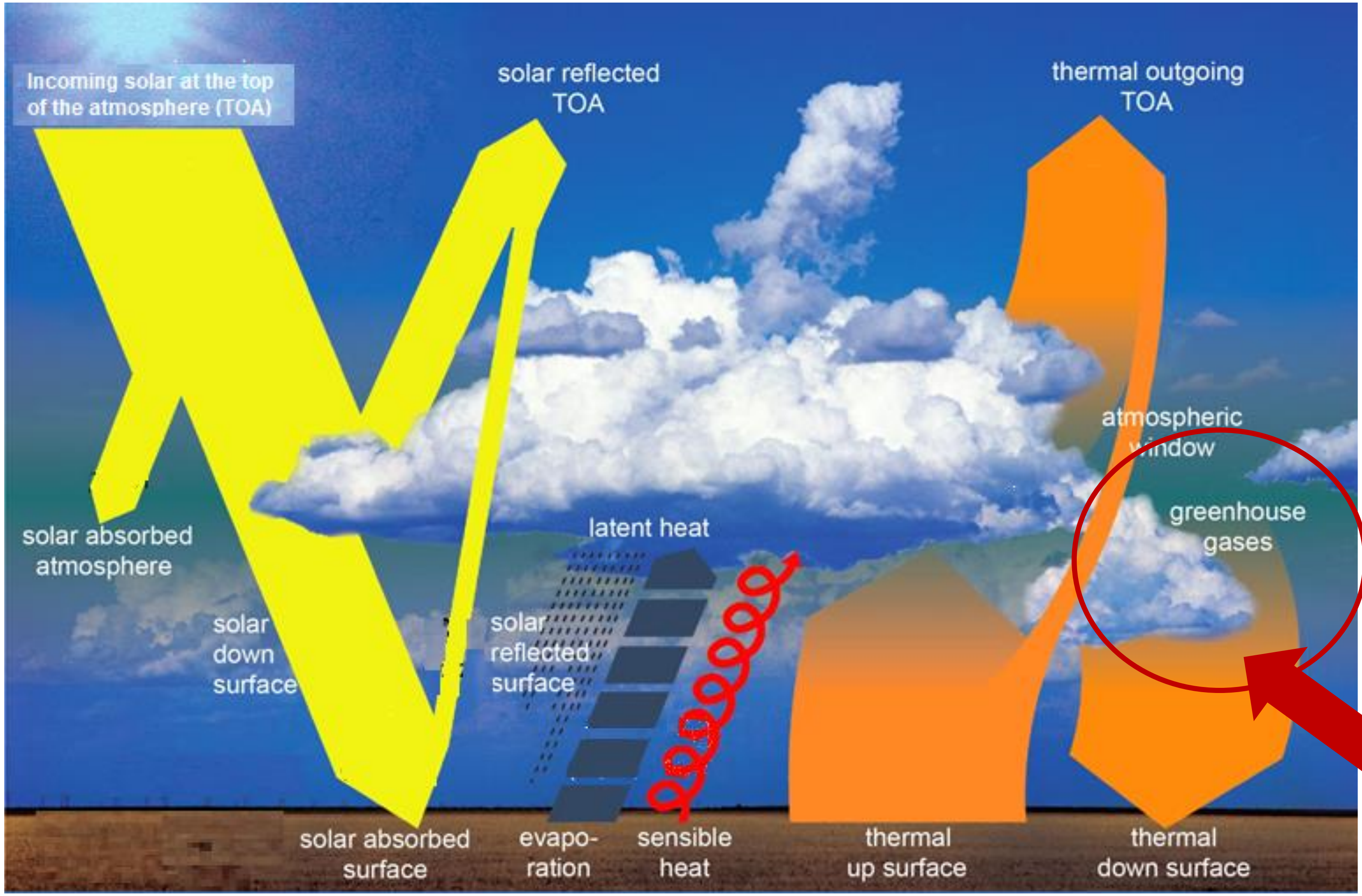


Global mean energy budget under present-day climate conditions
Source: IPCC AR5 (adapted)

The energy that is not reflected into space is absorbed by the Earth's surface and the atmosphere.

To balance the incoming energy, the Earth itself must radiate the same amount of energy back to space. Emitting this quantity of energy would result in a global mean surface temperature much colder than the real conditions by about 33°C.

GHG effect



Global mean energy budget under present-day climate conditions
Source: IPCC AR5 (adapted)

The greenhouses in the atmosphere retain a part of the reemitted energy (the outgoing radiation). **This phenomena is known as the greenhouse gas effect.**

The Natural GHGs in the atmosphere play an important role in the energy budget.

Without this natural effect, the surface earth average temperature would be around -19 °C.

The change in GHG concentrations would lead to a change in the energy balance and may consequently result in changes in climate patterns.

GHG effect

Types and Sources of main GHGs

Carbon Dioxide (CO_2)

A vital component of the atmosphere,
Released through natural processes (like volcanic eruptions)
and through human activities, such as burning fossil fuels (coal, oil, natural gas),
deforestation, and industrial processes (e.g., cement production)

Methane (CH_4)

From both natural and human-caused sources
Plant-matter breakdown in wetlands
Released from landfills and rice farming
Livestock animals (digestion and manure)
Leaks from fossil fuel production and transportation
Natural gas is 70% to 90% methane

Nitrous Oxide (N_2O)

A potent greenhouse gas produced by farming practices
Released during commercial and organic fertilizer production and use.
also comes from burning fossil fuels and vegetation, and industrial processes

Drivers of variability and change

Aerosols released from human activities

- Sulfate aerosols: From burning fossil fuels (especially coal) tend to reflect solar radiation and can modify clouds, generally leading to a cooling effect that partially offsets GHG warming.

- Black carbon from incomplete combustion (e.g., diesel engines, biomass burning) absorbs solar radiation and can warm the atmosphere, also reduces albedo when it is deposited on snow and ice.

Land-Use Change:

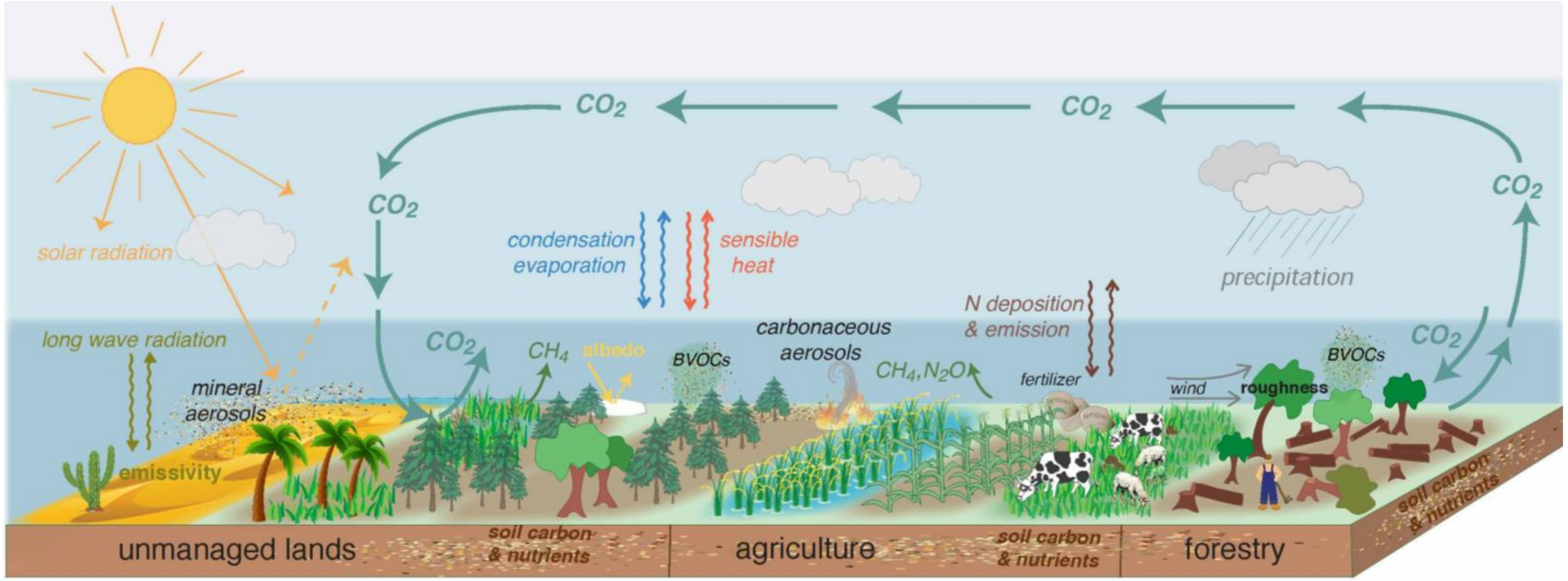
- Deforestation: Reduces the amount of CO2 absorbed by forests and releases stored carbon into the atmosphere. It also changes surface albedo, evapotranspiration, and local weather patterns.

- Urbanization: Result in "urban heat islands" and alters local surface properties.

- Agriculture: Result in changes of land cover and contributes to GHG emissions.

Land surface interactions

- Land surface characteristics such as albedo and emissivity determine the amount of solar and long-wave radiation absorbed by land and reflected or emitted to the atmosphere.
- Surface roughness influences turbulent exchanges of momentum, energy, water and biogeochemical tracers.
- Land ecosystems modulate the atmospheric composition through emissions and removals of many GHGs and precursors of SLCFs, including biogenic volatile organic compounds (BVOCs) and mineral dust.
- Atmospheric aerosols formed from these precursors affect regional climate by altering the amounts of precipitation and radiation reaching land surfaces through their role in clouds physics.



The structure and functioning of managed and unmanaged ecosystems that affect local, regional and global climate. Source IPCC: https://www.ipcc.ch/srccl/chapter/chapter-2/

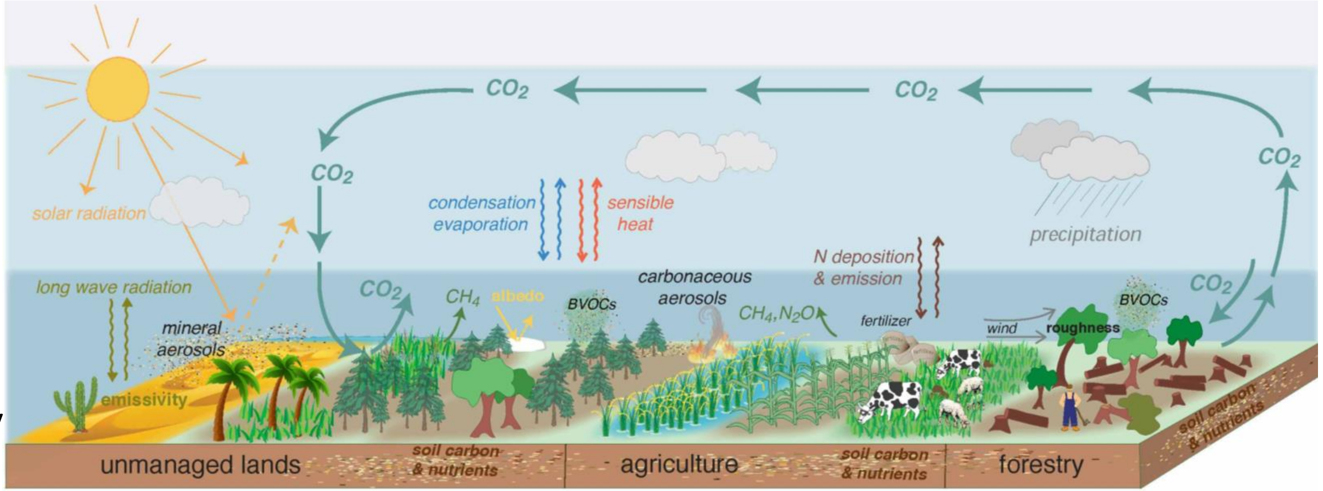
Land surface interactions

'Biophysical interactions' are exchanges of water and energy between the land and the atmosphere.

Land warms up from absorbing solar and long-wave radiation; it cools down through transfers of sensible heat (via conduction and convection) and latent heat (energy associated with water evapotranspiration) to the atmosphere and through long-wave radiation emission from the land surface

Exchanges of GHGs between the land and the atmosphere are referred to as 'Biogeochemical interactions', which are driven mainly by the balance between photosynthesis and respiration by plants, and by the decomposition of soil organic matter by microbes.

In addition to CO2, soils emit methane (CH4) and nitrous oxide (N2O). Soil temperature and moisture strongly affect microbial activities and resulting fluxes of these three GHGs



The structure and functioning of managed and unmanaged ecosystems that affect local, regional and global climate

IPCC: https://www.ipcc.ch/srccl/chapter/chapter-2/

Climate models

A climate model is a numerical representation of the climate system that reproduces the main complex interactions between the atmosphere, ocean, land surface, snow and ice, the global ecosystem, and a variety of chemical and biological processes.

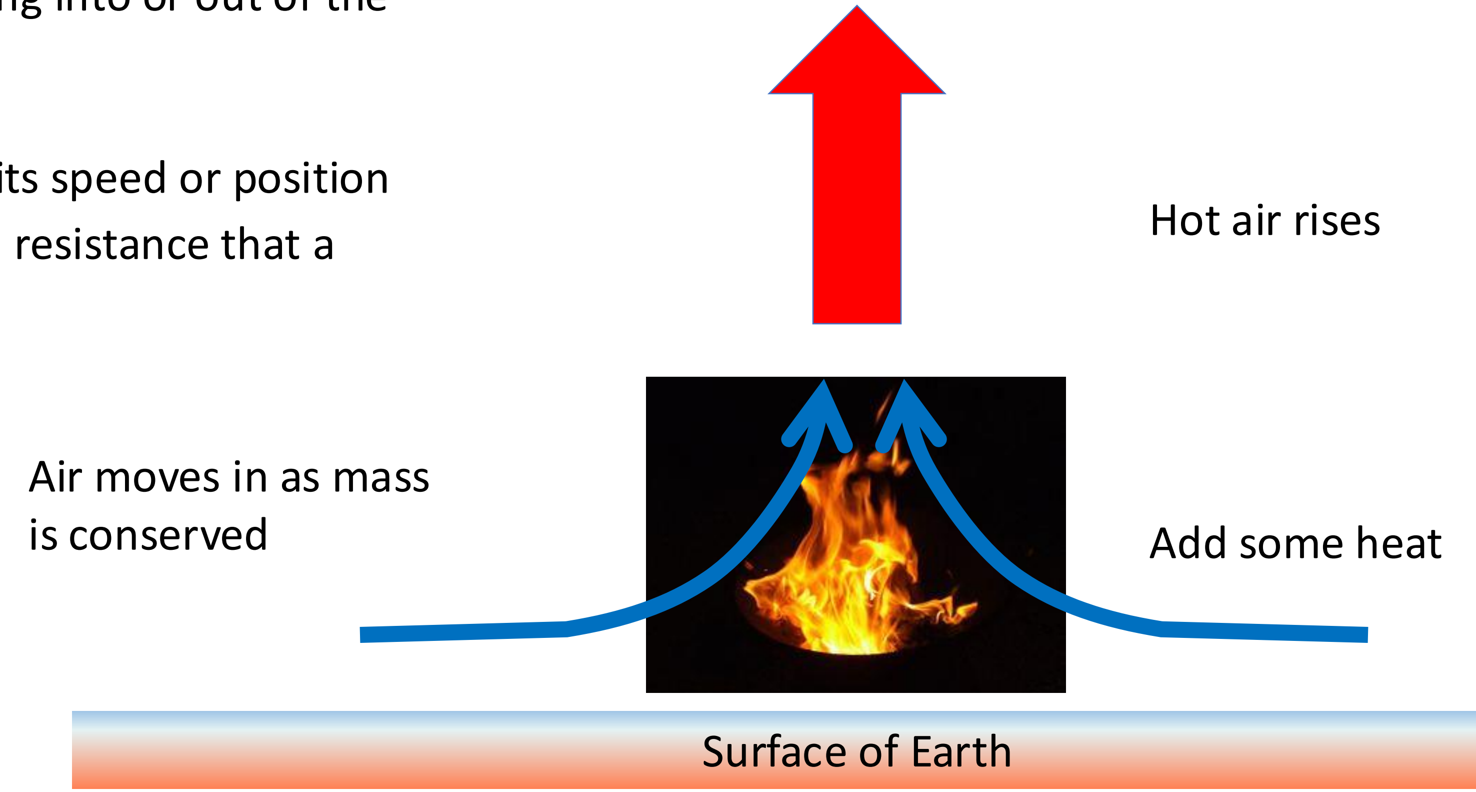
Climate models are used to study climate and predict their future changes.

Climate models

Based on well-established laws of physics and chemistry

Mass Conservation

- In a closed system, mass is neither created nor destroyed by chemical reactions or physical transformations
    - Closed means there is no mass/matter crossing into or out of the system
    - Mass is an intrinsic property of matter,
    - Mass is the resistance of matter to changing its speed or position
    - Weight is force of gravity on an object, or the resistance that a mass offers against Earth's gravity.



https://clasp.engin.umich.edu/people/richard-b-rood/
https://openclimate.org/

Climate models

Based on well-established laws of physics and chemistry

Mass Conservation

- ➔ Matter cannot be created or destroyed
- ➔ Conservation of mass leads the *continuity equation* principle/ equation (for air, water vapor, etc.)
- ➔ No holes in a fluid
- ➔ Crucial for understanding how various components of the Earth's system interact and how changes in one area affect others

The equation describes the time rate of change of mass (density)

$$\frac{1}{\rho}\frac{D\rho}{Dt} = -\nabla \bullet \mathbf{u}$$

The change in mass (density) following the motion is equal to the *divergence*

Convergence = increase in density (compression)
Divergence = decrease in density (expansion)

The change of mass in a box is equal to the mass that flows into the box minus the mass that flows out of the box = (flux) x (area)

ρ ≡ density = mass per unit volume
u = velocity

$$\rho = \frac{m}{V}$$

Definition of ***divergence***

$$\frac{\partial\rho}{\partial t} = -\nabla \bullet (\rho\mathbf{u})$$

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https://openclimate.org/

Climate models

Based on well-established laws of physics and chemistry

Conservation of Momentum (Newton's Second Law of Motion):

➔ The rate of change of motion (acceleration) of air or water is proportional to the net forces acting upon it.

➔ The basis of the equations of motion that predict winds and ocean currents.

➔ Key forces: pressure gradients, gravity, the Coriolis effect, and friction.

$$\text{Momentum: } \rho \frac{D\vec{u}}{Dt} = -\nabla p - \nabla \cdot \vec{\tau} + \rho \vec{g}$$

$(p = \text{pressure};\ \vec{\tau} = \text{stress};\ g\text{=gravity})$

$$\tau = -\mu\left(\nabla\vec{u} + \nabla\vec{u}^{T} - \frac{2}{3}\nabla\cdot\vec{u}\right)$$

https://ocw.mit.edu/

Climate models

Based on well-established laws of physics and chemistry

Conservation of Energy (First Law of Thermodynamics):

➔ Energy is only transformed (not created nor destroyed).

➔ The thermodynamic energy equation, which tracks how temperatures change (through solar radiation, outgoing infrared radiation, heat transport by winds and currents, and latent heat release/absorption during phase changes of water).

Thermodynamics (atmosphere):

$$c_p \frac{dT}{dt} - \alpha \frac{dp}{dt} = \dot{Q} \qquad (\alpha = \text{specific volume}, \dot{Q} = \text{heating})$$

https://ocw.mit.edu/

Global Energy Balance

Conservation of Energy is a fundamental rule of nature, requiring that energy be neither created nor destroyed.

Change in Energy = **Energy Received** - **Energy Emitted**

If a system is in a state of **energy balance** then the total energy within the system must be unchanging, which implies:

Energy Received = **Energy Emitted**

Paul Ullrich | Energy and the Earth System | Spring 2020

Global Energy Balance

Since we know that

(1) the Earth has had a very long time to equilibrate its temperature, and

(2) the amount of energy received by the Earth does not change significantly on time scales of millions of years,

it is a natural consequence that **the Earth system is, to a close approximation, in a state of energy balance:**

Energy Received by the Earth = **Energy Emitted by the Earth**

Note that energy balance is <u>not affected</u> by human activities. Even under global warming, **in equilibrium energy emitted must equal energy received.**

Paul Ullrich | Energy and the Earth System | Spring 2020

Climate models

Equation of State:

➔This relates key thermodynamic variables of a fluid.

➔For the atmosphere, the **Ideal Gas Law** (or more complex relation) links pressure, temperature, and density of air.

- . Pressure is proportional to temperature times density
- Temperature is proportional to the average kinetic energy (mass times velocity squared) of the molecules of a gas
- Density is the mass divided by the volume:

$$\rho = \frac{m}{V}$$

- One form of the ideal gas law is:

  $p\ V = n\ R^*\ T$

  where the number of moles n in mass m (in grams) of a substance is given by

  $n = m\ /\ M$
- M is the molecular weight of a substance, e.g. for nitrogen (N_2) in the gas phase: M = 28.0116 g / mol
- p, V, T: pressure, volume and temperature
- R^* = 8.3145 J/(K mol): universal gas constant

https://clasp.engin.umich.edu/people/richard-b-rood/
https://openclimate.org/

- Another form of the ideal gas law for dry air:

  $$p = \rho R_d T$$

  where R_d is the gas constant for 1 kg of dry air

- ρ is the dry air density (kg/m^{3})
- Dry air is a mix of different gases, mainly :

  nitrogen N_2, oxygen O_2, argon (Ar), carbon dioxide CO_2

https://clasp.engin.umich.edu/people/richard-b-rood/
https://openclimate.org/

Climate models

Radiative Transfer:

Describes how solar (shortwave) radiation and terrestrial (longwave/infrared) radiation are absorbed, emitted, and scattered by the Earth's surface, atmosphere (gases, aerosols, clouds), and oceans.

Chemistry and Biogeochemistry:

For more complex Earth System Models, principles of chemical reactions (e.g., ozone chemistry, aerosol formation) and biogeochemical cycles (e.g., carbon cycle, nitrogen cycle) are included.

Climate models

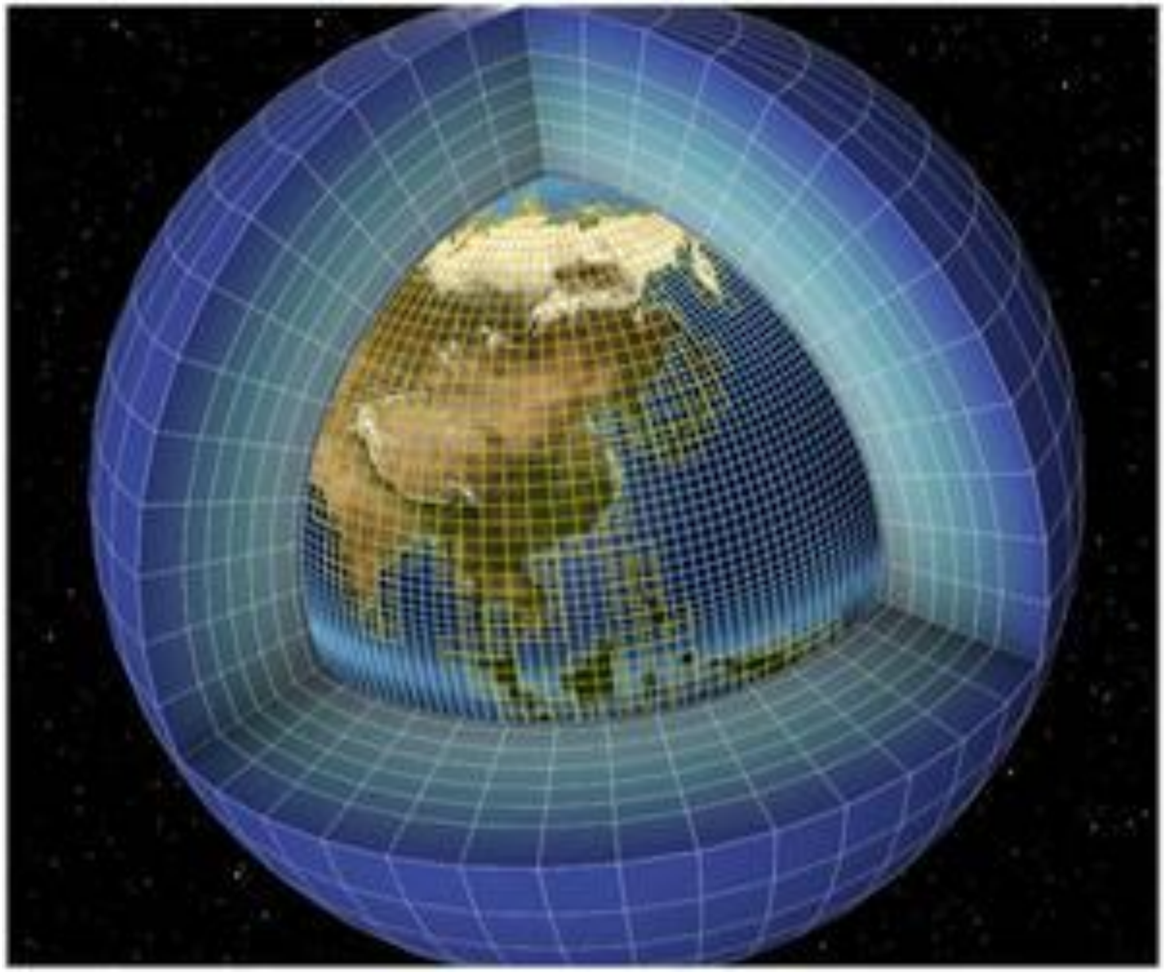


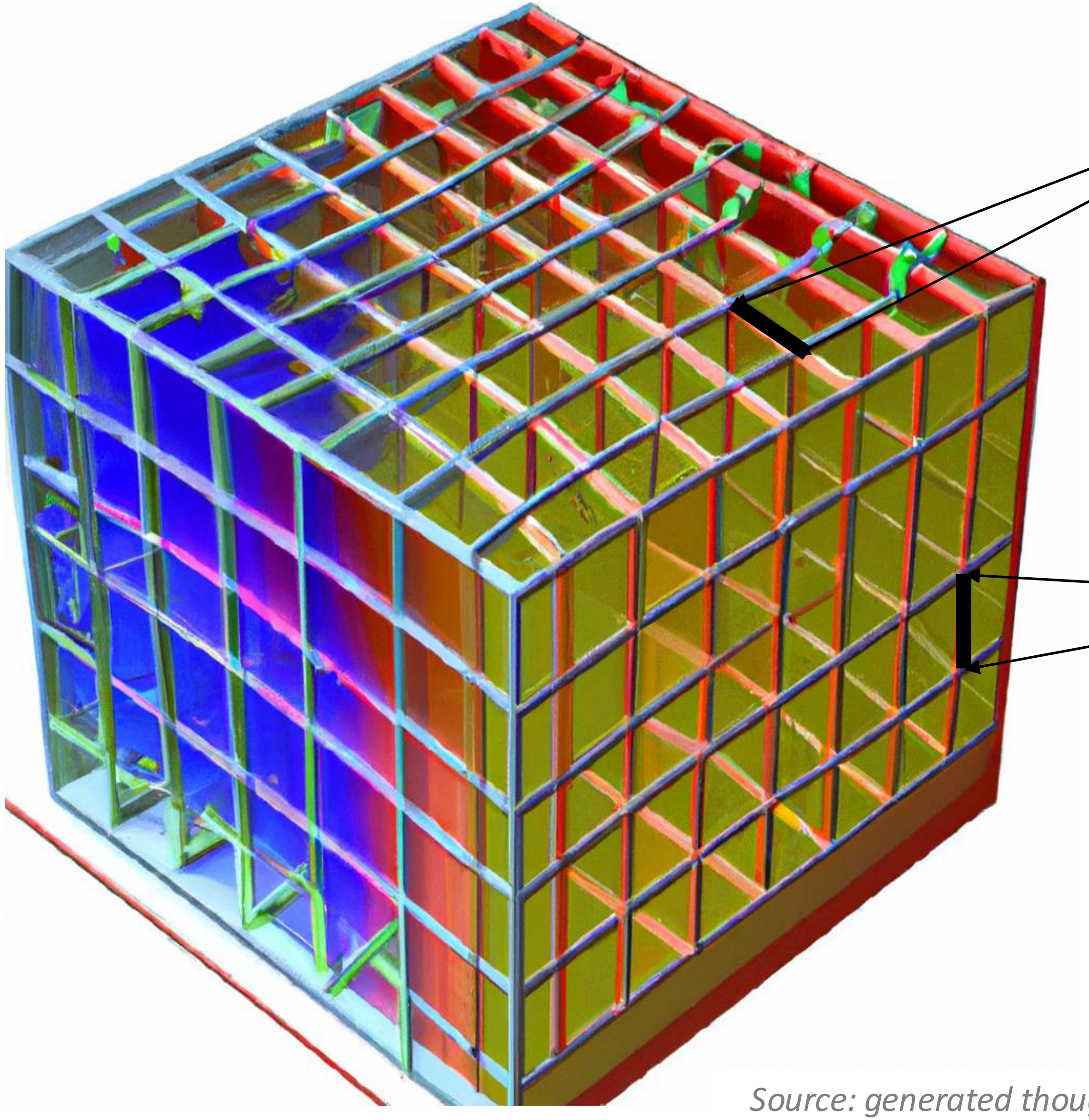
Illustration of a climate model grid.
Source: IPSL, CEA www.ipsl.fr

- **Discretization (**space and time) **is used by** Climate models to solve the governing equations.
- The model divides the earth into three-dimensional **grid** of boxes.
- The time step: the discrete interval at which the model equations are solved, and the model state is updated.
- The values of the predicted variables, such as pressure, wind, temperature, and rainfall are calculated at each grid point for each time step

Climate models

- The resolution is the physical distance between each point on the grid used to compute the equations.

- Each model grid is defined by a vertical and a horizontal resolution



Horizontal resolution

The size of the grid cells in the horizontal (latitude and longitude).

Vertical resolution

The number of layers in the vertical dimension

Source: generated though labs.openai.com

Climate models

- **Numerical methods:** climate models use numerical methods to find approximate solutions to the equations governing fluid motion, thermodynamics, etc.
    - **Finite Difference Method:** Approximates derivatives in the equations using differences between values at discrete grid points. Commonly used.
    - **Spectral Method:** Represents variables as a sum of mathematical basis functions (e.g., spherical harmonics). Often used for horizontal representation in atmospheric models due to its accuracy for smooth flows on a sphere.
    - **Finite Volume Method:** Based on ensuring conservation laws are upheld within each grid cell.
    - **Finite Element Method:** Divides the domain into smaller, flexible elements. Gaining popularity for its ability to handle complex geometries and unstructured grids
- **Time steps:** Numerical schemes (e.g., explicit, implicit, semi-implicit) are used for time integration

Climate models

- **Physical Parameterizations:**

Small-scale processes or too complex ones to be explicitly resolved on the model grid are represented by "parameterizations.

- Simplified mathematical relationships that estimate the net effect of these processes on the resolved-scale variables. (Instead of ignoring them)
- Allow incorporating the influence of important sub-grid scale processes into the climate simulation, the model is more physically realistic.
- Examples: individual cloud formation, convection, turbulence, small-scale variations in land surface properties (e.g., soil moisture) and their influence on heat and moisture fluxes.

Climate models

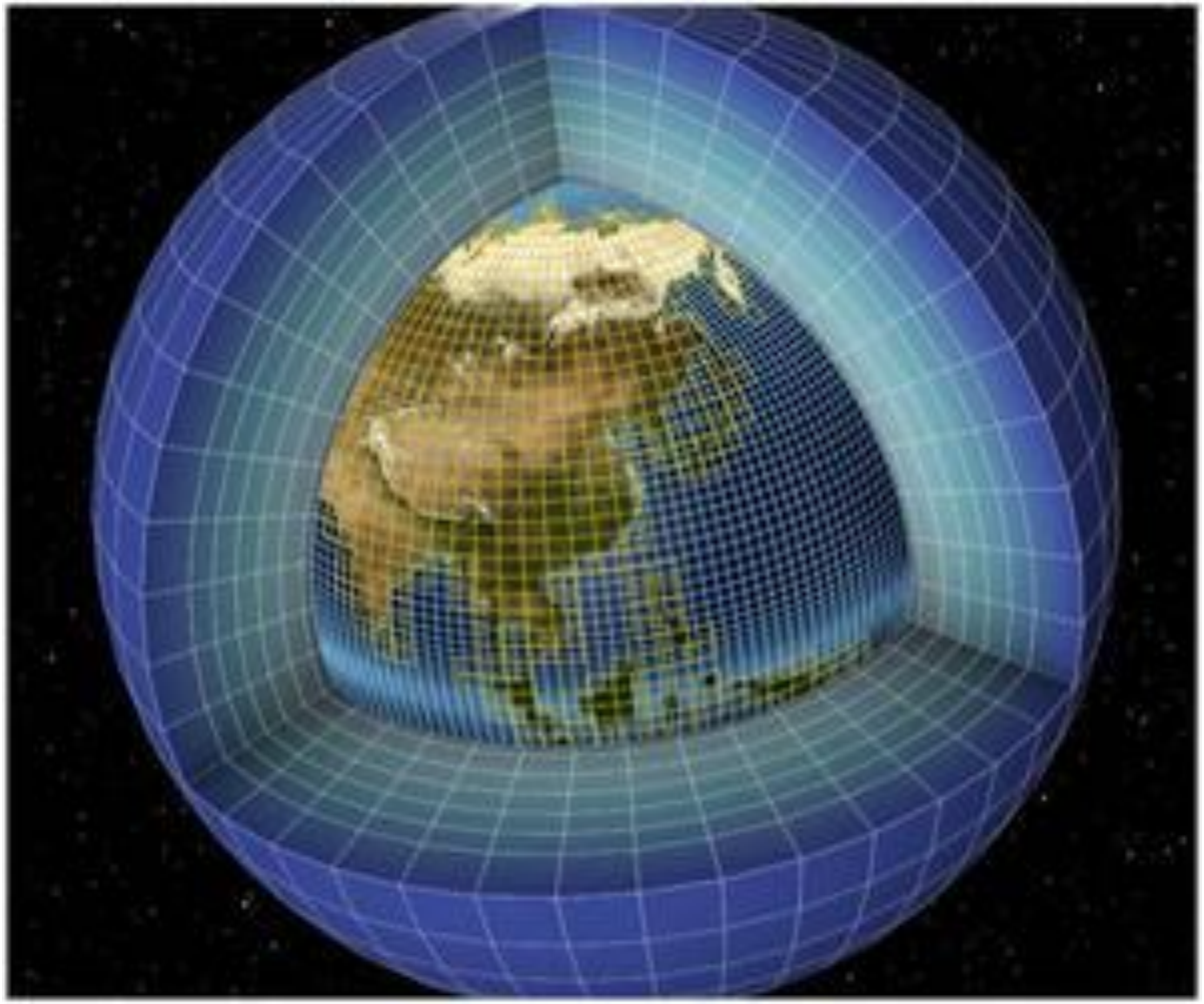


Illustration of a climate model grid.

Source: IPSL, CEA www.ipsl.fr

The degree of complexity of models varies based on, for example, the extent to which physical, chemical or biological processes are explicitly represented furthermore to dynamical aspects.

Climate models

Types of Climate Models (1)

- **Energy Balance Models (EBMs)** The simplest type, focusing on the balance of energy entering and leaving the Earth:
  - **0-D:** Treat the Earth as a single point and calculate the global average temperature based on a simple energy balance between incoming solar radiation and outgoing infrared radiation.
  - **1-D (Latitudinal Average):** Resolve variations in one dimension, typically latitude. They can simulate the equator-to-pole temperature gradient and include simplified heat transport between latitude bands.

- **Radiative-Convective Models:**
  - **1-D (Vertical):** Focus on the vertical structure of the atmosphere at a single location or averaged globally. They explicitly calculate radiative transfer and convective heat transport in the vertical, helping to understand atmospheric temperature profiles and the greenhouse effect.

Climate models

Types of Climate Models (2)

- **Earth System Models of Intermediate Complexity (EMICs):**
  - Used to study long-term climate variations, like glacial-interglacial cycles
  - simplify some aspects of the climate system (e.g., simple representation of atmospheric dynamics or a 2D ocean)
  - often include more components of the Earth system than simpler models (biogeochemical cycles or ice sheet dynamics)
  - Computationally less expensive than GCMs, allows for longer simulations or exploration of a wider range of scenarios.

Climate models

Types of Climate Models (3)

- **General Circulation Models / Global Climate Models (GCMs) :**
  - The most complex and comprehensive type of climate model, representing physical processes in the atmosphere, ocean, and land surface
  - The fundamental equations of fluid dynamics and thermodynamics are solved on a 3D grid covering the entire globe
  - for the atmosphere only : Atmospheric GCMs – AGCMs
  - For the oceans only (Ocean GCMs - OGCMs).
  - Coupled GCMs: Combine atmospheric and oceanic processes, representing a higher level of complexity. Often called Coupled Atmosphere-Ocean GCMs (AOGCMs).

Climate models

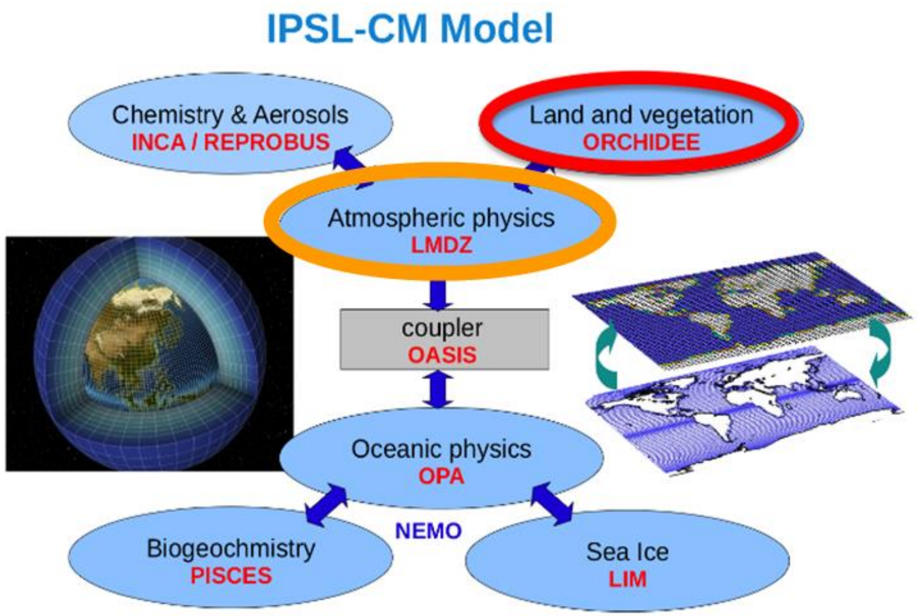
Types of Climate Models (4)

- **Earth System Models (ESMs):**
    - Further integrated models that include the carbon cycle and other feedback processes.
    - An extension of GCMs/AOGCMs that include explicit representations of more components of the Earth system and their interactions, such as:
        - Biogeochemical cycles (e.g., carbon cycle, nitrogen cycle) in the atmosphere, land, and ocean.
        - Dynamic vegetation (how vegetation changes in response to climate and vice-versa).
        - Atmospheric chemistry (e.g., ozone, aerosols).
        - Ice sheet dynamics (for Greenland and Antarctica).
    - ESMs allow for the study of feedbacks between the physical climate system and biogeochemical processes.

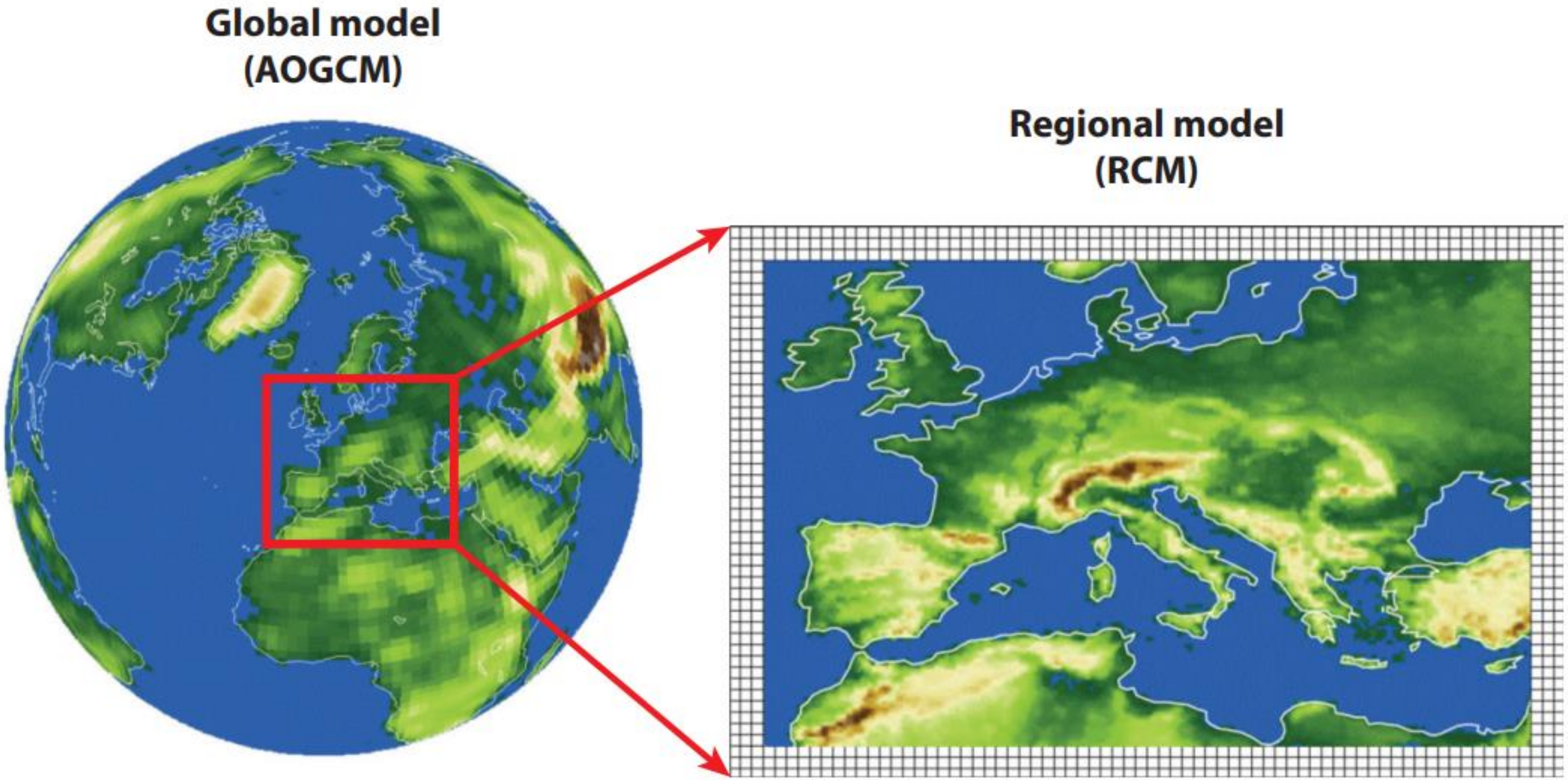
Climate models

Main Parts/Components of GCM & ESM

- **Atmospheric Model:** Simulates atmospheric dynamics (winds), temperature, pressure, humidity, clouds, precipitation, and radiative transfer.
- **Ocean Model:** Simulates ocean currents, temperature, salinity, sea level, and sometimes marine biogeochemistry.
- **Land Surface Model:** Simulates processes occurring on the land surface, including soil moisture, evapotranspiration, runoff, energy fluxes, snow cover, and often vegetation dynamics and land carbon cycle.
- **Sea Ice Model:** Simulates the formation, melt, and movement of sea ice.
- **Ice Sheet Model (in some ESMs):** Simulates the dynamics of large ice sheets like Greenland and Antarctica, including accumulation, flow, and melt.
- **Biogeochemistry Models (in ESMs):** Simulate the cycling of key elements like carbon and nitrogen through the different Earth system components.
- **Atmospheric Chemistry Models (in some ESMs):** Simulate chemical reactions in the atmosphere, including those involving ozone and aerosols.
- **Coupler:** Manages the interactions and exchanges of energy, mass, and momentum between these different model components at regular intervals (coupling frequency).



Boucher et al., 2020



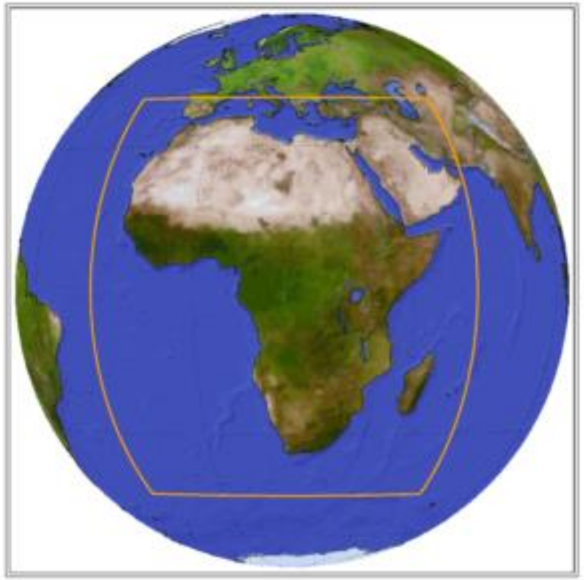
Source: Giorgi and Gutowski (2015)
Regional Dynamical Downscaling and the CORDEX Initiative

Climate models can also be divided in two main categories: the models that cover the entire earth such as General Circulation models (GCMs) and Regional Climate models with a limited domain.

Dynamical downscaling

- The GCMs have a spatial horizontal resolution that ranges generally between 1 and 3 hundred kilometres.

This does not allow assessing climate changes and their impacts at regional or finer scales such as on cities.

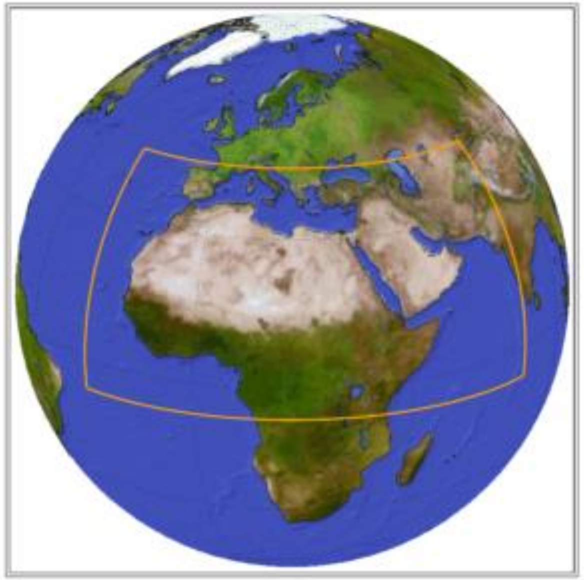


- RCMs have representations of climate processes comparable to those in the GCMs.

They can, however, be run at higher resolutions and more quickly.

Due to their higher resolution, RCMs allow filling the gap by producing climate information in greater detail over the area covered by their grid.

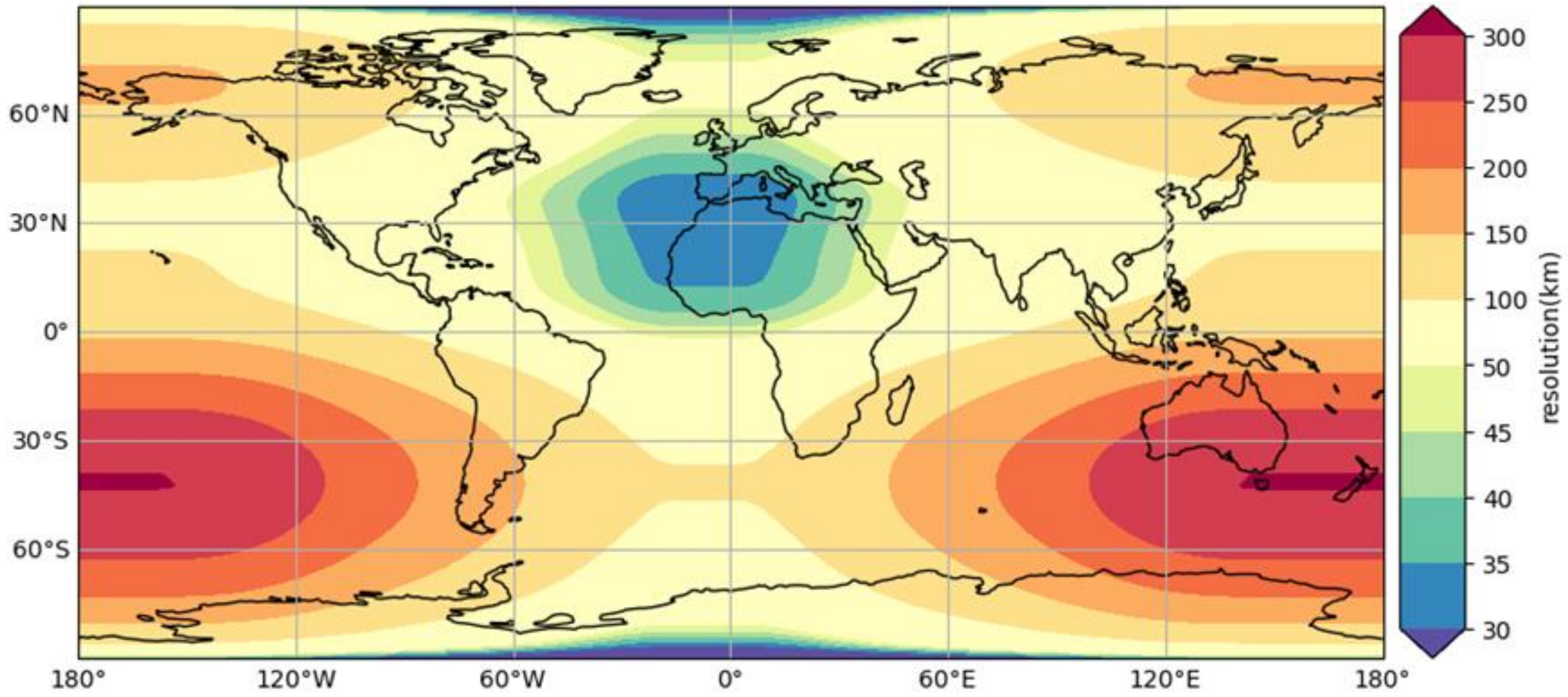
The information they need from outside their domain to perform calculations is taken from GCM outputs.



➔ **Dynamical downscaling.**

Dynamical downscaling

Example of grid of a climate variable resolution models:
spatial repartition of the horizontal resolution



Courtesy: Saloua Balhane

Dynamical downscaling can also be performed by GCMs that have a variable resolution grid as shown in the figure.

This allows having finer climate information in the zoomed area than the remaining parts of the earth.

Main Sources:

African Urban Economic Development in the Context of Climate Change | African Cities Lab (Module 1)

www.ipcc.ch

IPCC WGI Interactive Atlas

https://www.ux1.eiu.edu

https://www.clivar.org/

https://www.metlink.org

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IPCC WGI Interactive Atlas

Open Climate - Course Collection: Introduction to Dynamic Meteorology (CLIMATE/EARTH 401 @ U-M)

Paull Rich