Meteo
All about
weather

Climate modelling and applications

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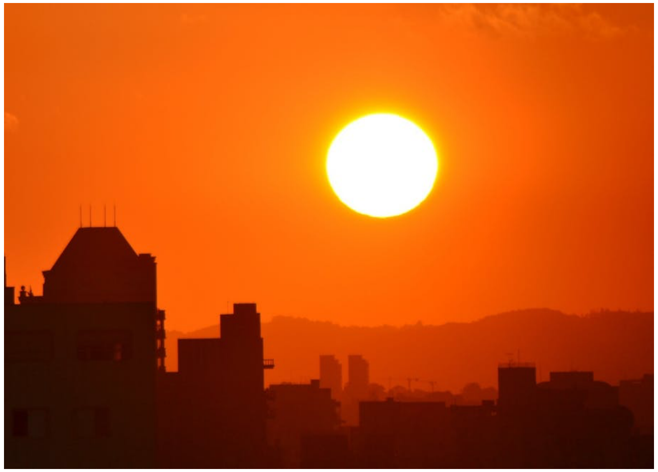
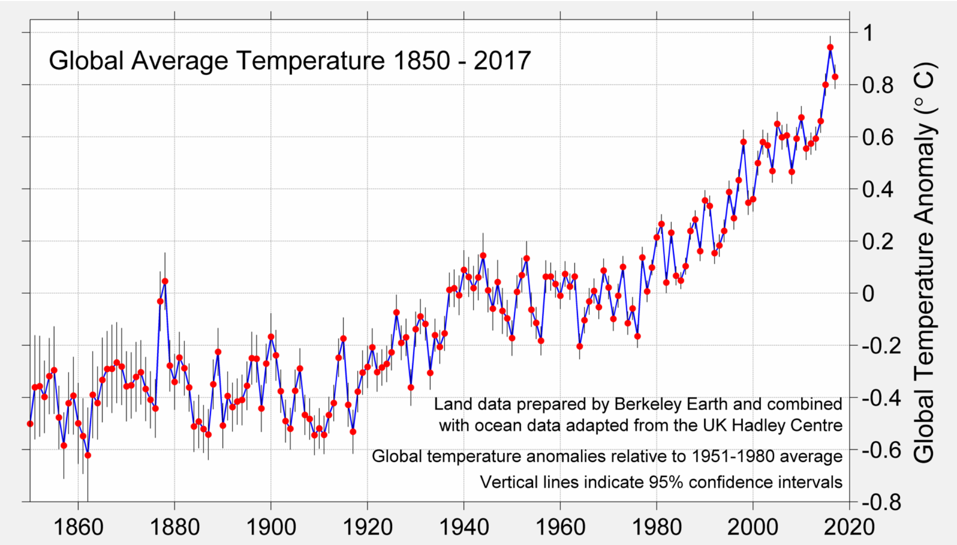
A harsh truth

"*Climate change is no longer a distant future problem. It happens* ***here****. It happens* ***now***". Barack Obama, President of the USA.



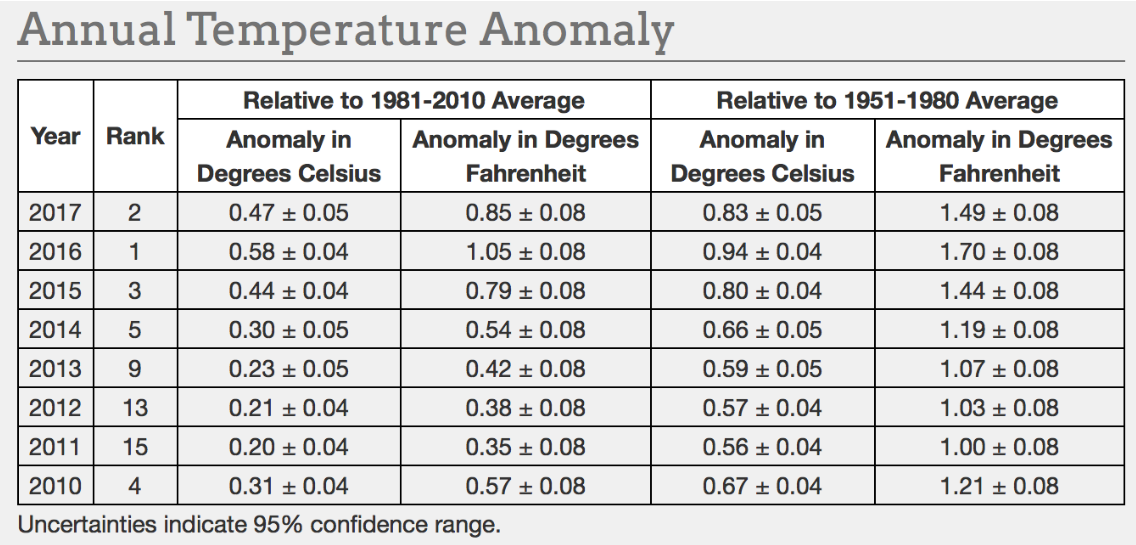
An indisputable fact


Global Average Temperature 1850 - 2017

Land data prepared by Berkeley Earth and combined with ocean data adapted from the UK Hadley Centre

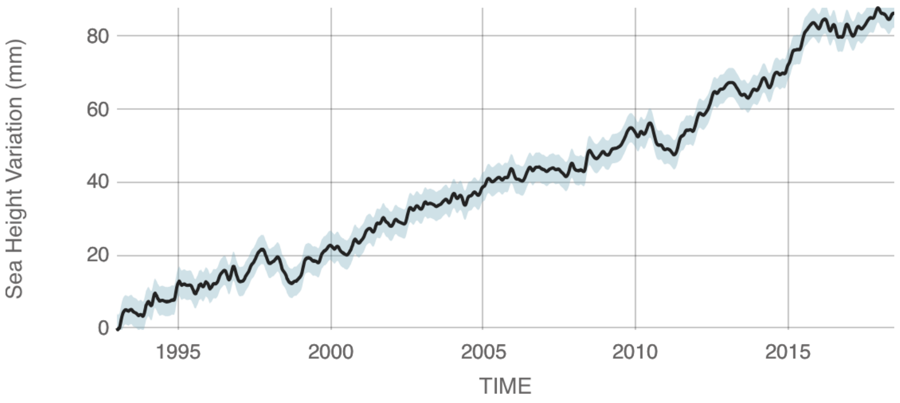
Global temperature anomalies relative to 1951-1980 average

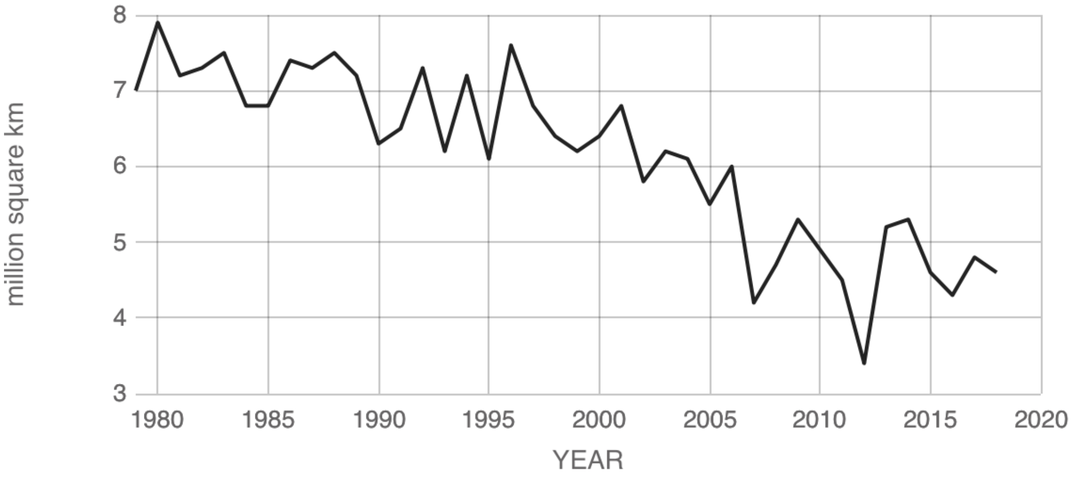
Vertical lines indicate 95% confidence intervals


Annual Temperature Anomaly

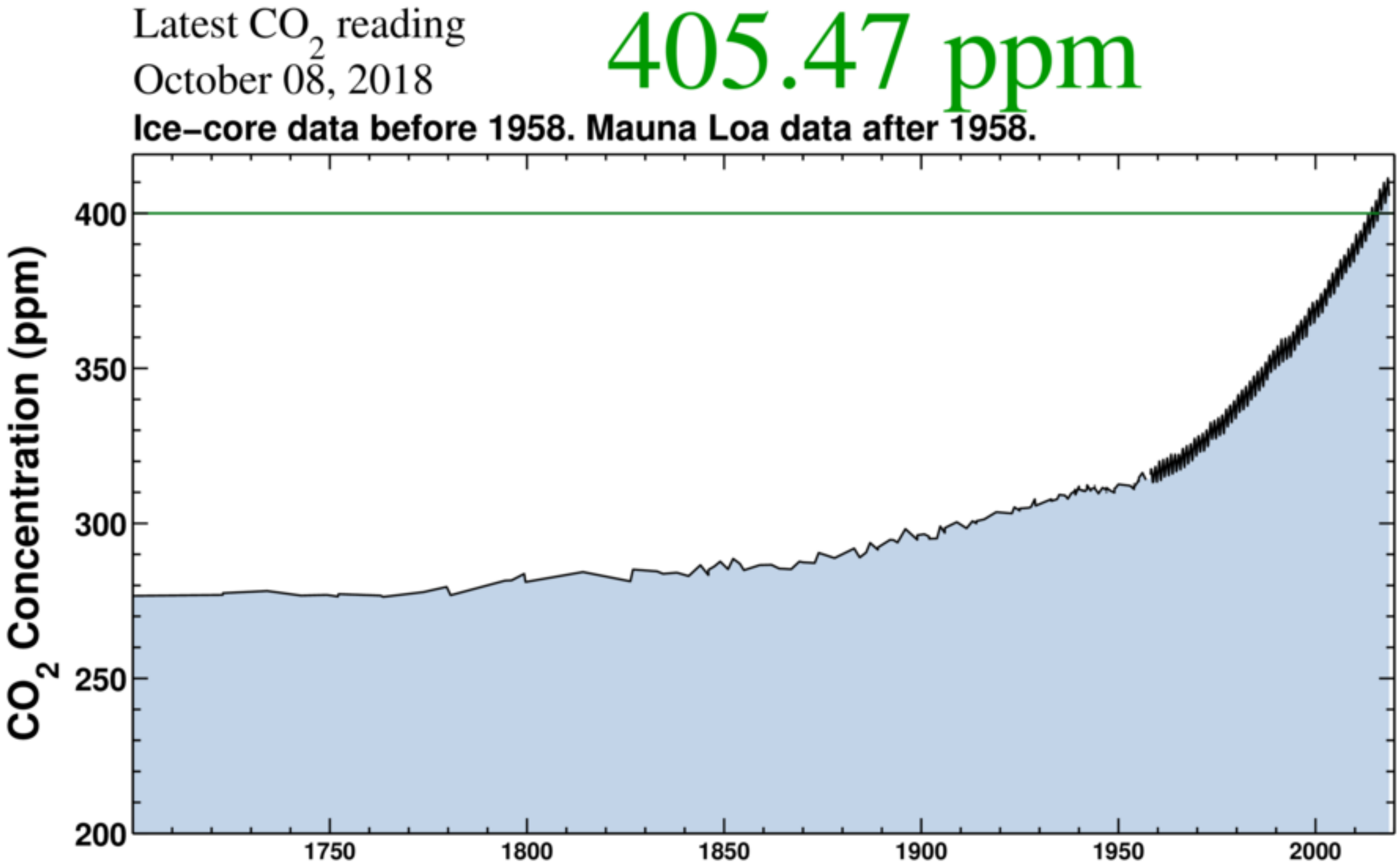
Year	Rank	Relative to 1981-2010 Average		Relative to 1951-1980 Average	
		Anomaly in Degrees Celsius	Anomaly in Degrees Fahrenheit	Anomaly in Degrees Celsius	Anomaly in Degrees Fahrenheit
2017	2	0.47 ± 0.05	0.85 ± 0.08	0.83 ± 0.05	1.49 ± 0.08
2016	1	0.58 ± 0.04	1.05 ± 0.08	0.94 ± 0.04	1.70 ± 0.08
2015	3	0.44 ± 0.04	0.79 ± 0.08	0.80 ± 0.04	1.44 ± 0.08
2014	5	0.30 ± 0.05	0.54 ± 0.08	0.66 ± 0.05	1.19 ± 0.08
2013	9	0.23 ± 0.05	0.42 ± 0.08	0.59 ± 0.05	1.07 ± 0.08
2012	13	0.21 ± 0.04	0.38 ± 0.08	0.57 ± 0.04	1.03 ± 0.08
2011	15	0.20 ± 0.04	0.35 ± 0.08	0.56 ± 0.04	1.00 ± 0.08
2010	4	0.31 ± 0.04	0.57 ± 0.08	0.67 ± 0.04	1.21 ± 0.08

Uncertainties indicate 95% confidence range.



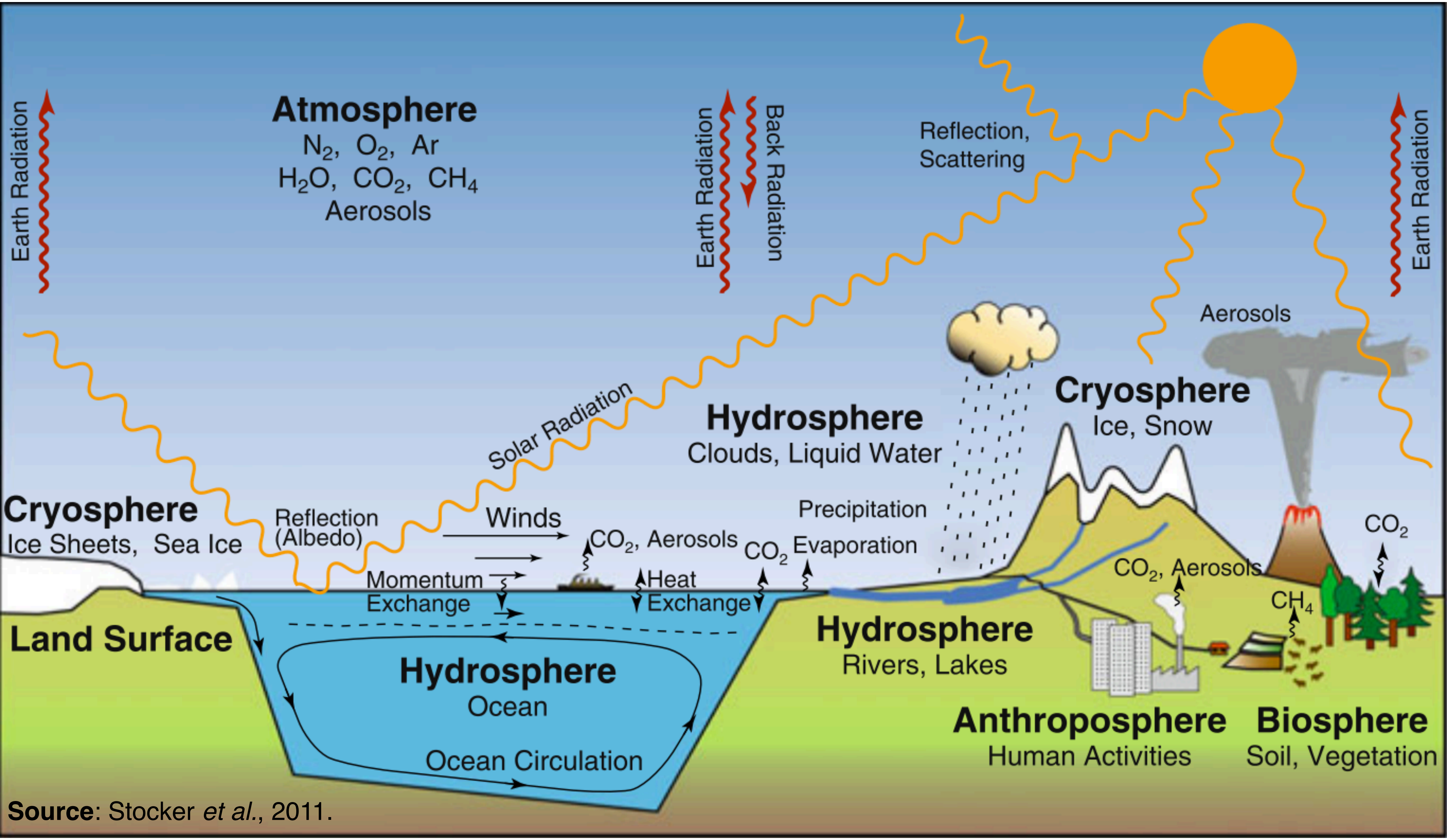


A well-known root cause



The climate system of Earth [1]

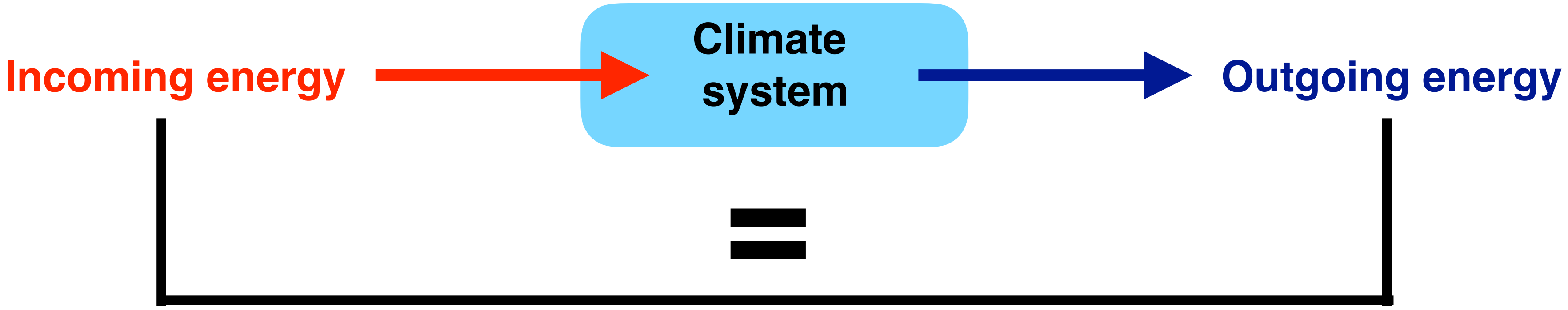
Climate modelling aims at simulating the **flow of energy** through the **climate system** of Earth, via many **interacting processes**.



Source: Stocker *et al.*, 2011.

The climate system of Earth [2]

The climate system is in a **steady** state.



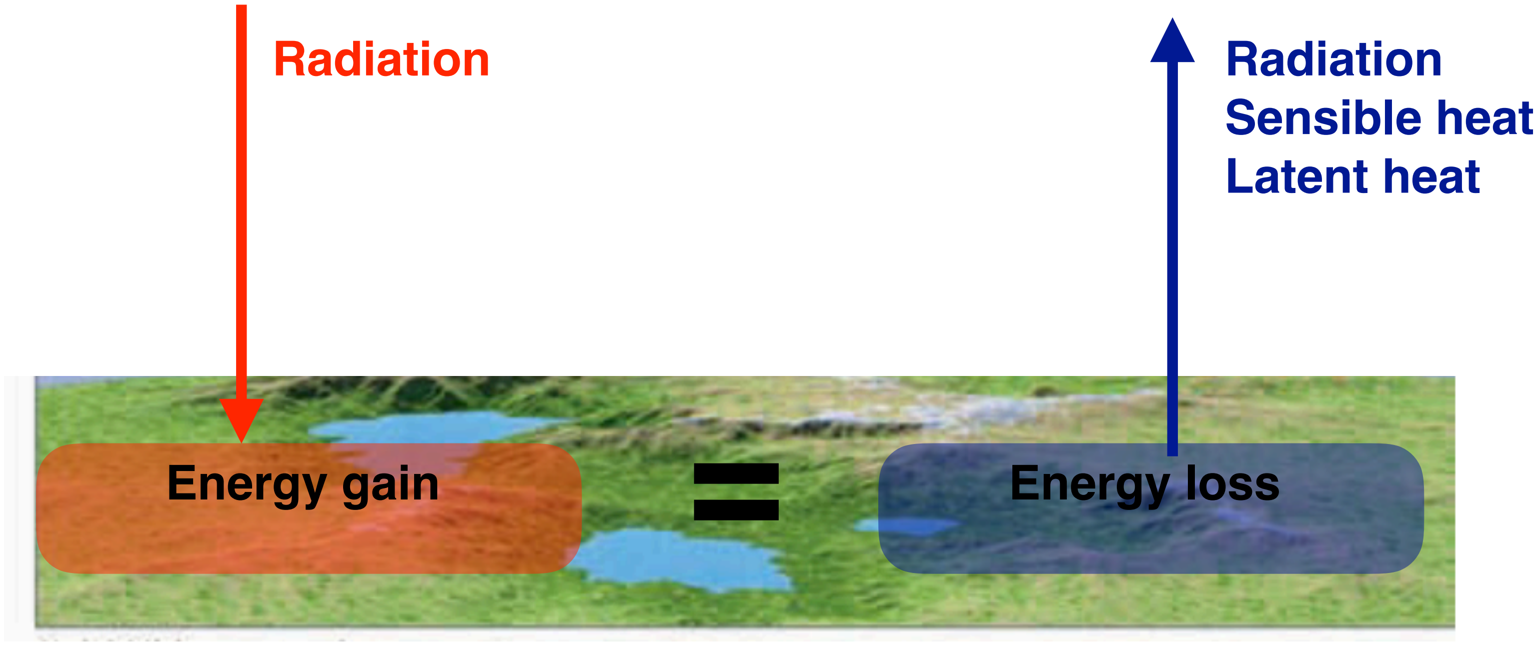
Incoming energy

Climate system

Outgoing energy

=

Looking down at the surface…

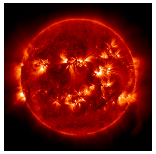


Radiation

Radiation
Sensible heat
Latent heat

Energy gain = **Energy loss**

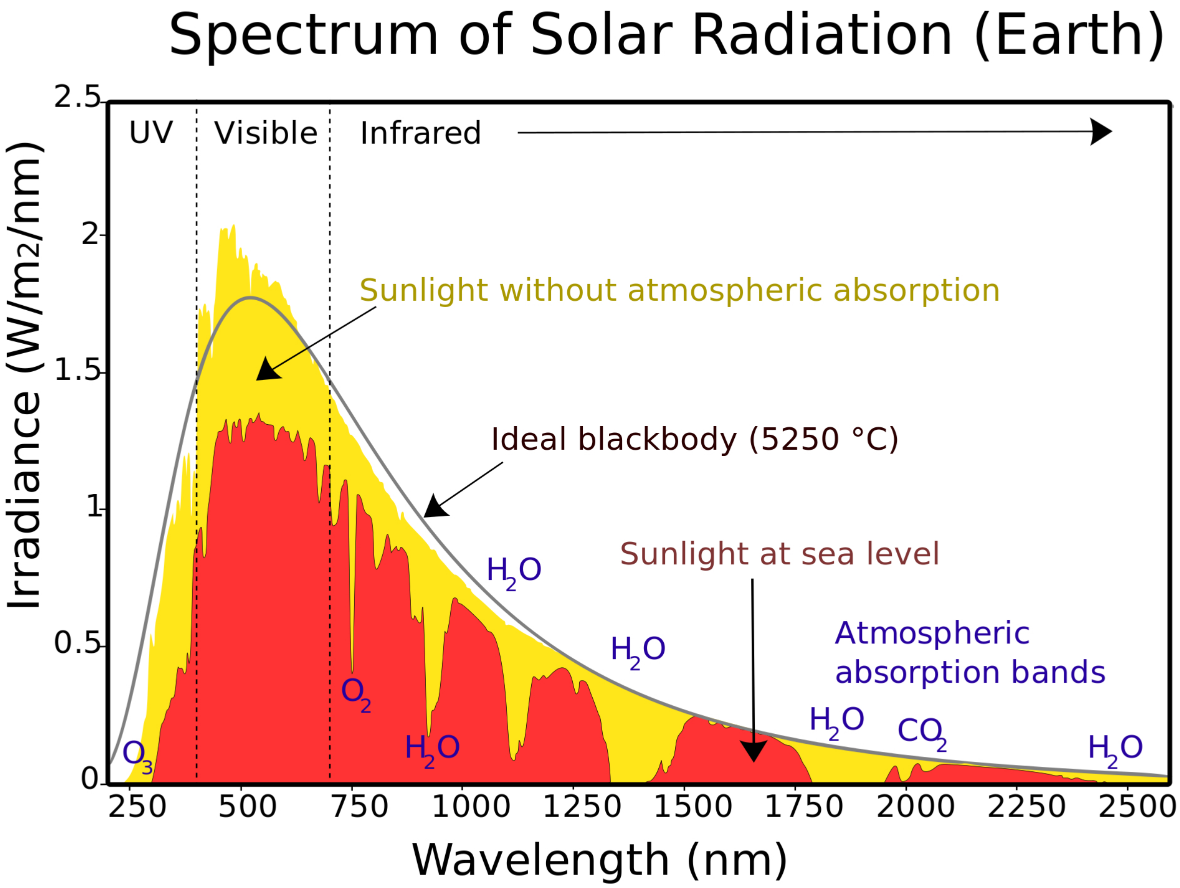
Solar radiation [1]



Solar radiation is the **driving force** of Earth's **climate system** and the only source of **incoming energy**.

The **Sun** is assumed to irradiate energy as a **black body** with a surface temperature of about **5000 K**.

At the **surface**, we are only interested in the radiation between **0.3 - 1.4 μm**: **Ultraviolet** (UV) - **Visible** (VIS) - **Infrared** (IR).

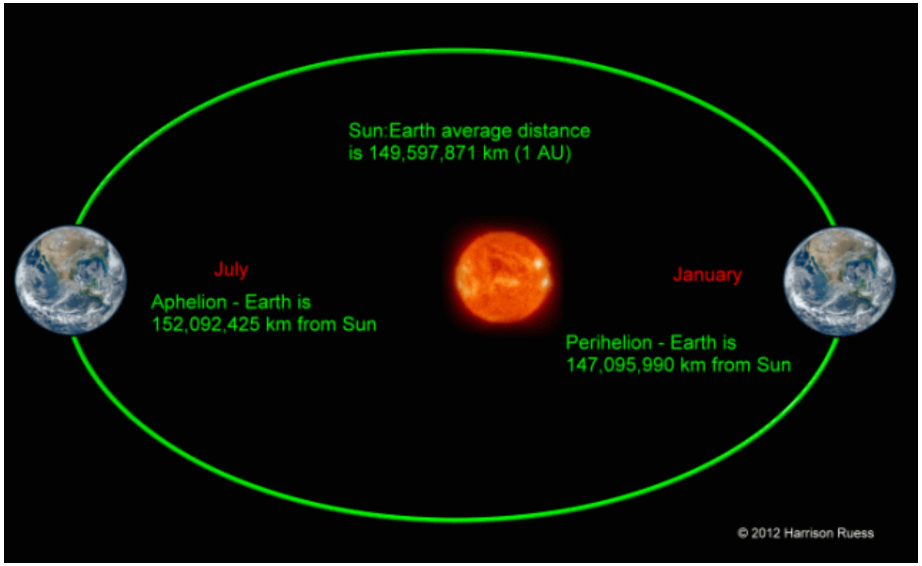


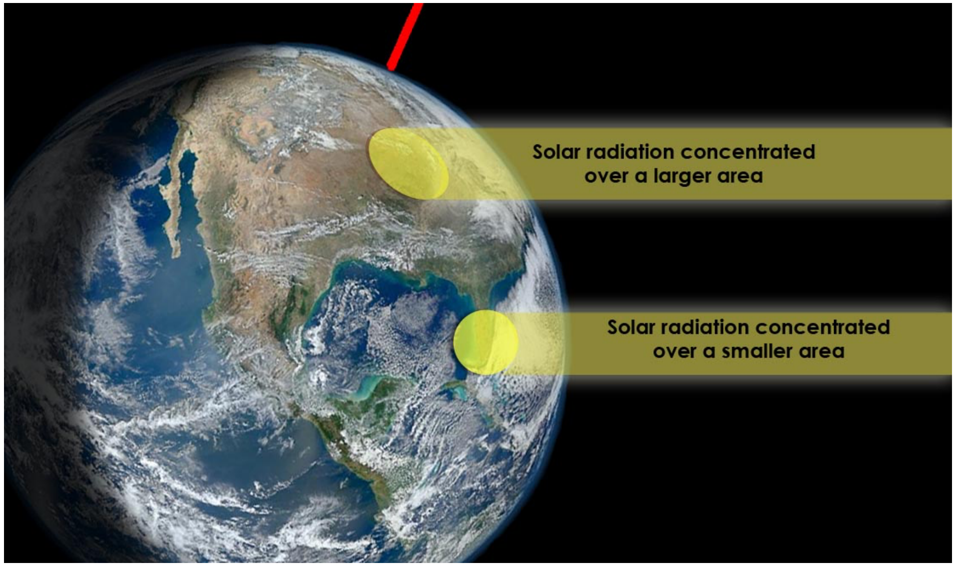
- **UV** ($\lambda<0.4$ μm): ~8%
- **VIS** ($0.4<\lambda<0.7$ μm): ~46%
- **IR** ($\lambda>0.7$ μm): ~46%

Solar radiation [2]

The exact amount of **solar radiation, available** to the climate system **depends** on:

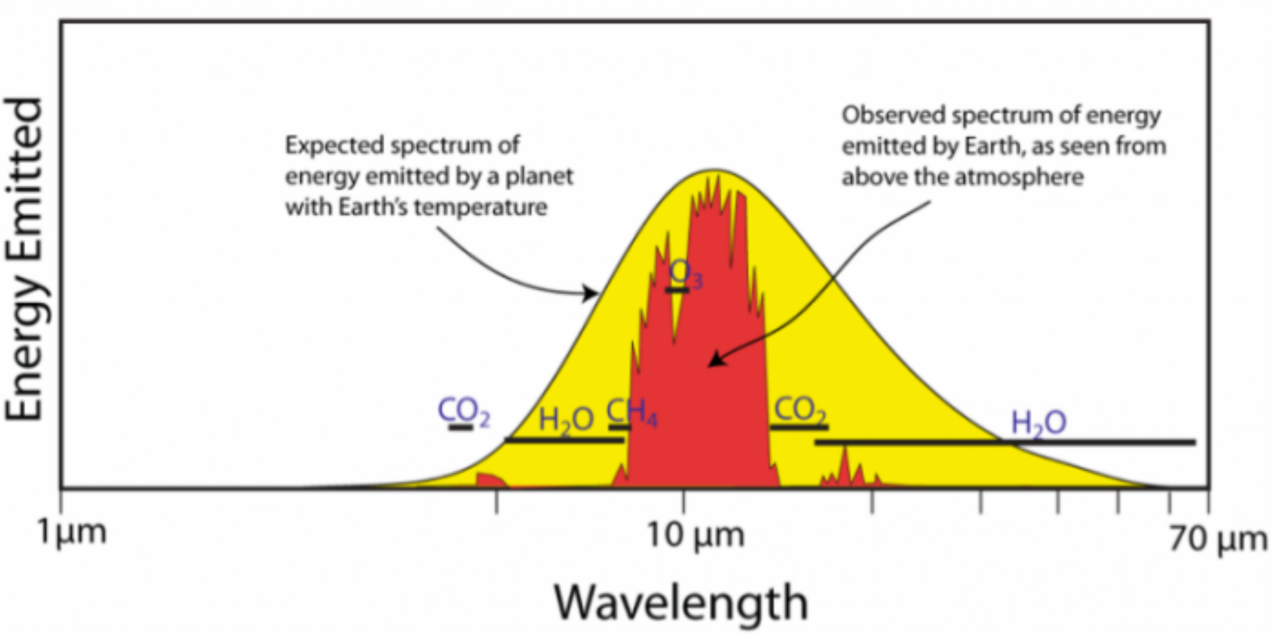
- the position of the Earth relevant to the Sun (**annual cycle**)
- the rotation of the Earth around its axis (**daily cycle**)
- the geographical location of the considered region (**equator versus poles**)
- the presence of **clouds** and **aerosols** in the atmosphere
- the properties of the surface that receives the radiation (**albedo**)





Terrestrial radiation

We assume that **Earth** irradiates energy as a **black body** with a surface temperature of **288 K**. In fact, however, the radiation emitted by the Earth's surface corresponds to a **body** with emissivity in the range of **0.85 - 0.99**.

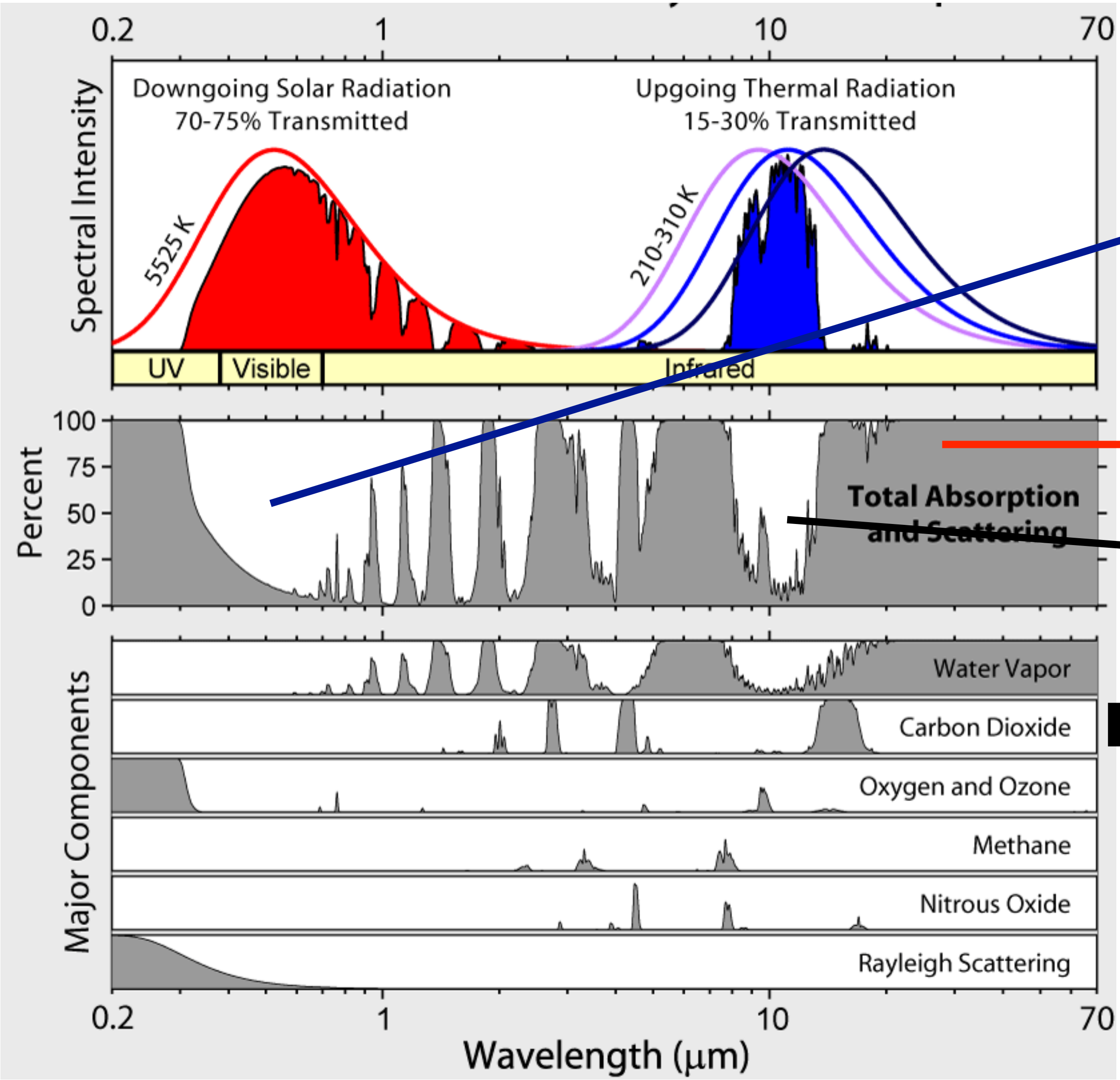


Terrestrial radiation extends between **4 - 100 µm**, with **maximum** emission (~400 W m^{-2}) taking place at about **10 µm**.

Terrestrial radiation is the only source of **outgoing energy**.

Radiative transfer

The **atmosphere** interacts with both **solar** and **terrestrial** radiation, through **selective absorption** and re-emission of radiation.



Transparent to solar radiation

Opaque to terrestrial radiation

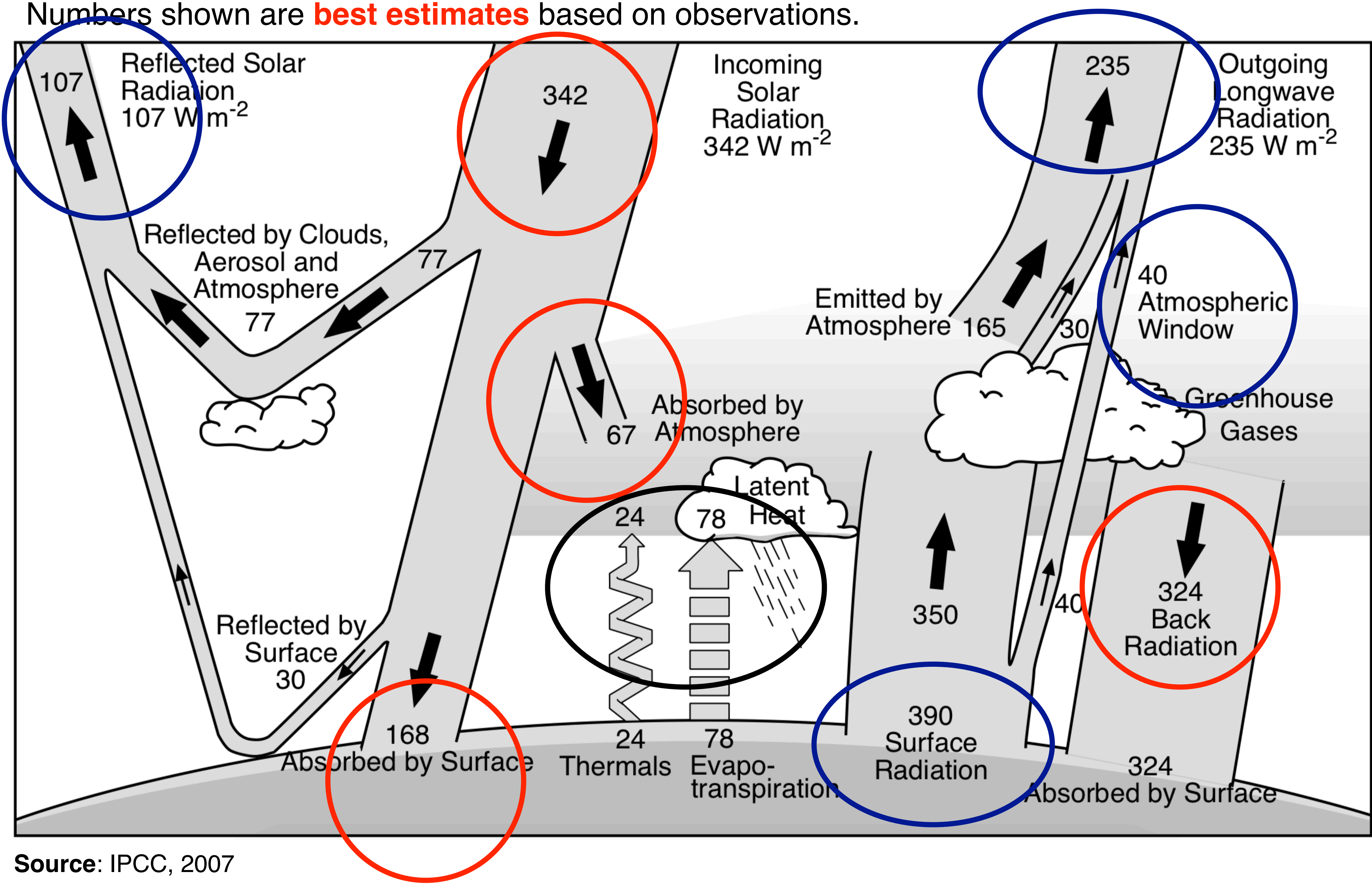
Atmospheric window

Greenhouse gases

- H_2O
- CO_2
- CH_4
- O_3

The earth-atmosphere energy balance

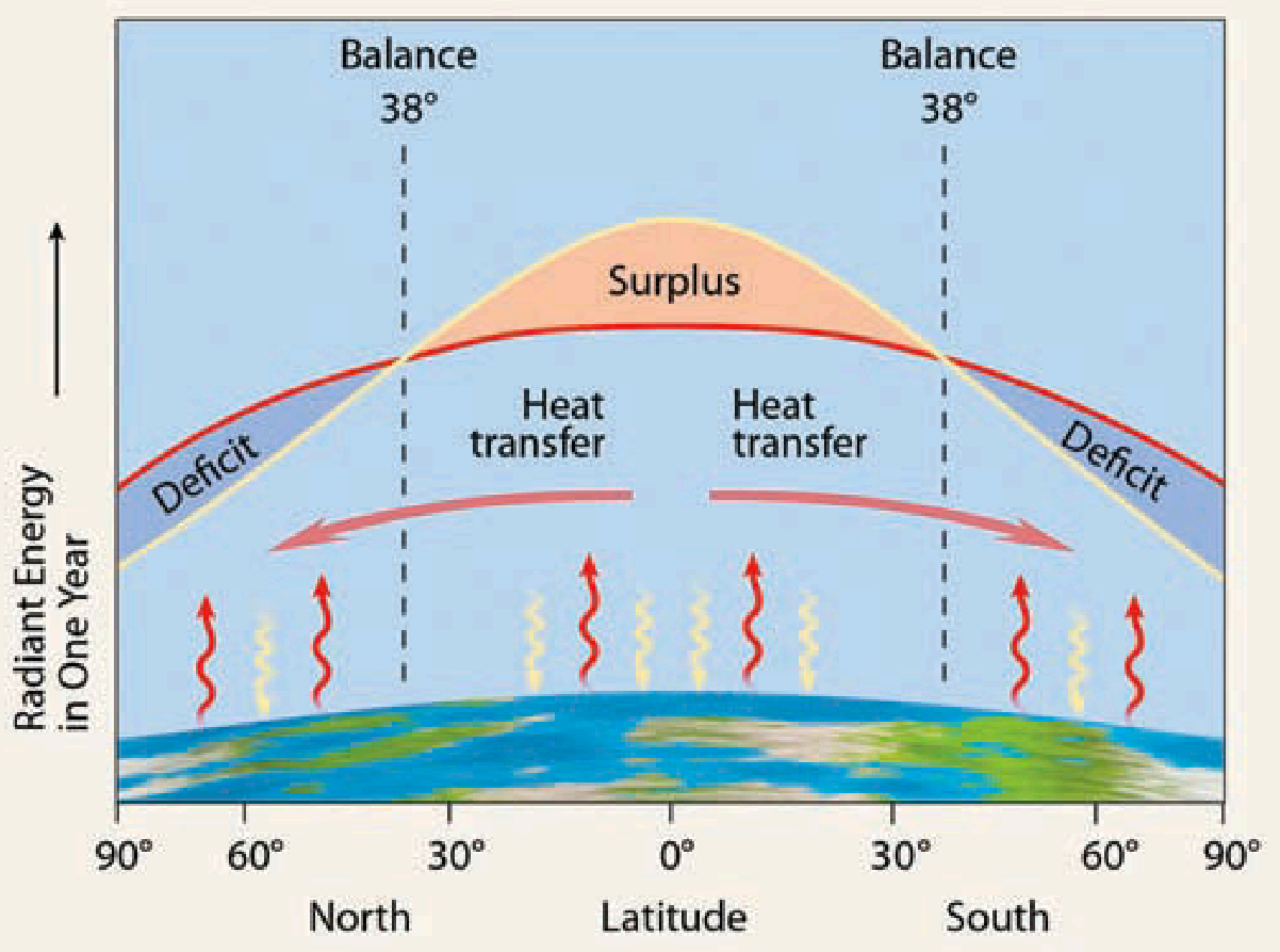
Numbers shown are **best estimates** based on observations.



Source: IPCC, 2007

Atmospheric dynamics

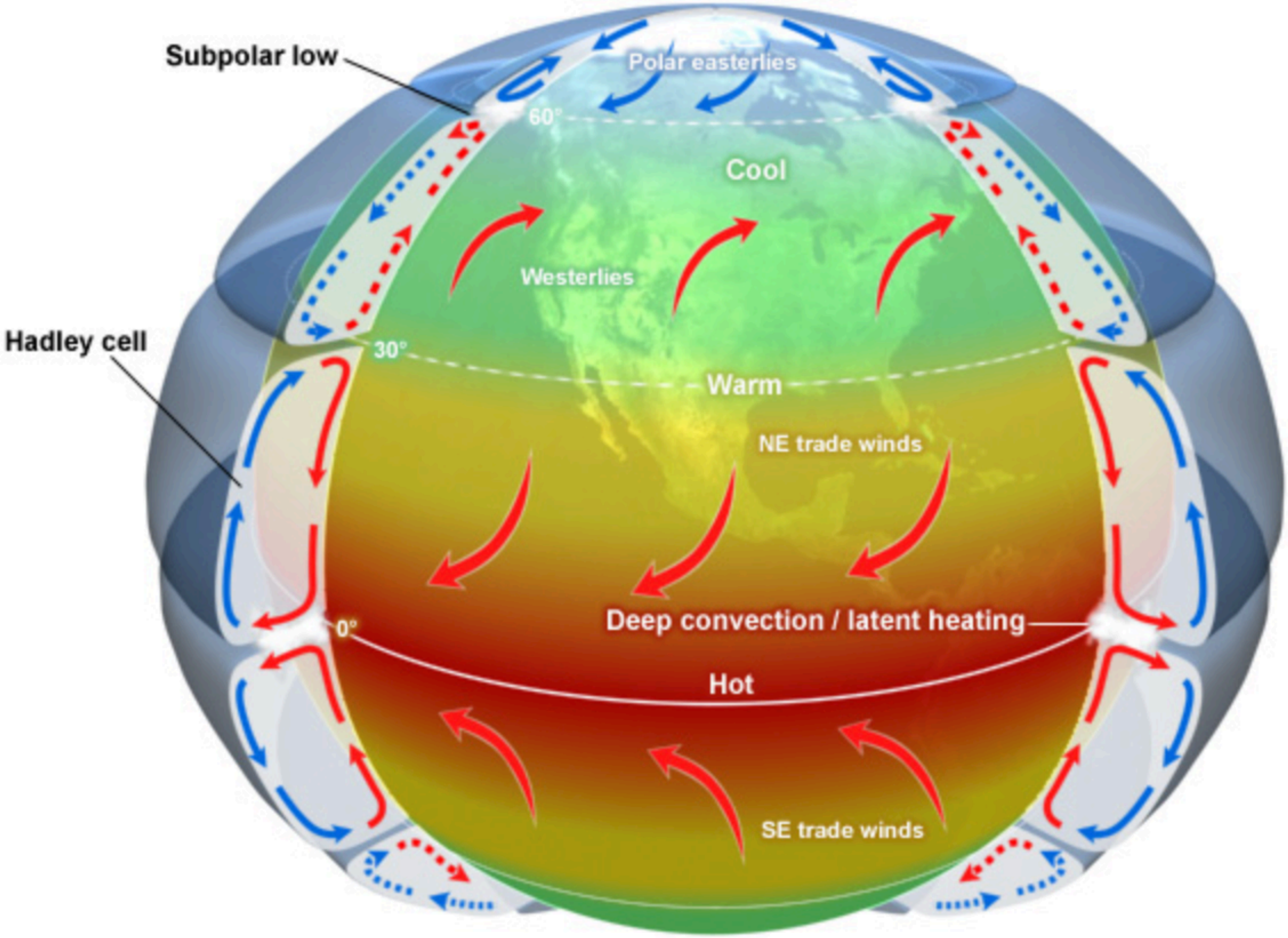
Equatorial regions receive **more energy** through incoming solar radiation compared to regions lying near the **poles**.



Source: Ahrens, 2009

Atmospheric dynamics

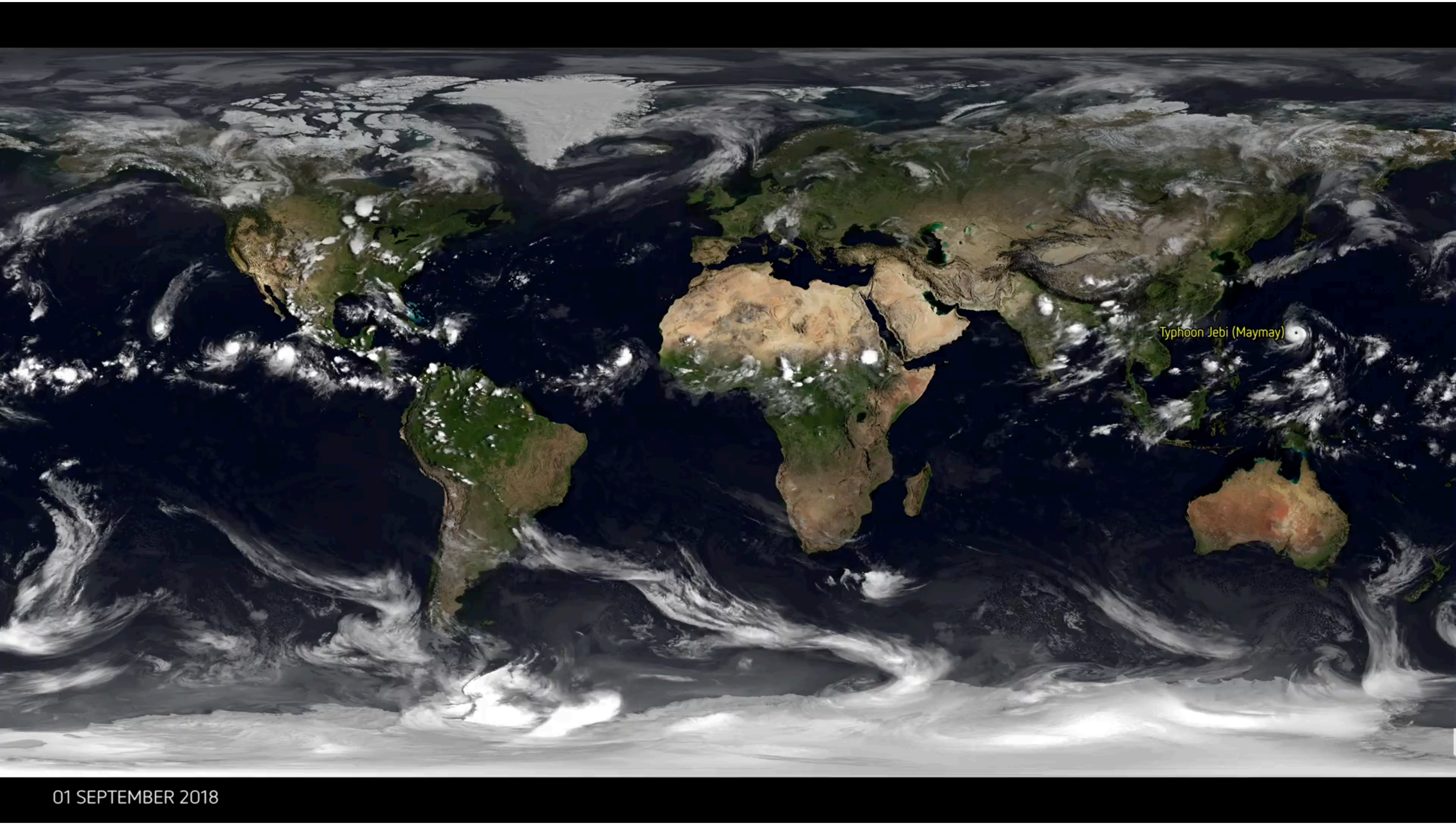
Atmospheric **circulations** develop in response to the **unequal distribution** of energy. These circulations are responsible for **redistributing energy** from the equator towards the poles.



Source: The COMET program, 2009

Storm systems

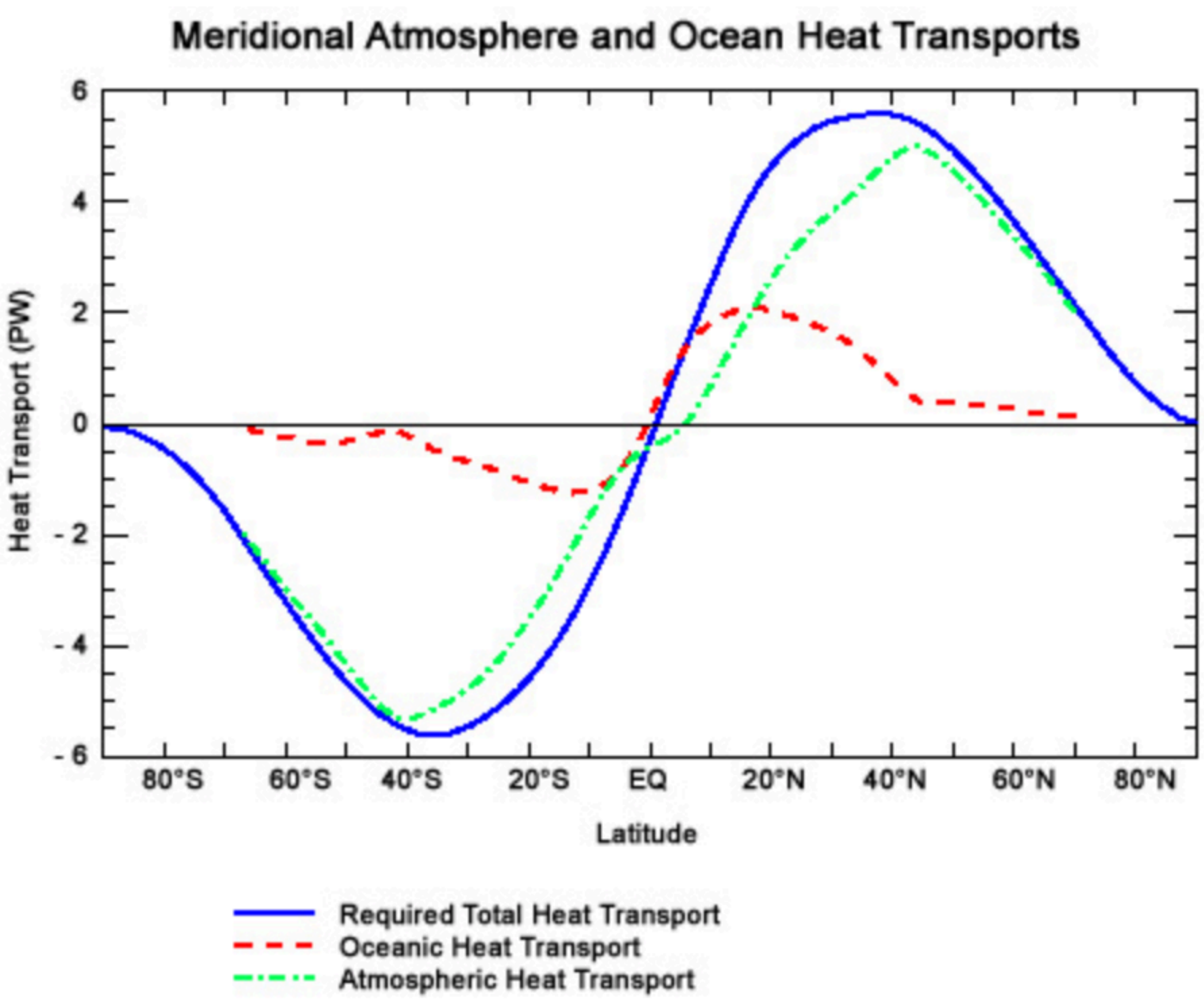
Storm systems are **smaller-scale** features **embedded** within the **large-scale** atmospheric circulations.



Source: EUMETSAT, 2018

Global heat transport

Most of the **heat** is redistributed, on a global scale, through the **atmosphere**. **Oceans** also play an important role.

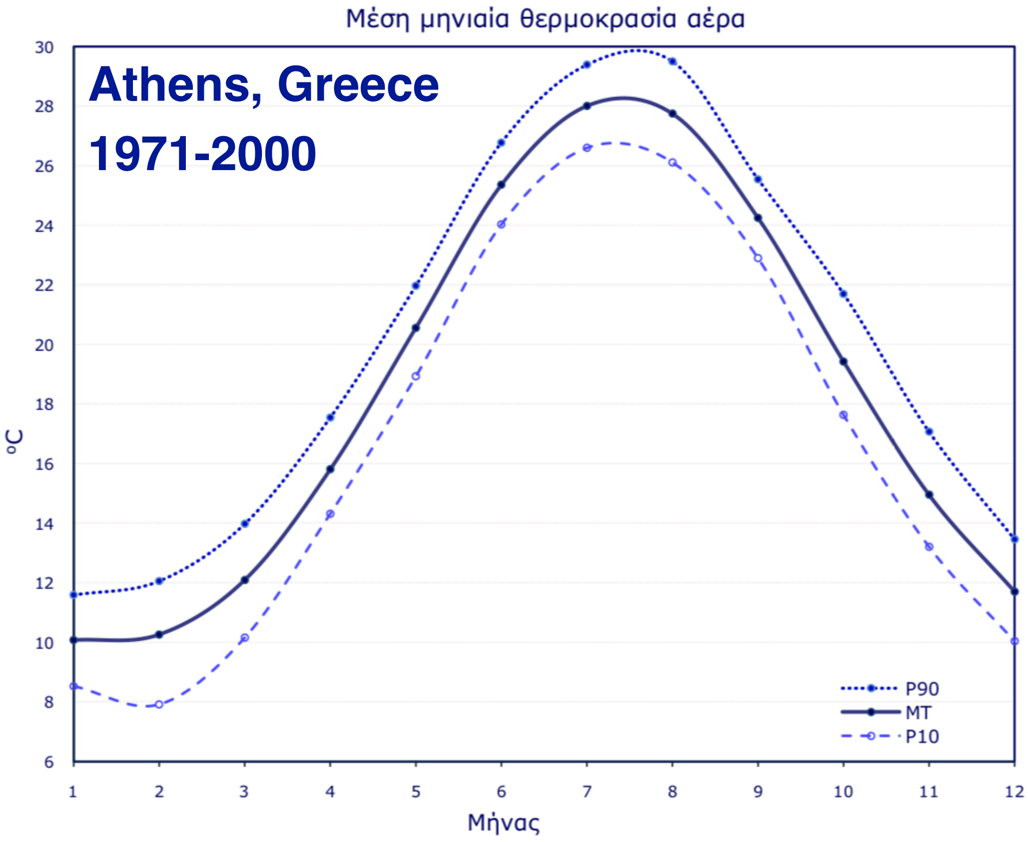


Source: Trenberth and Carol, 2001

Definition and description of climate

Climate: The **mean state of the atmosphere** on a given **time scale** (years, decades and longer).

For the **description of clime** the following variables are most often used: **(1)** temperature, **(2)** precipitation (amount, type), **(3)** wind (speed, direction), **(4)** humidity, **(5)** cloud cover/sunshine duration, **(6)** pressure, and **(7)** visibility.



	MxT	P90	MT	P10	MnT
IAN	12.0	11.6	10.1	8.5	8.1
ΦΕΒ	13.5	12.1	10.3	7.9	7.8
ΜΑΡ	14.2	14.0	12.1	10.2	8.5
ΑΠΡ	17.9	17.6	15.8	14.3	13.1
ΜΑΙ	22.2	22.0	20.6	18.9	18.6
ΙΟΥΝ	27.6	26.8	25.4	24.0	23.3
ΙΟΥΛ	30.1	29.4	28.0	26.6	26.4
ΑΥΓ	29.9	29.5	27.8	26.1	25.1
ΣΕΠ	27.4	25.6	24.3	22.9	22.2
ΟΚΤ	22.0	21.7	19.4	17.6	17.5
ΝΟΕ	17.4	17.1	15.0	13.2	12.3
ΔΕΚ	14.3	13.5	11.7	10.0	7.6

P10: 10° εκατοστημόριο
P90: 90° εκατοστημόριο
MxT: μεγαλύτερη μέση μηνιαία θερμοκρασία αέρα
MnT: μικρότερη μέση μηνιαία θερμοκρασία αέρα
MT: μέση μηνιαία θερμοκρασία αέρα

Climate versus weather

The **key difference** between climate and weather is a matter of **time scale**.

According to climate data, the **mean monthly precipitation** of **October**, in Athens, equals **40.2 mm**. However, last October, the amount of **recorded** precipitation in Athens was **0.6 mm**.

Weather forecast models:

- Start with **initial conditions**
- Simulate how these conditions **evolve** in time

Climate models:

- Are used for deriving **statistics** of weather (e.g. mean and variability)
- Do **not** depend so much on initial conditions, except from **initial ocean conditions**

Initial versus boundary conditions [1]

Weather is a problem of **initial** conditions; **climate** is a problem of **boundary** conditions.

Initial conditions quantify the **initial state** of the atmosphere:

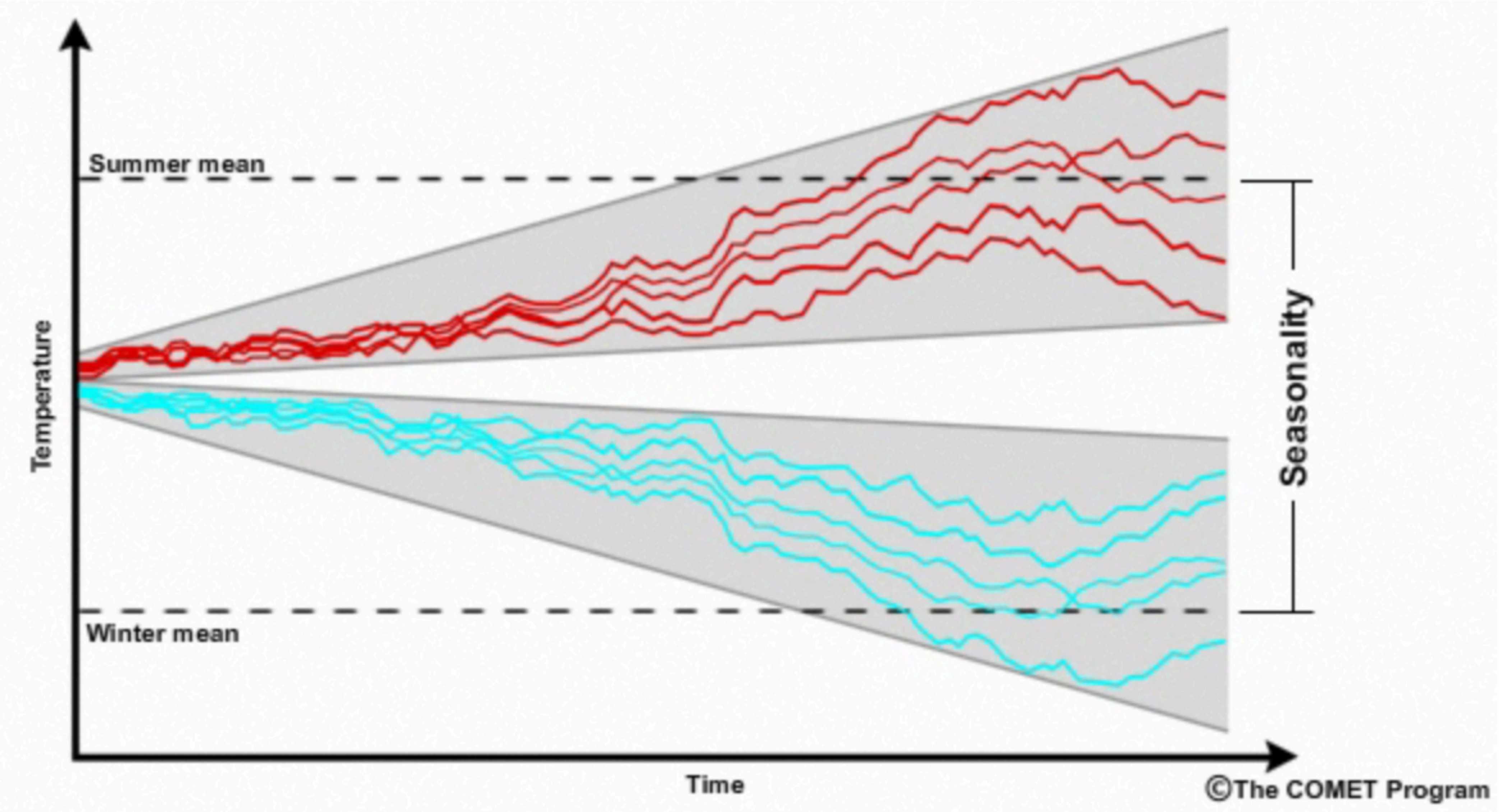
- Temperature
- Pressure
- Wind
- Humidity

Boundary conditions are a **prescribed forcing**, set by the modeller:

- Solar radiation intensity
- Atmospheric composition

Weather depends on **initial conditions**, but **climate** is heavily dependent on **boundary conditions**.

Initial versus boundary conditions [2]



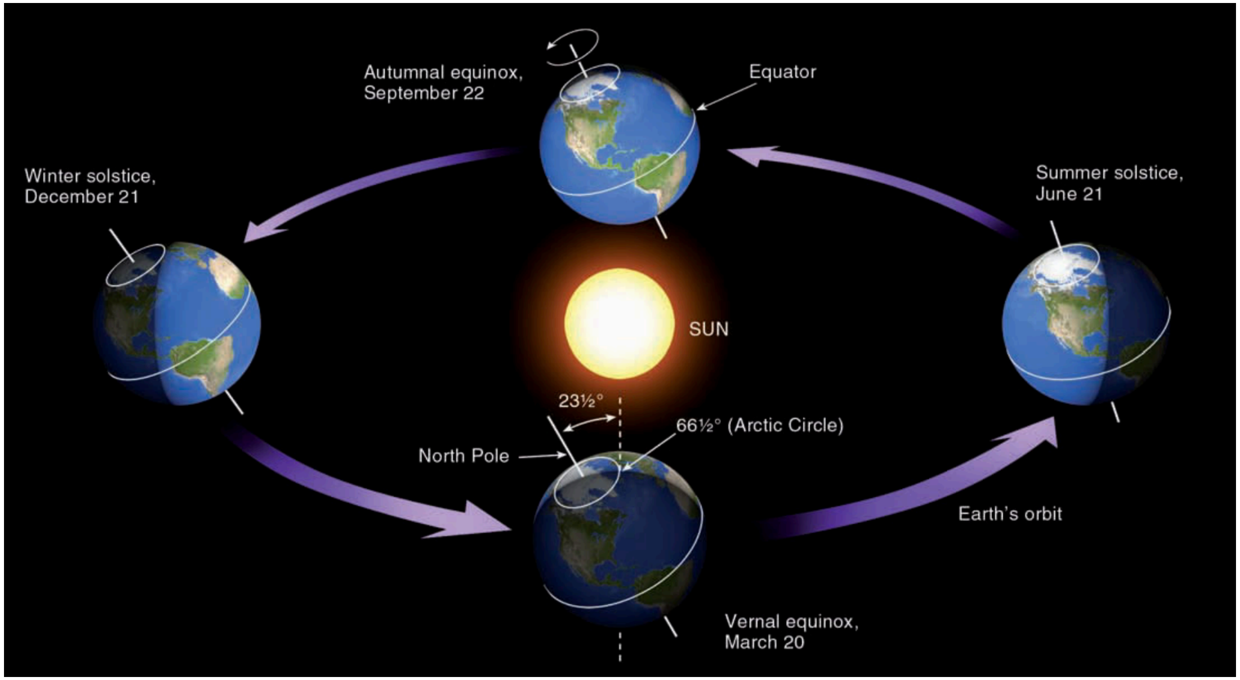
Initial versus boundary conditions

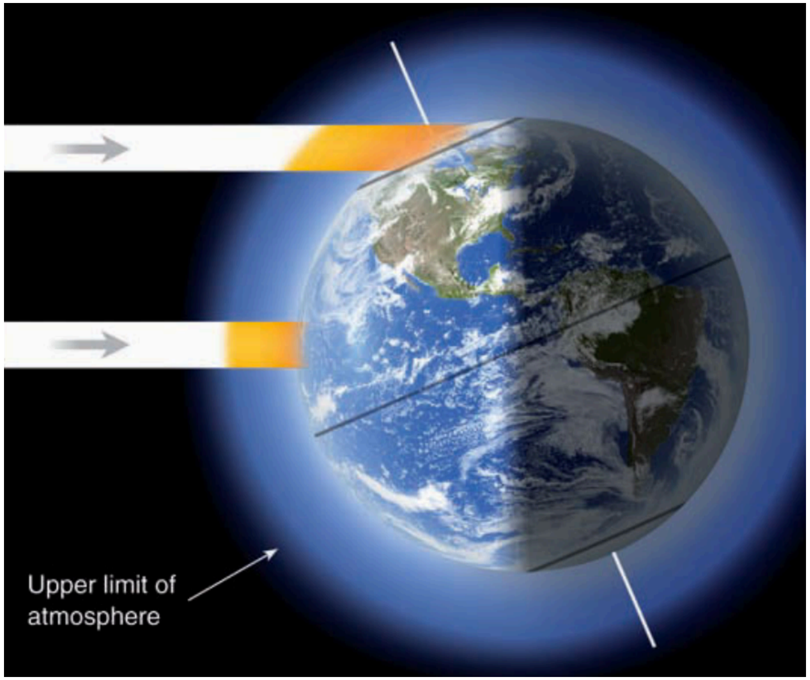
Greece is **warmer** in **summer** than in **winter**.

The **boundary condition** that differs from summer to winter is the **intensity** and **daily amount** of incoming energy through **solar radiation**.

Responsible for this difference is the **tilt** of Earth's axis:
Norther hemisphere gets more sunlight during summer than during winter.

Seasonality of **solar radiation** is a **boundary** condition.

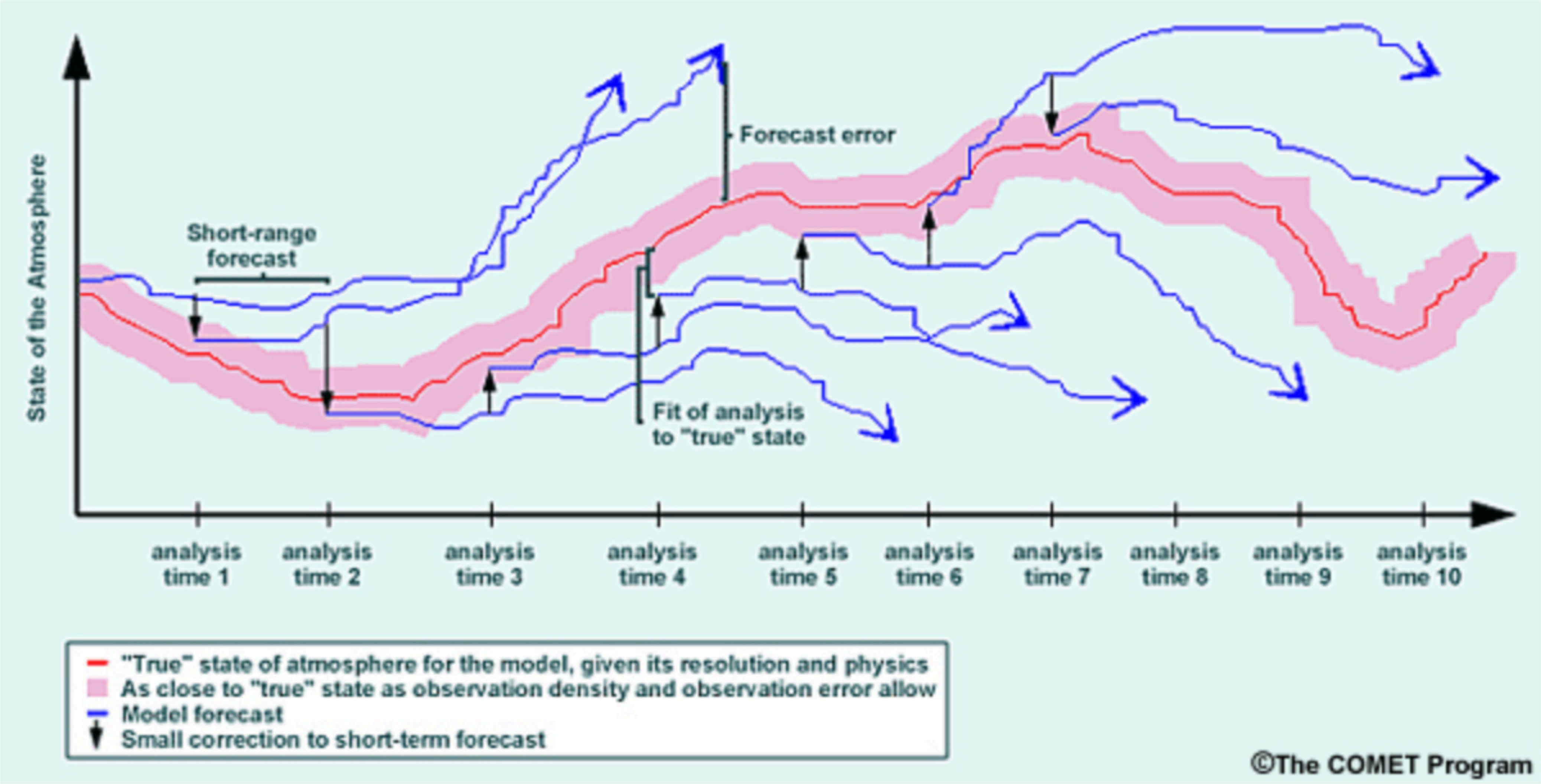




Initial versus boundary conditions

Weather forecast models rely on the provision of accurate **initial conditions**.

For **climate** models, it is **boundary conditions** that matter.



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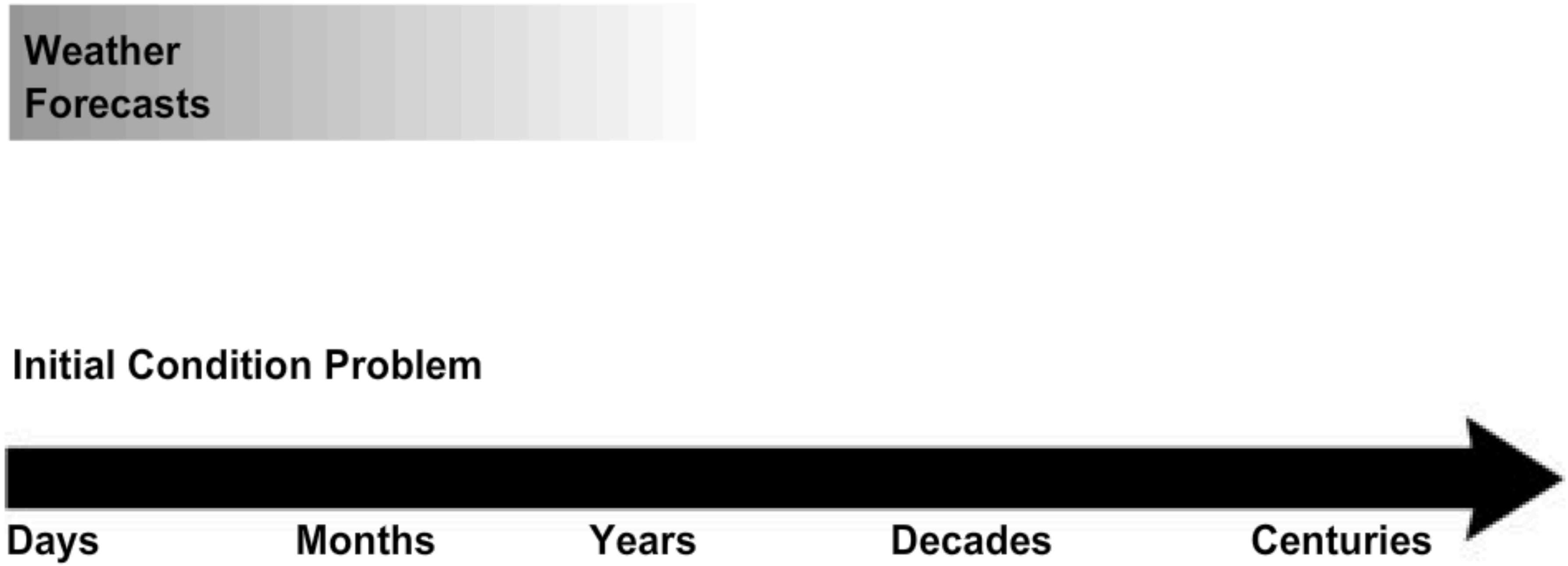
Prediction versus projection [1]

Weather forecasting

- Knowledge of **initial conditions** allows for predicting weather.
- Observational data collection and **assimilation**.
- **Evaluation** of model initialisation.
- **Comparison** of model analysis against observations.



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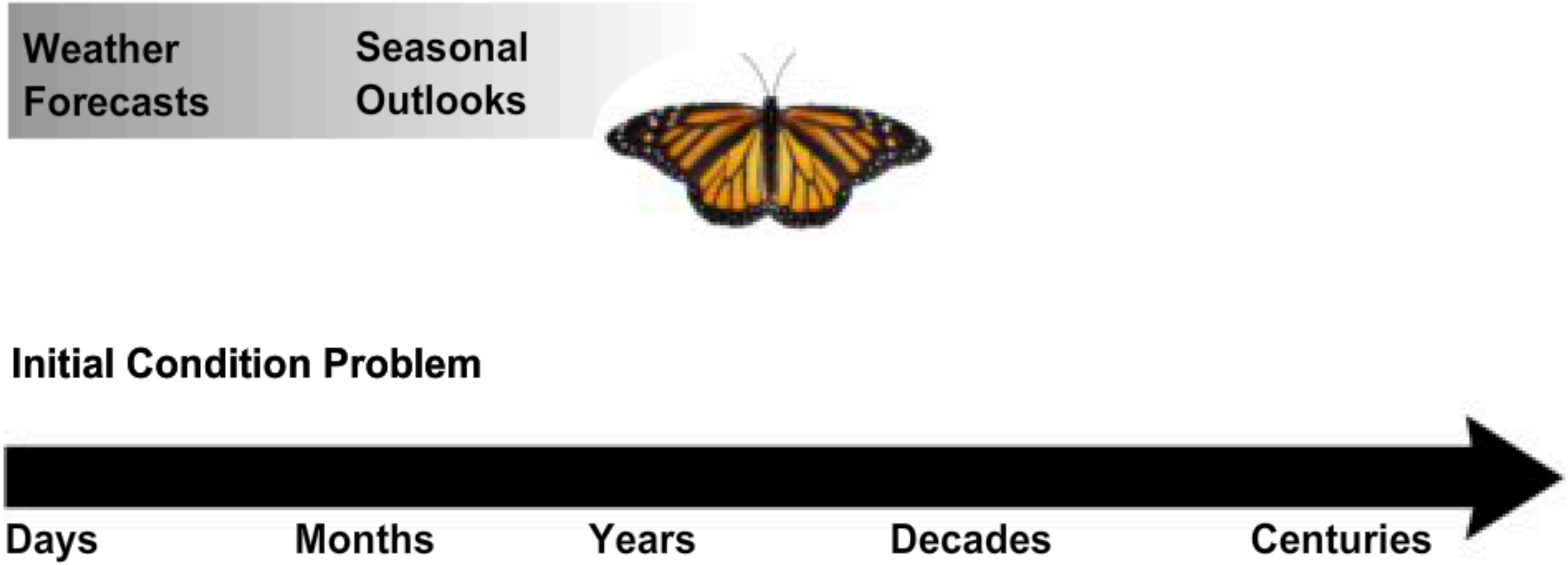
Prediction versus projection

Seasonal outlooks

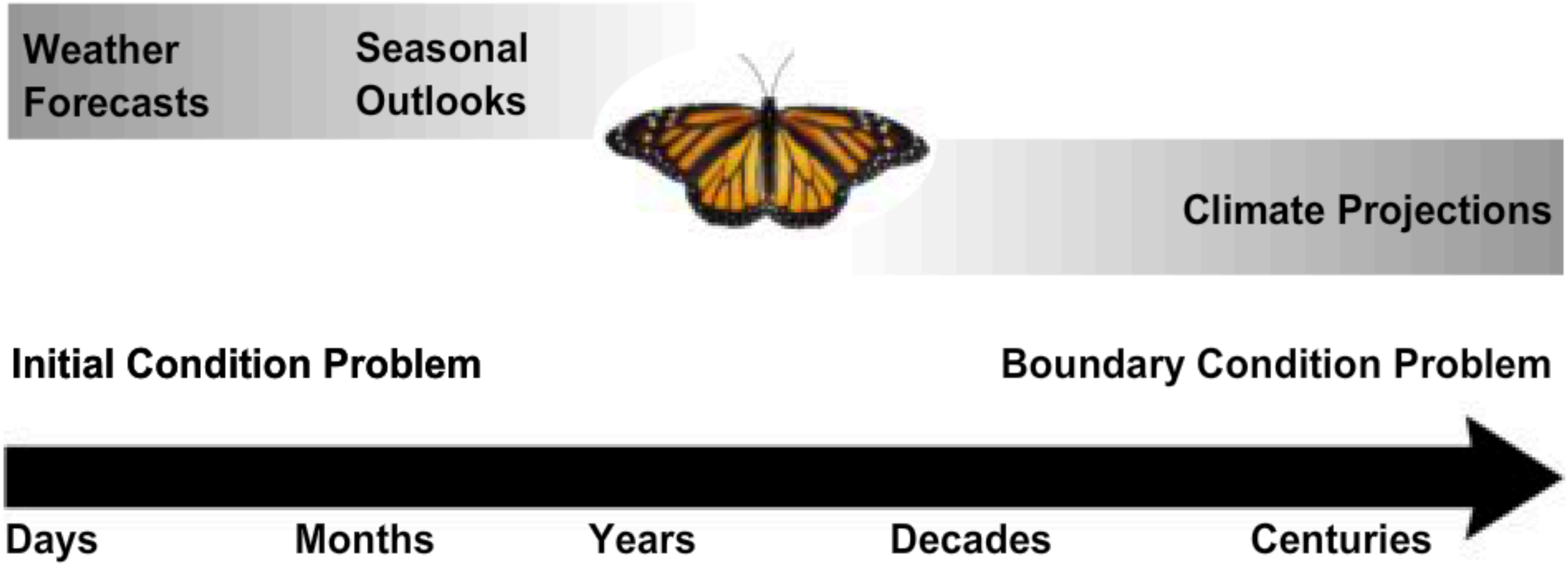
- **No structural difference** to a daily weather forecast.
- Limit of **predictability**.
- Perturbations in initial conditions **contaminate** weather forecasts.
- The atmosphere is a **chaotic** system.



Prediction versus projection

Climate simulations

- Initial conditions do **not** matter.
- **Statistics** of the climate system in response to changing **boundary conditions**.
- Study of the factors that influence the **flow of energy**.
- Increased **solar activity**: More energy available to the system.
- Increased **CO2** concentration: Absorption of IR radiation.
- **Deforestation**: Modification of surface albedo.



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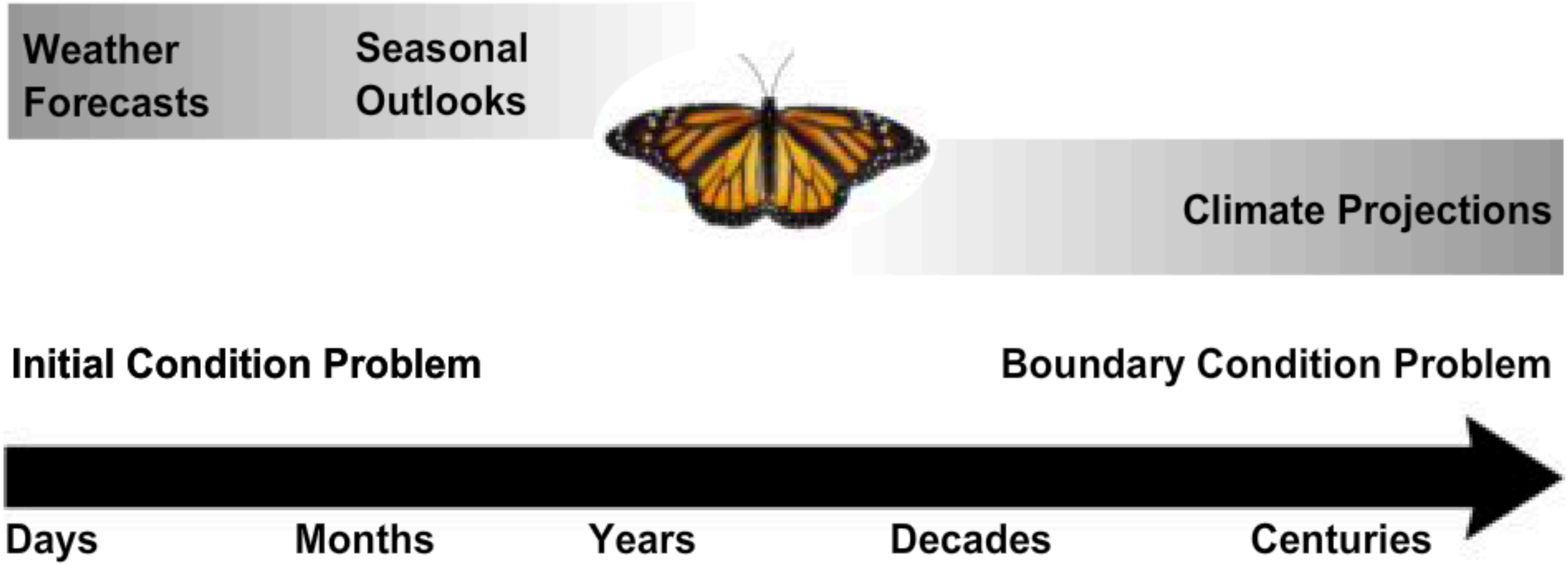
Prediction versus projection

Projection: Changes in climate system **statistics** in response to **changes** in **boundary conditions**.

Prediction: **Short-term** evolution of the climate system, starting from an **initial state** and under **constant** boundary conditions.



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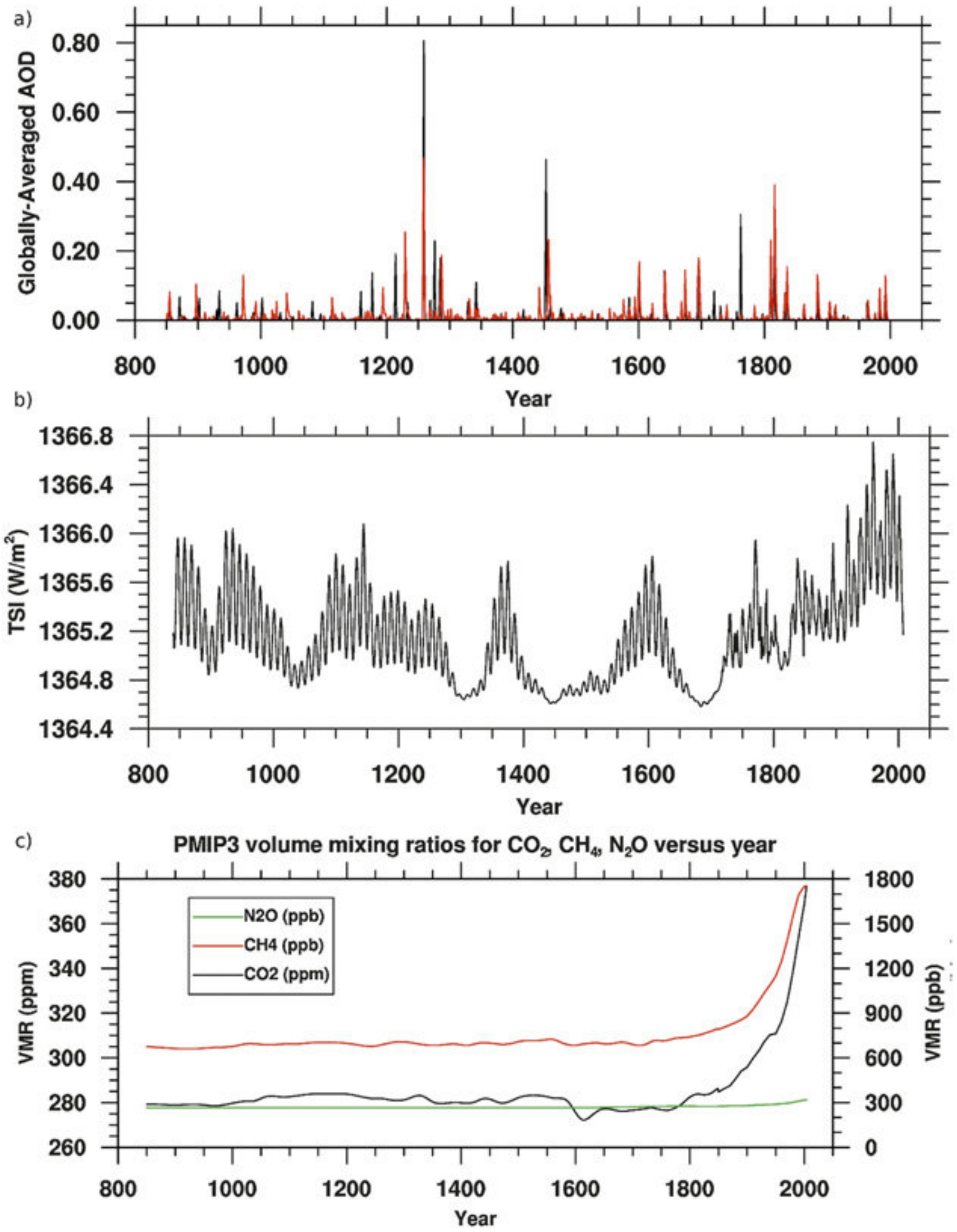
Boundary conditions [1]



Boundary conditions:

- Define the **flow of energy** in the climate system via the many interacting processes
- Are not predicted, but are prescribed
- **Natural** & **anthropogenic**

Natural boundary conditions:

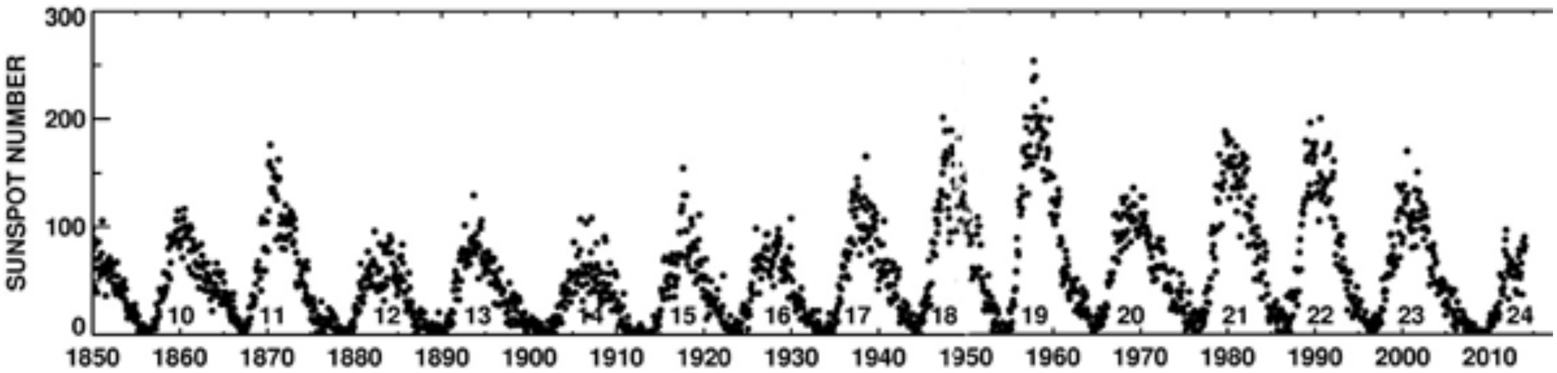
- **Volcanic** activity
- **Solar** radiation

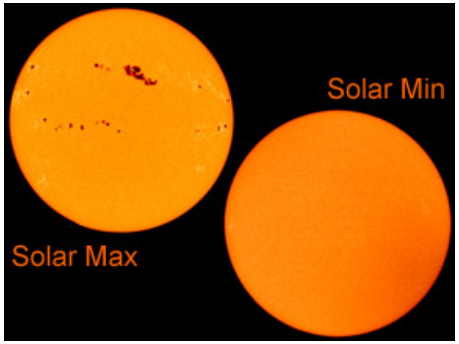
Anthropogenic boundary conditions:

- Atmospheric **composition**
- **Land use** change

Boundary conditions [2]

Solar radiation





Solar activity exhibits variations with a period of **10 - 12 years**. This variability, known as the **11-year solar cycle**, is associated with the number of **sun spots** on Sun's surface. The more the sun spots, the more the energy that sun irradiates.

Between a **solar maximum** and a solar **minimum**:

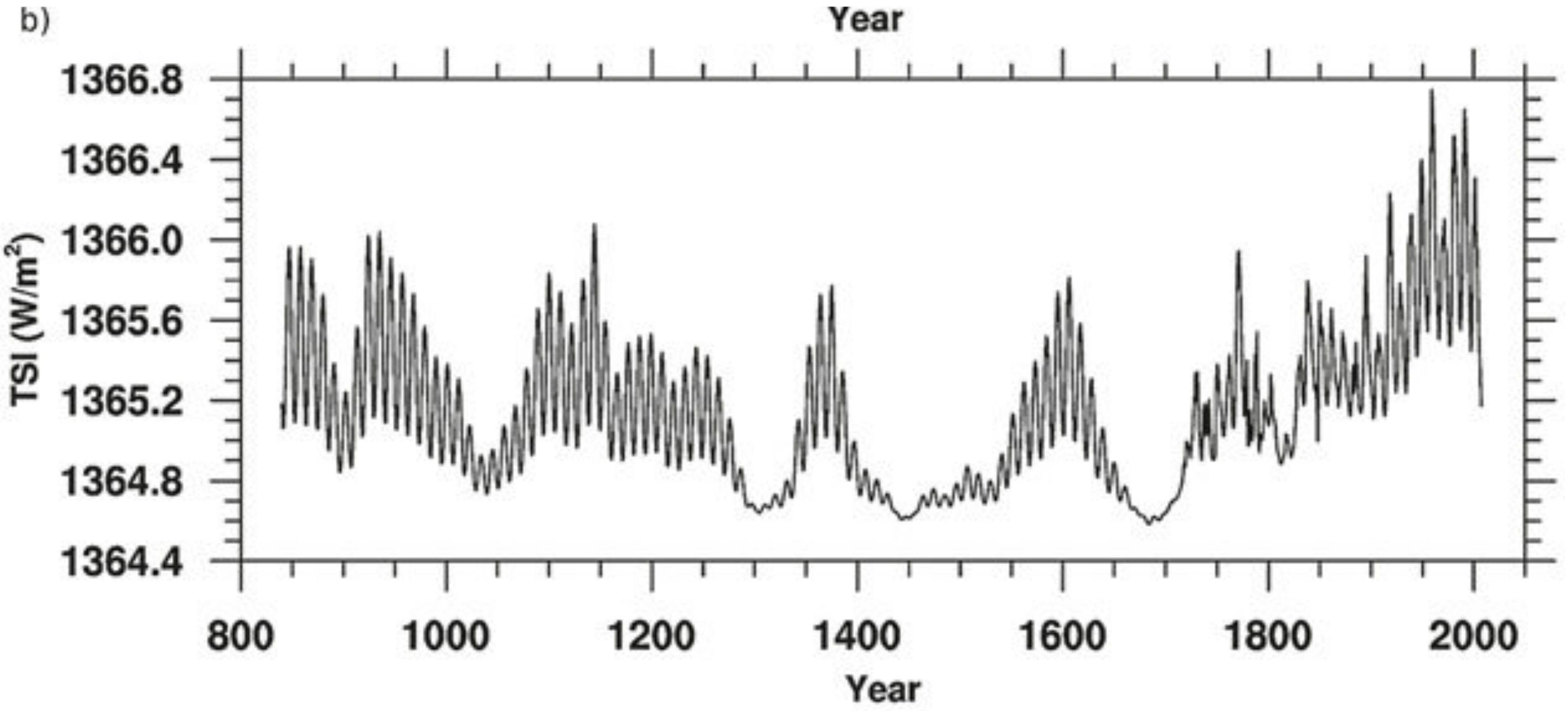
- Solar radiation that reaches the **top of the atmosphere** varies by about **1.5 W m^{-2}**
- Solar radiation **absorbed** at the Earth's surface varies by about **0.2 W m^{-2}**

Variability in the period of the solar cycle also influences the energy made available to the climate system:

- **Shorter periods** of the solar cycle are associated with **warmer** periods of the climate system

Boundary conditions

Solar radiation

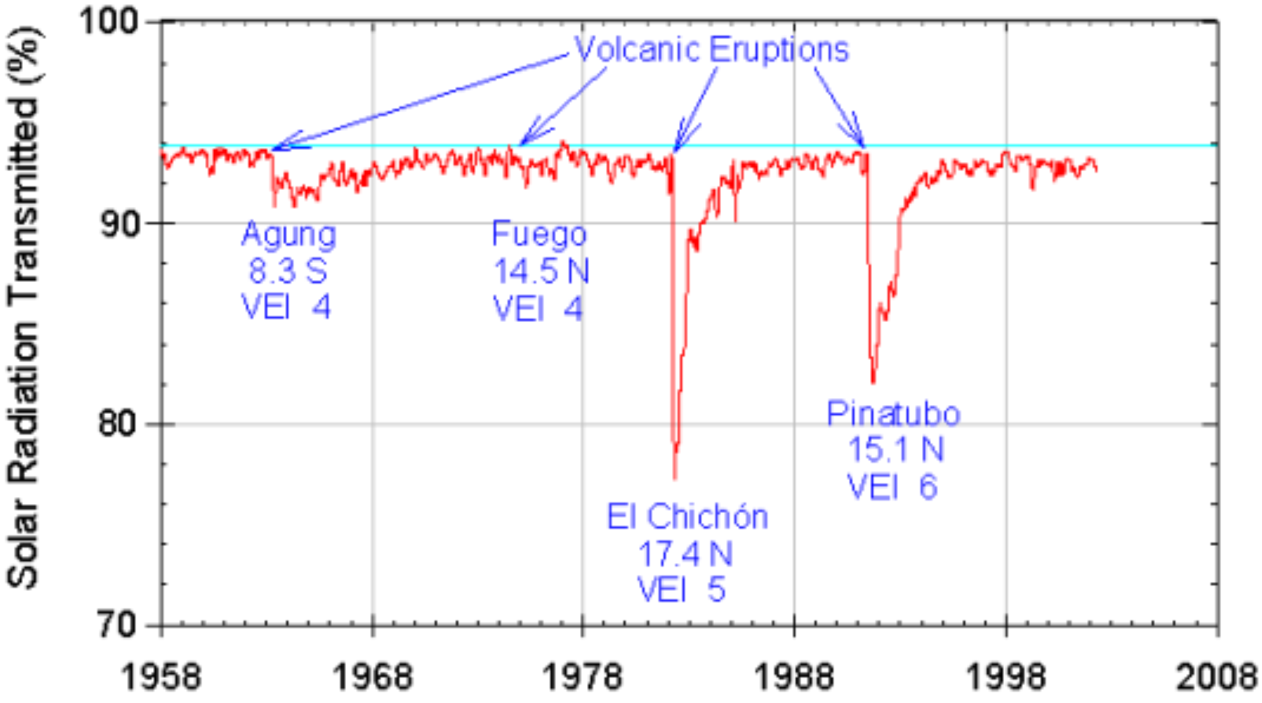


Less than 2 W m^{-2} in total solar radiation reaching the **top of the atmosphere**.

Boundary conditions subject to **daily** and **annual cycle** of solar radiation.

Boundary conditions

Volcanic gases and aerosols

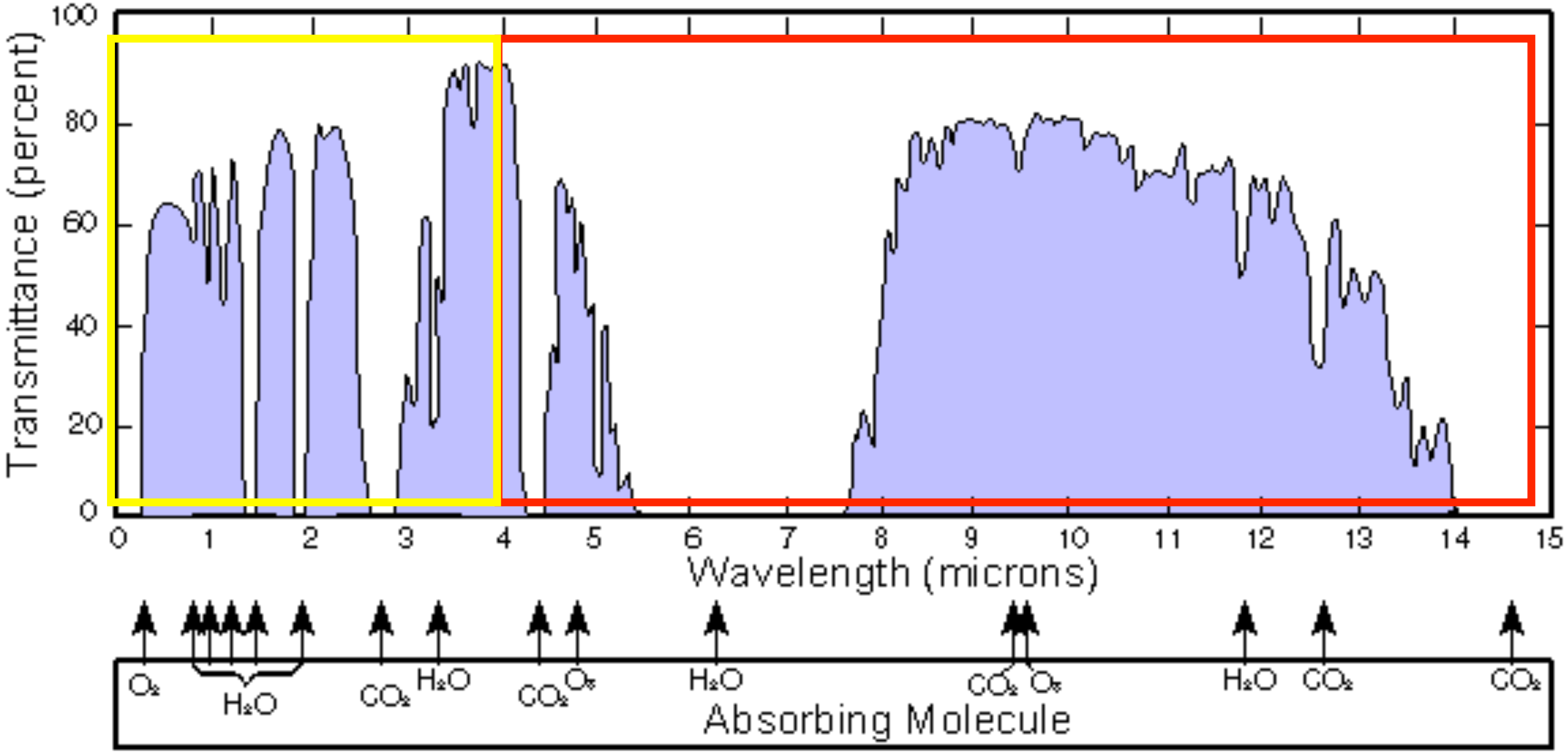


Volcanic eruptions are able to inject large quantities of **gases** and **aerosols** in the atmosphere. As a result, they have a profound impact on the **radiative transfer**, which can last up to **several years**.

Past volcanic activity data are used as boundary conditions in **past climate simulations**.

Boundary conditions

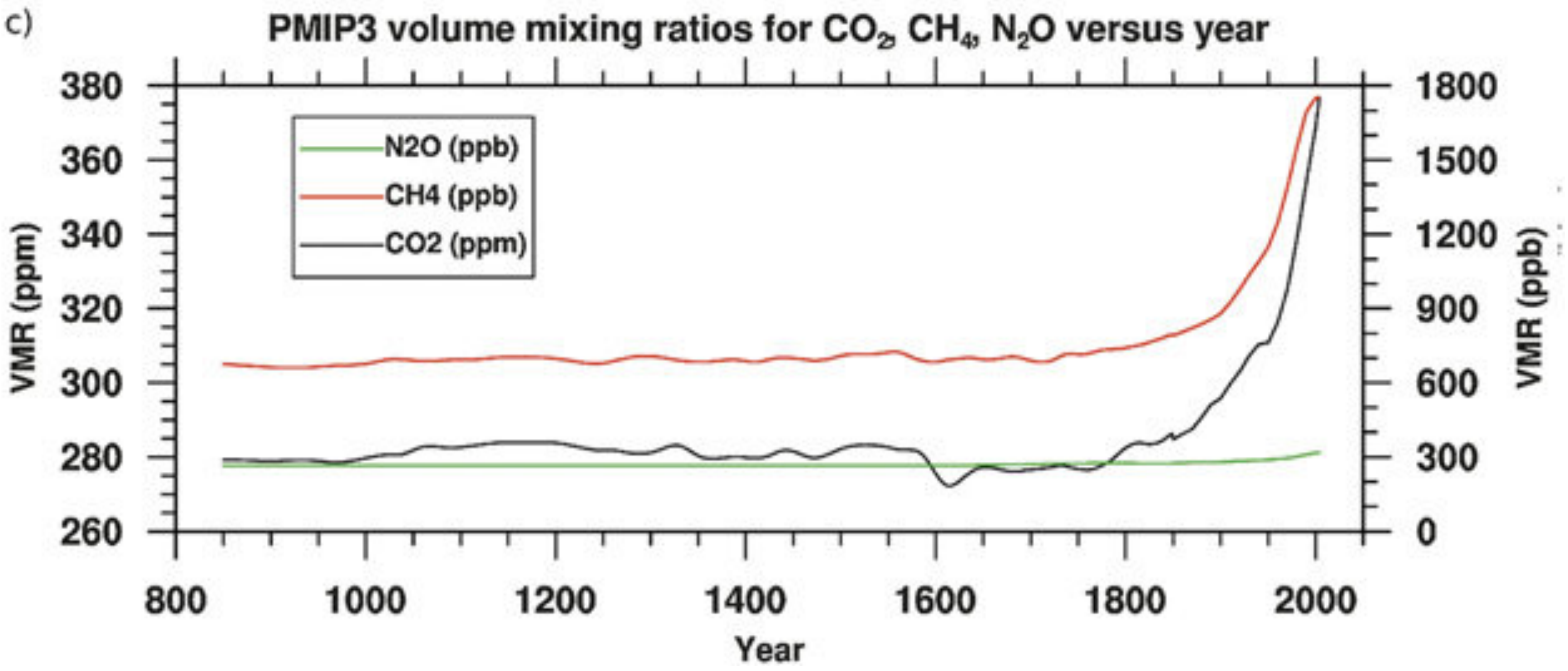
Greenhouse gases



- Water **vapour** absorbs terrestrial radiation between **5 - 8 µm**.
- **CO_2** absorbs terrestrial radiation between **13 - 15 µm**.
- The climate system **cools** through radiation escaping to space via the **atmospheric window**, between **8 - 13 µm**.

Boundary conditions

Greenhouse gases



Sharp increase of greenhouse gases concentrations over the past two centuries, attributed to the use of **fossil fuels** and **deforestation**.

CO_2 **entering** the atmosphere **exceeds** by large CO_2 that is **removed** (forests, oceans).

The atmospheric composition w.r.t. **greenhouse gases** is prescribed as **boundary conditions**.

Summary

- **Climate modelling** aims at simulating the **flow of energy** through the **climate system**, via many interacting processes.

- **Radiative transfer** in the atmosphere plays a **key role** in determining the energy **gains** and **losses** of the climate system.

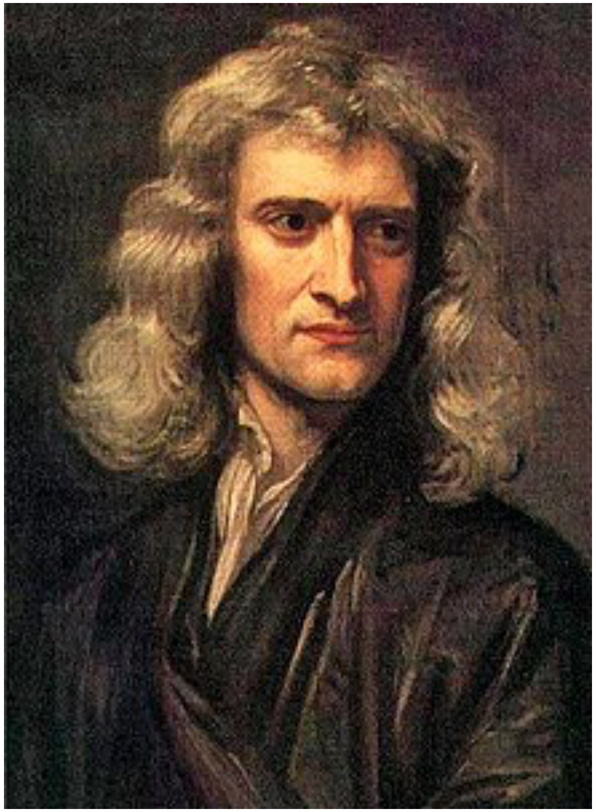
- **Weather** and **climate** models rely on the **same** principles, but look at **different problems**.

- **Weather prediction** is a problem of **initial conditions**; **Climate modelling** is a problem of **boundary conditions**.

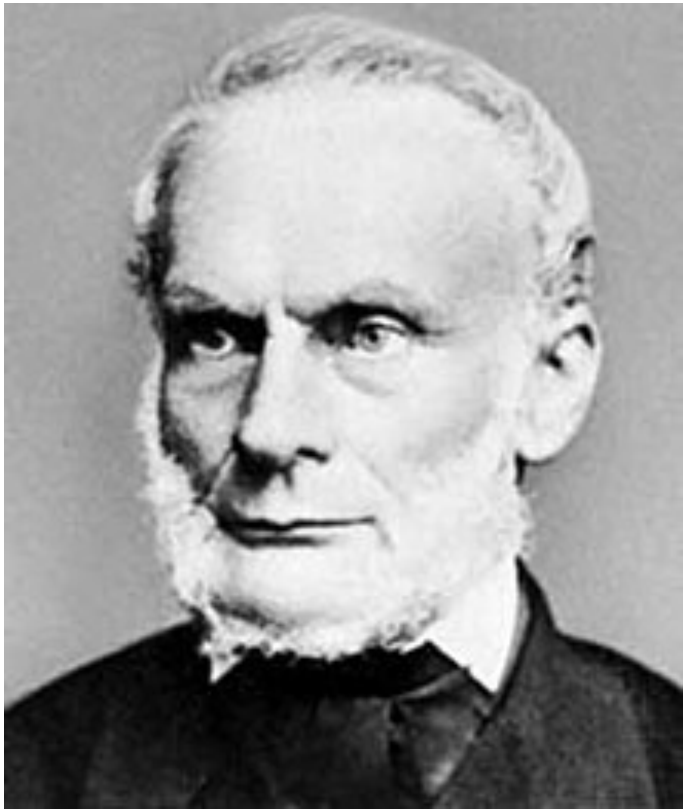
- Boundary conditions can be either **natural** (solar radiation, volcanos) or **anthropogenic** (greenhouse gases).

- The **outcome** of a climate simulation depends heavily on **boundary conditions**, which need be to **prescribed** by the modeller.

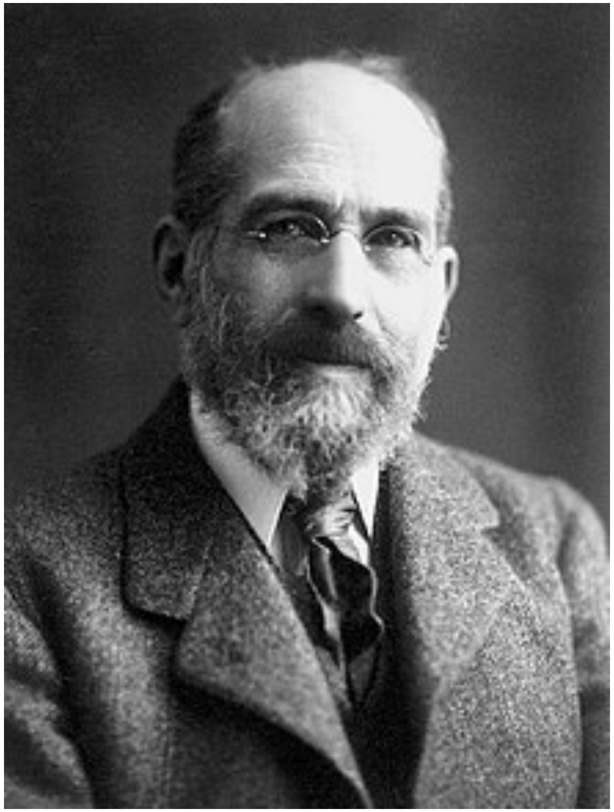
History of climate modelling [1]



Sir Issac Newton



Rudolf Clausius



Arthur Schuster

Fundamentals of physics, applied in modelling:

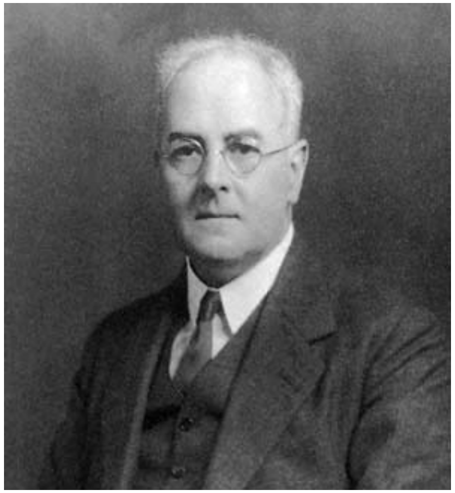
- Newton’s **laws of motion**
- Clausius’ **1st law of thermodynamics**
- Schuster’s governing equations of **radiative transfer**

History of climate modelling

Vilhelm Bjerkness (1862 - 1951), Norwegian Physicist - Meteorologist

*"…the **necessary** and **sufficient** conditions for the rational solution of weather forecasting are the following:*

1. *A sufficiently **accurate knowledge** of the **state** of the atmosphere **at a given time***
2. *A sufficiently **accurate knowledge** of the **laws** according to which one state of the atmosphere develops from another."*



Lewis Fry Richardson (1881 - 1953), British Mathematician - Physicist

Weather Prediction by Numerical Process

Development and application of **numerical methods** for solving the **primitive equations** of the atmosphere:

- horizontal **momentum conservation**
- continuity equation (**conservation of mass**)
- **ideal gas law**

History of climate modelling

John von Neumann (1903 - 1957), Hungarian/American Physicist - Mathematician - Computer Engineer

“*Weather forecasting was, par excellence, a **scientific problem** suitable for solution using a **large computer***”

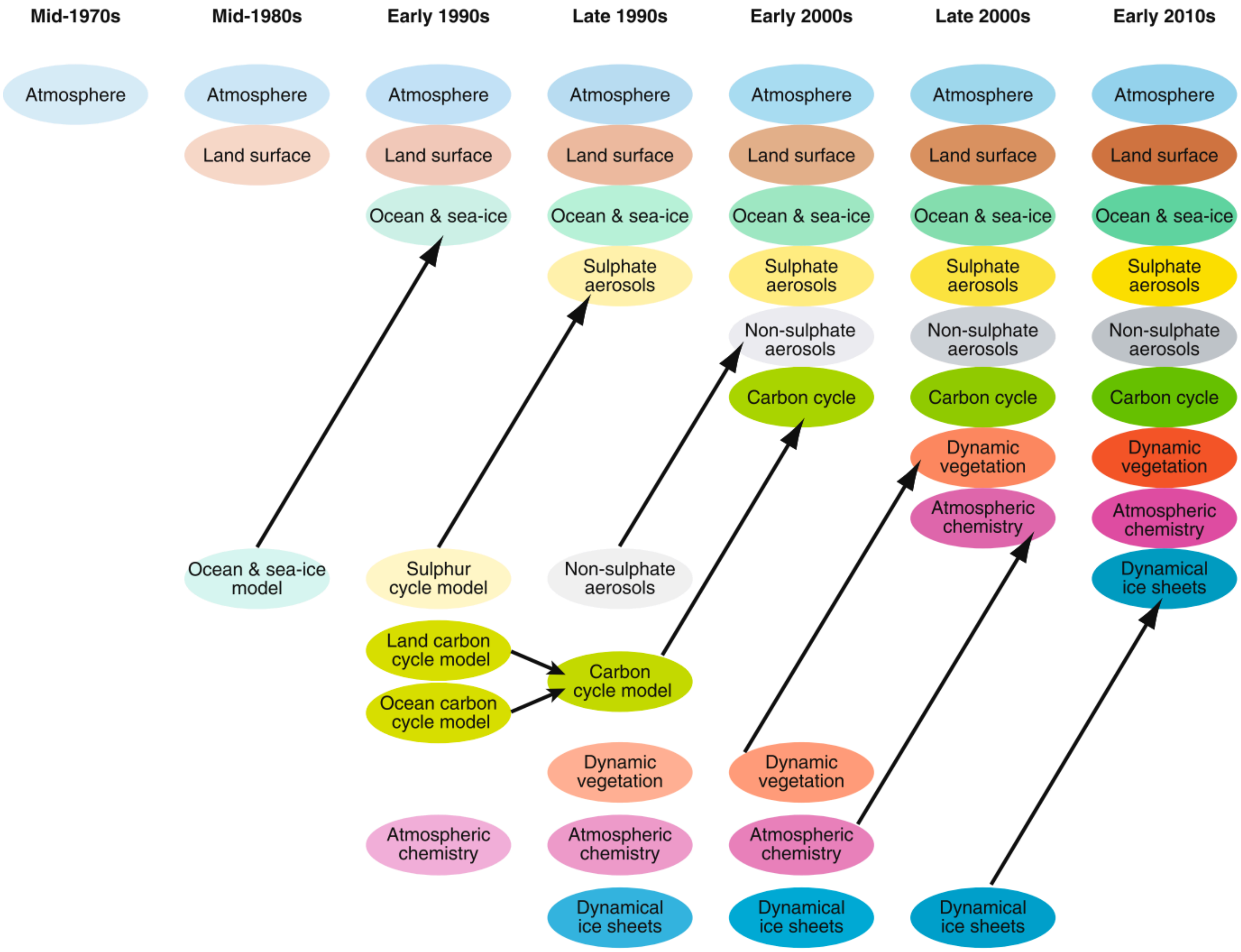
Ragnar Fjortoft (1913 - 1998), Norwegian Meteorologist

Jule Charney (1917 - 1981), American Meteorologist

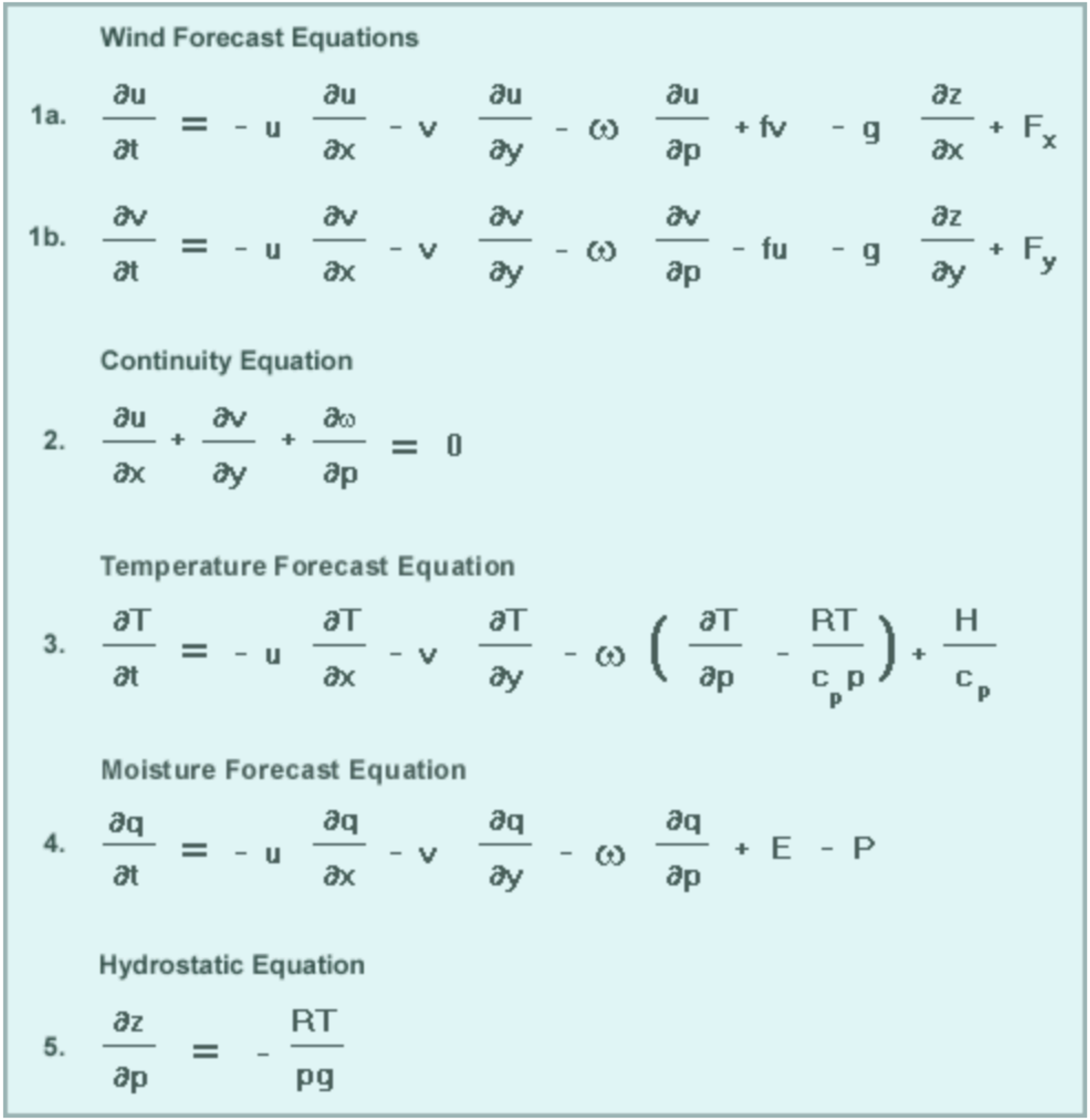
First successful numerical weather prediction using **ENIAC**.

History of climate modelling

[4]



Building a climate model: Resolved dynamics [1]



Wind Forecast Equations

1a. $$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - \omega\frac{\partial u}{\partial p} + fv - g\frac{\partial z}{\partial x} + F_x$$

1b. $$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \omega\frac{\partial v}{\partial p} - fu - g\frac{\partial z}{\partial y} + F_y$$

Continuity Equation

2. $$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

Temperature Forecast Equation

3. $$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - \omega\left(\frac{\partial T}{\partial p} - \frac{RT}{c_p p}\right) + \frac{H}{c_p}$$

Moisture Forecast Equation

4. $$\frac{\partial q}{\partial t} = -u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y} - \omega\frac{\partial q}{\partial p} + E - P$$

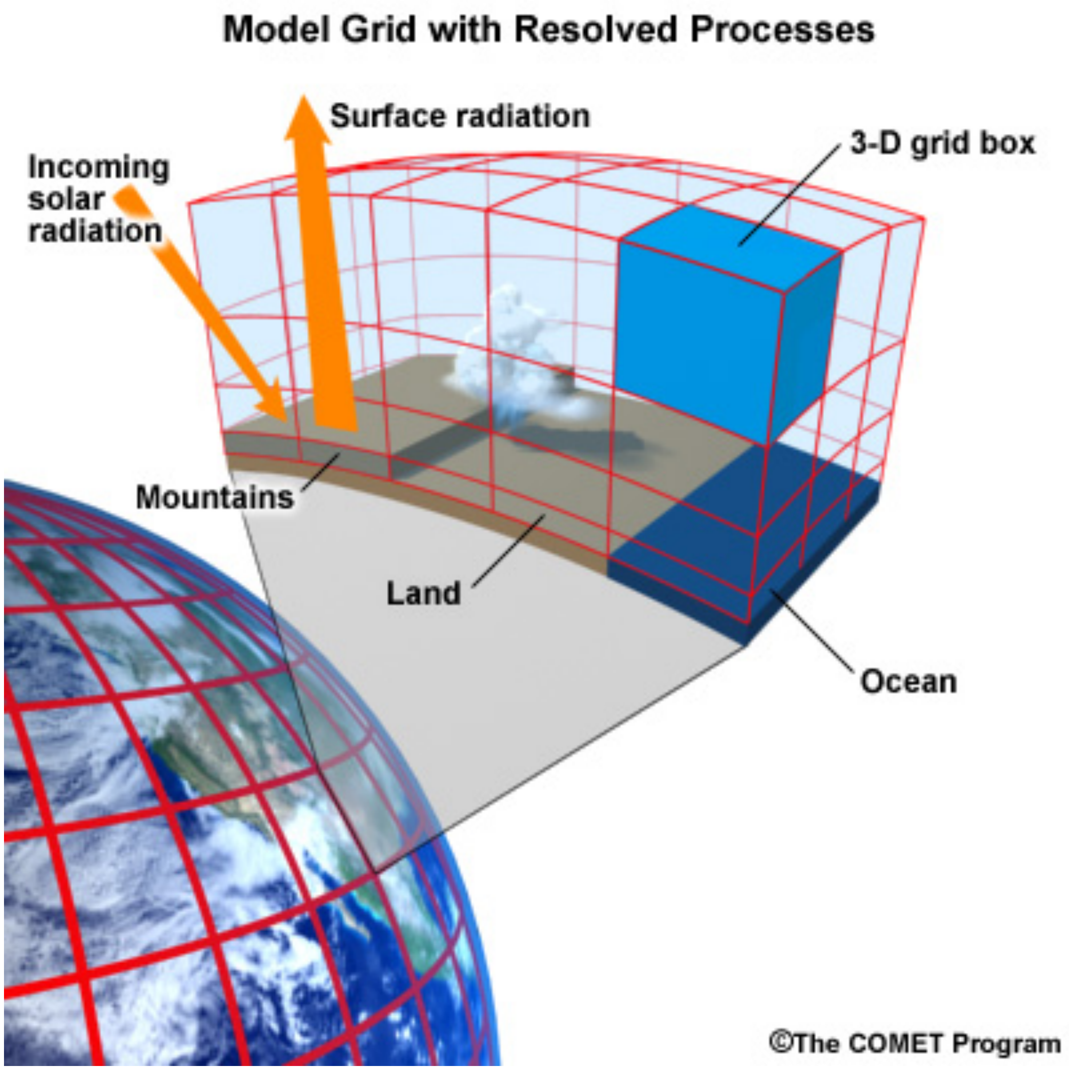
Hydrostatic Equation

5. $$\frac{\partial z}{\partial p} = -\frac{RT}{pg}$$

Primitive equations

- **Balancing** of forces in 3D
- **Conservation** of mass
- **Tracking** of state variables
- **Tracking** of trace atmospheric products

Building a climate model: Resolved dynamics [2]



Computers can only do **arithmetics** (**+, -, *, /**) and **no algebra**.

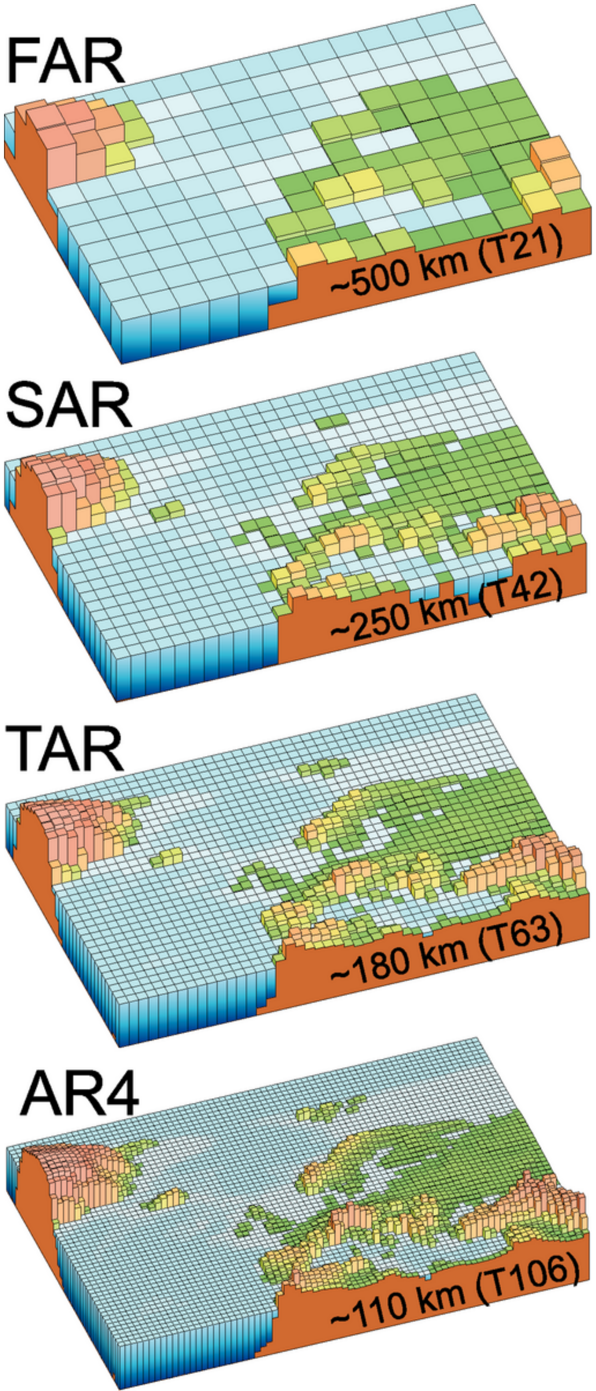
The **atmosphere** needs to be divided into a **finite** number of **grid boxes** in 3D.

Numerical methods are applied for solving the **primitive equations** at the **centre** of each **grid box**.

Finite differences are used for **approximating** the **derivatives** present in the primitive equations.

Processes taking place **between** the **grid boxes** are characterised as **resolved processes**.

Building a climate model: Resolved dynamics [3]



Early models had horizontal **grid spacings** of the order of **500 km**, and only few (<10) vertical levels.

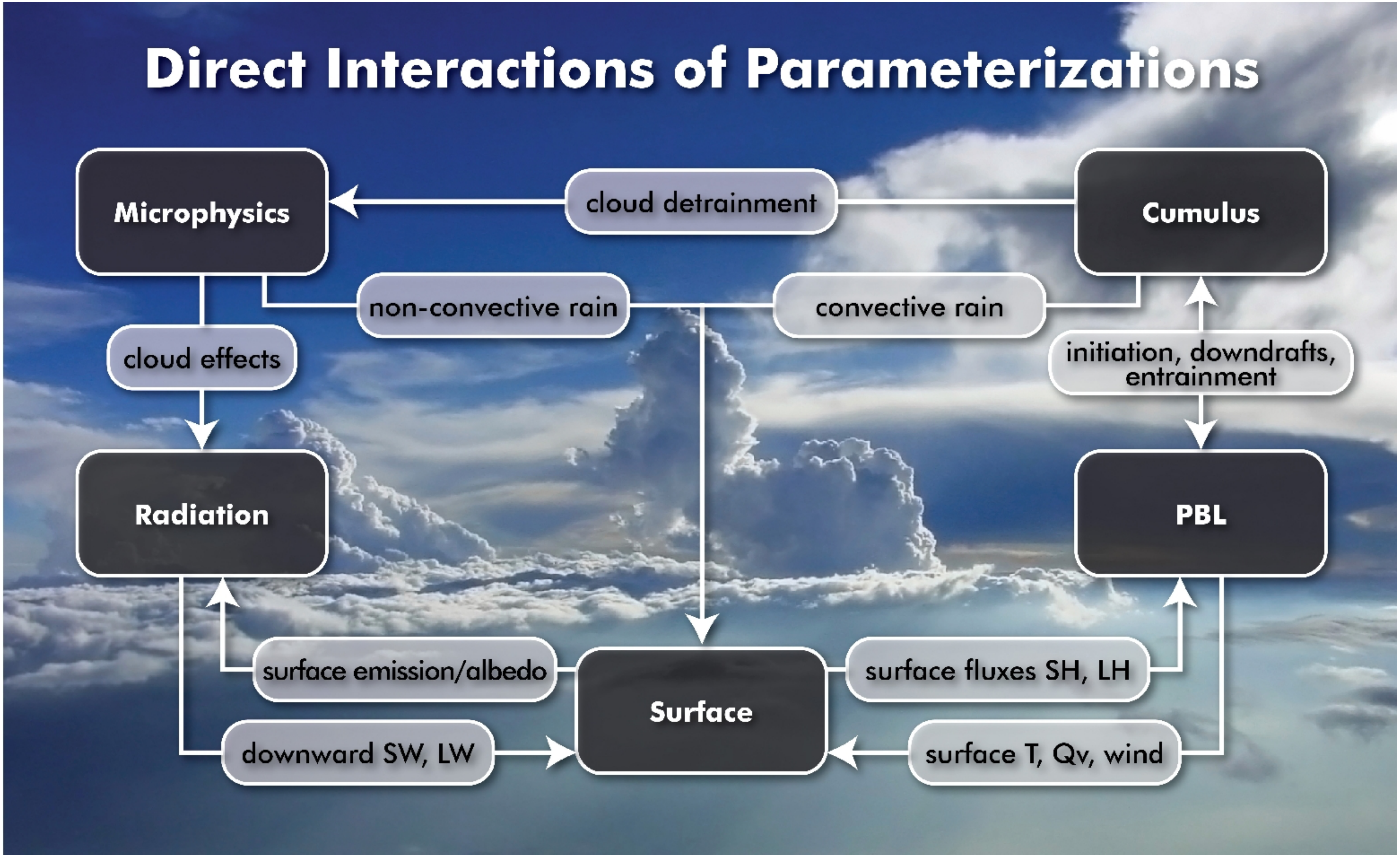
The **progress** made in **computing** science allowed for gradually **increasing** the **horizontal** and **vertical** resolution.

Today, **global climate models** are able to run on resolutions as low as **~30 km**, while **regional climate models** may be run at the **kilometre scale**.

Building a climate model: Parameterisations [1]

Sub-grid scale processes are **represented** with **parameterisations**.

Parameterised processes **interact** with each other in **numerous** ways, affecting also, **indirectly**, resolved processes.



Direct Interactions of Parameterizations

Microphysics

Cumulus

Radiation

PBL

Surface

cloud detrainment

non-convective rain

convective rain

cloud effects

initiation, downdrafts, entrainment

surface emission/albedo

surface fluxes SH, LH

downward SW, LW

surface T, Qv, wind

Building a climate model: Parameterisations

Parameterisations:

- are based on the **laws of physics** and **observations**
- are **not** a type of “**best guess**”

Cloud microphysics example

- **Conservation** laws dictate water mass **budget**.
- **Empirical** RH thresholds define **condensation** and **formation** of clouds.
- **Physical** processes drive **coalescence** and formation of **droplets**.
- Droplets **precipitate** as rain or snow, based on **observational** evidence.

Building a climate model: Parameterisations [3]

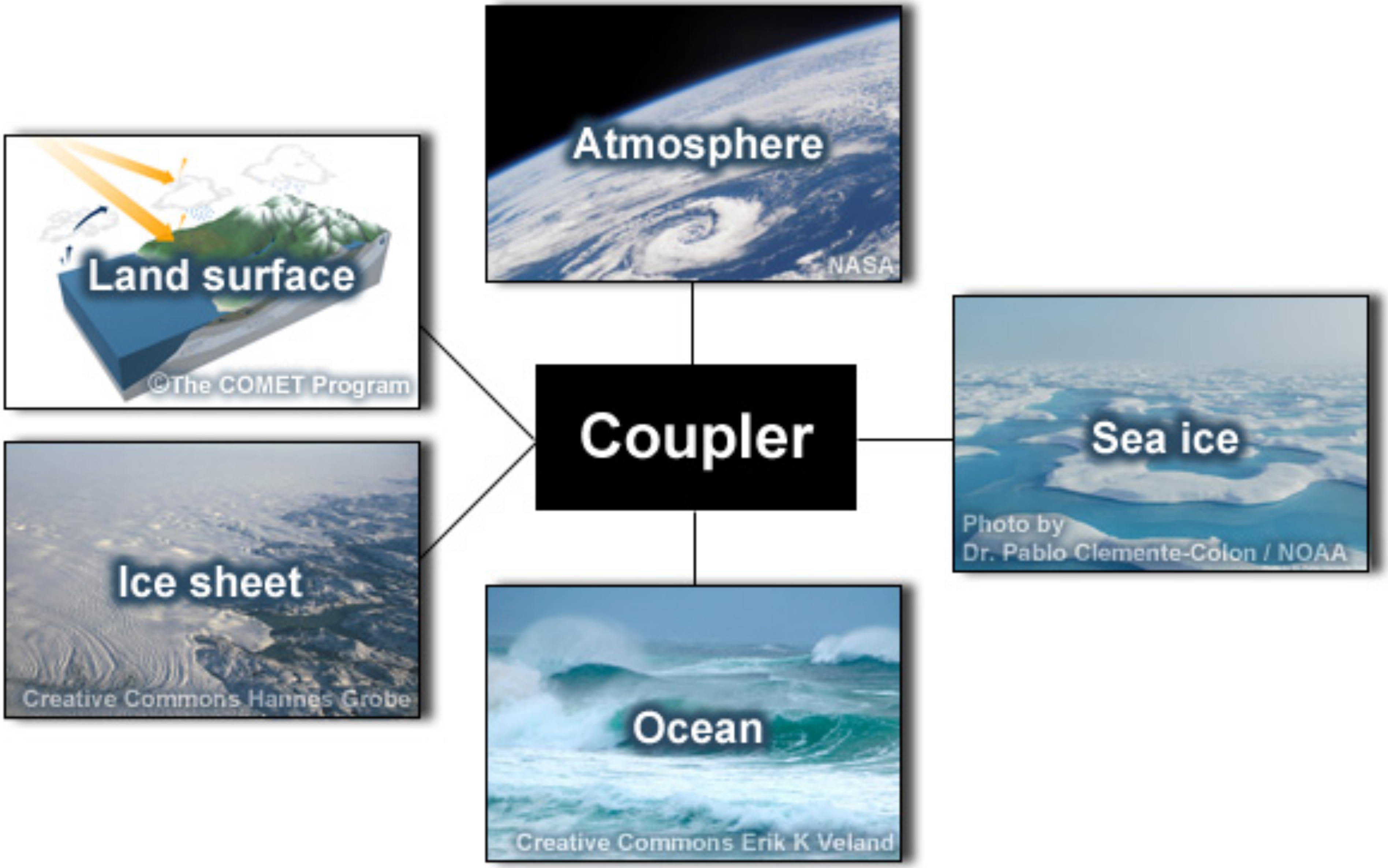
Parameterisations introduce **uncertainty** in model simulations, since there are processes that are better understood than others.

In fact, **all model processes** come with inherent **uncertainty**; even the numerical representation of the primitive equations.

Though, model uncertainty **decreases**:

- as our **understanding** of physical processes **increases**
- as **computing** capacity **increases**

Climate model components



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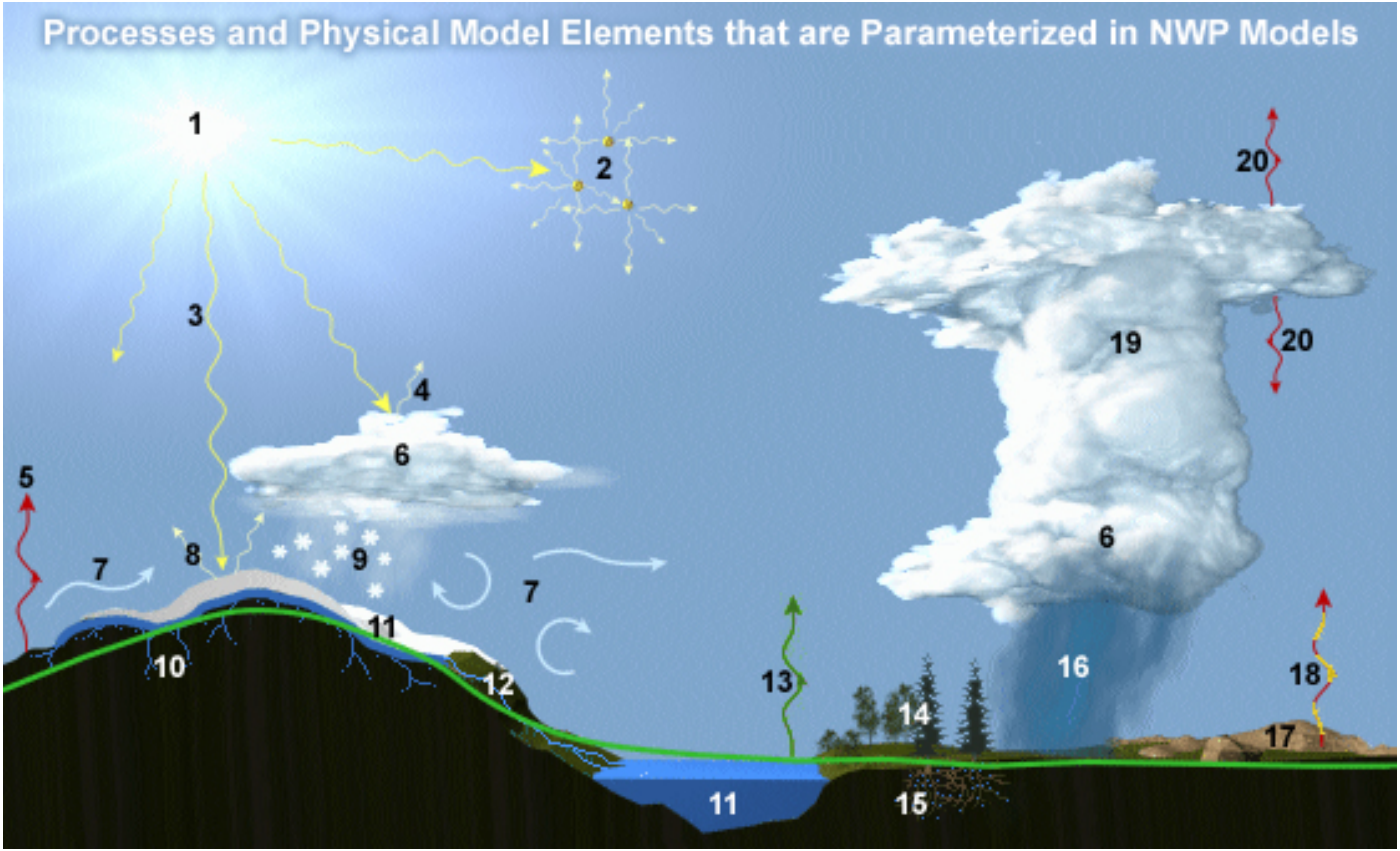
Climate model components: Atmospheric model



Structure similar to that of a typical weather model.

Climate model components: Atmospheric model [2]

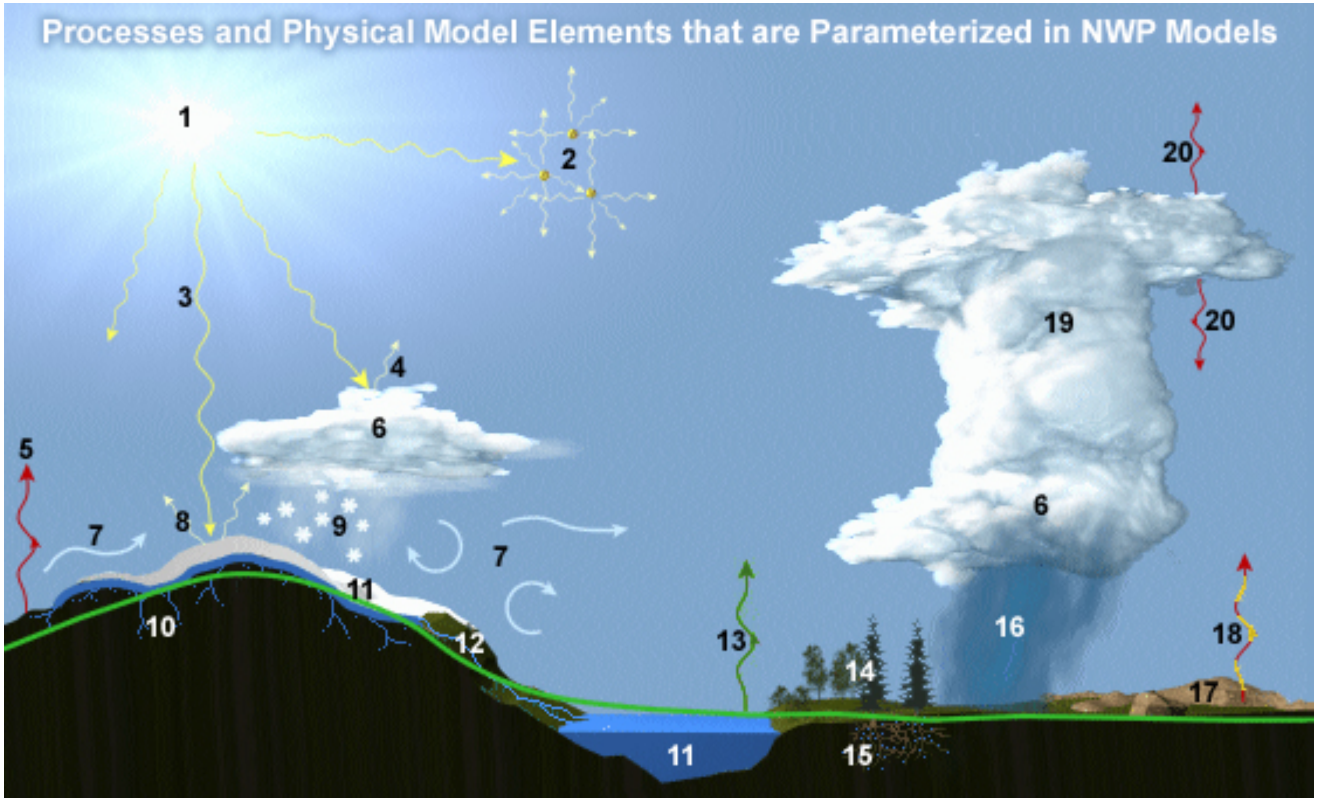
Equations of motion are solved at each grid point:

- **Pressure-gradient** force
- **Coriolis** effect
- Forces due to the **curvature** of the flow

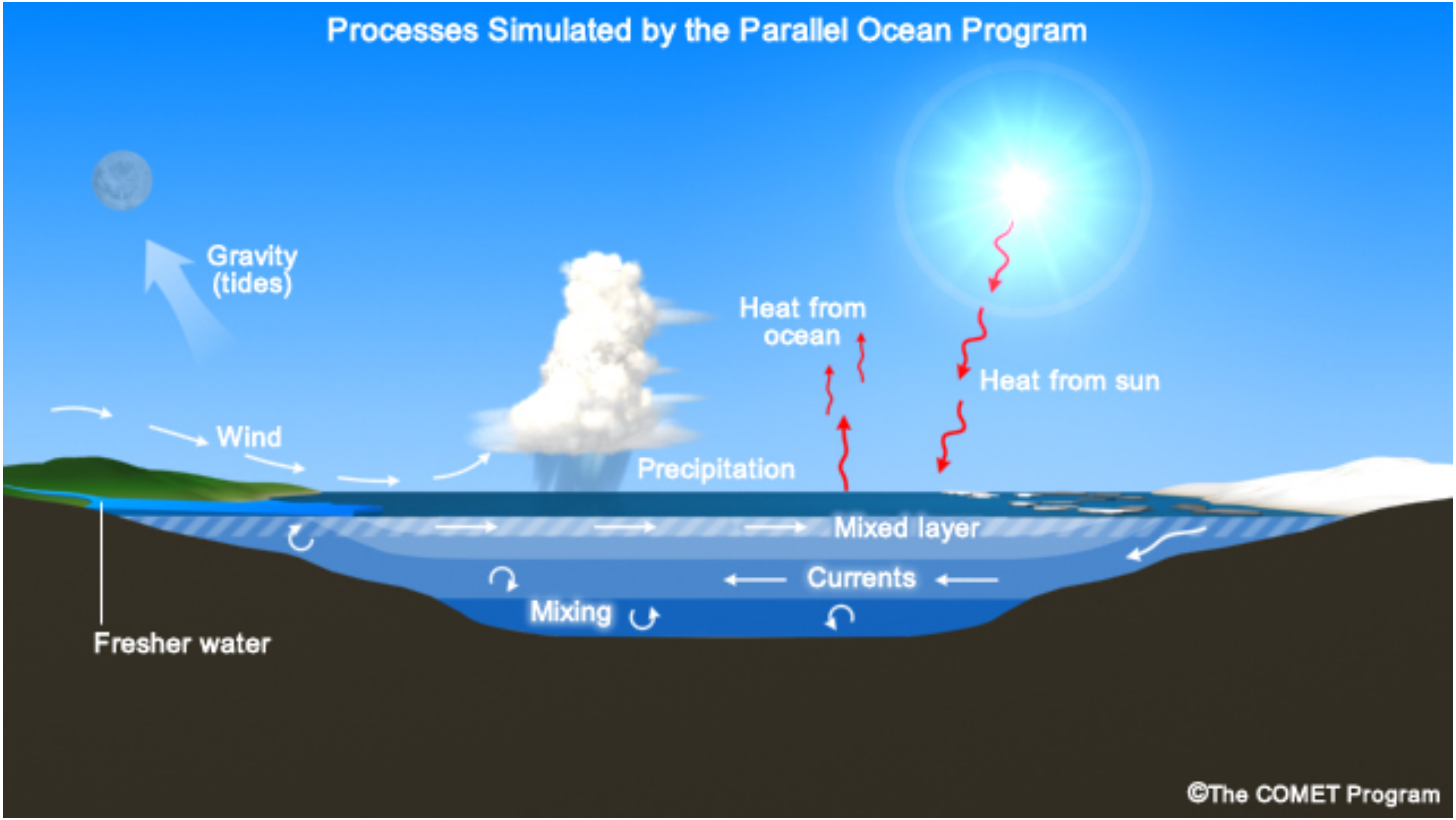
Unresolved atmospheric **dynamics** are **parameterised**, e.g. gravity wave drag.

Most **physical processes** are **parameterised**:

- Radiative transfer
- Cloud microphysics
- Convection
- Planetary boundary layer



Climate model components: Ocean model



Proper climate simulations need to take into account the **ocean**:

- largest **heat sink**
- major contributor to **natural climate variability**

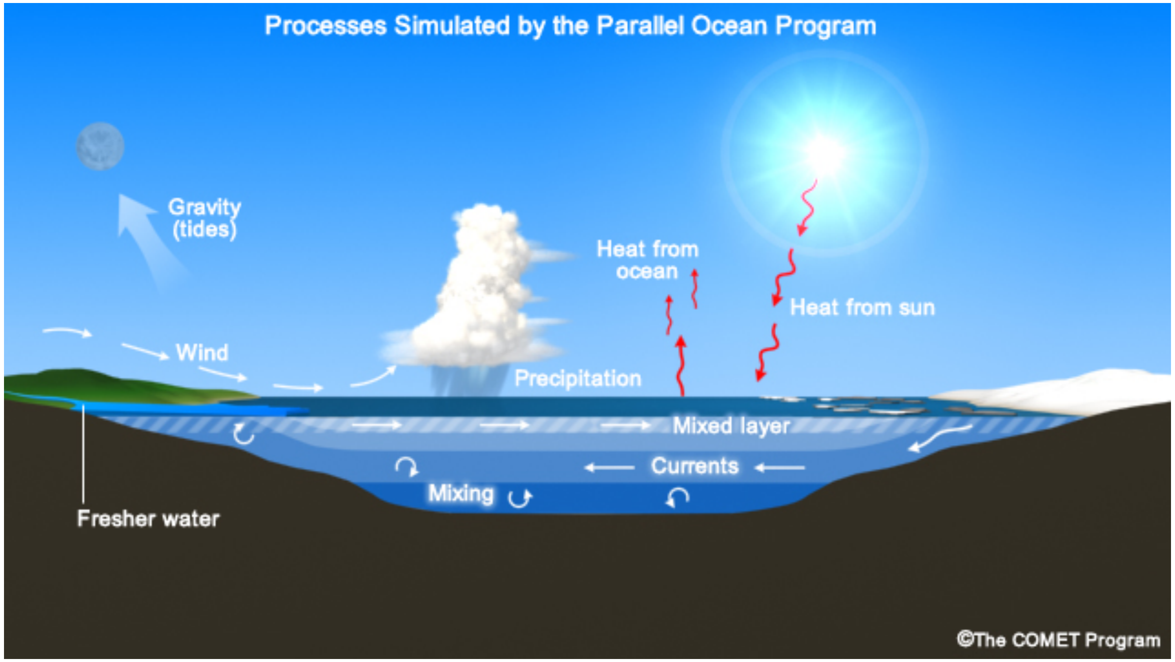
Climate model components: Ocean model

Ocean - Atmosphere differences w.r.t. climate modelling:

- Ocean processes operate on **much larger time scales** compared to atmospheric processes: centuries/decades versus years/days.
- Ocean **observations** are **very sparse** and satellites provide information only for the ocean surface.

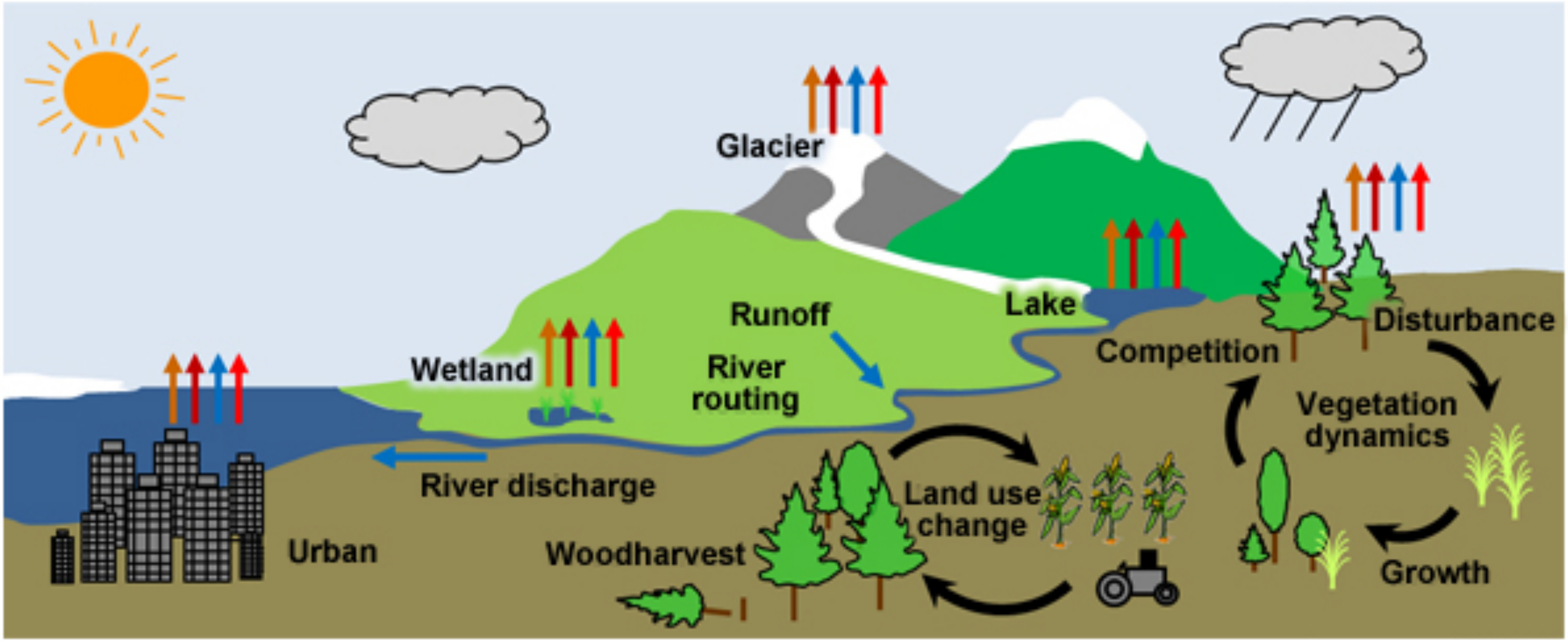
Ocean - Atmosphere models are **similar** w.r.t. the **equations of motion**, but:

- **Forcing** takes place only at the ocean **surface**.
- **Salinity** needs to be considered, since it determines density.
- Most surface **currents** resolved are **wind-driven**.



Climate model components: Land model

Processes Simulated by the Community Land Model 4.0



Lawrence et al. 2011

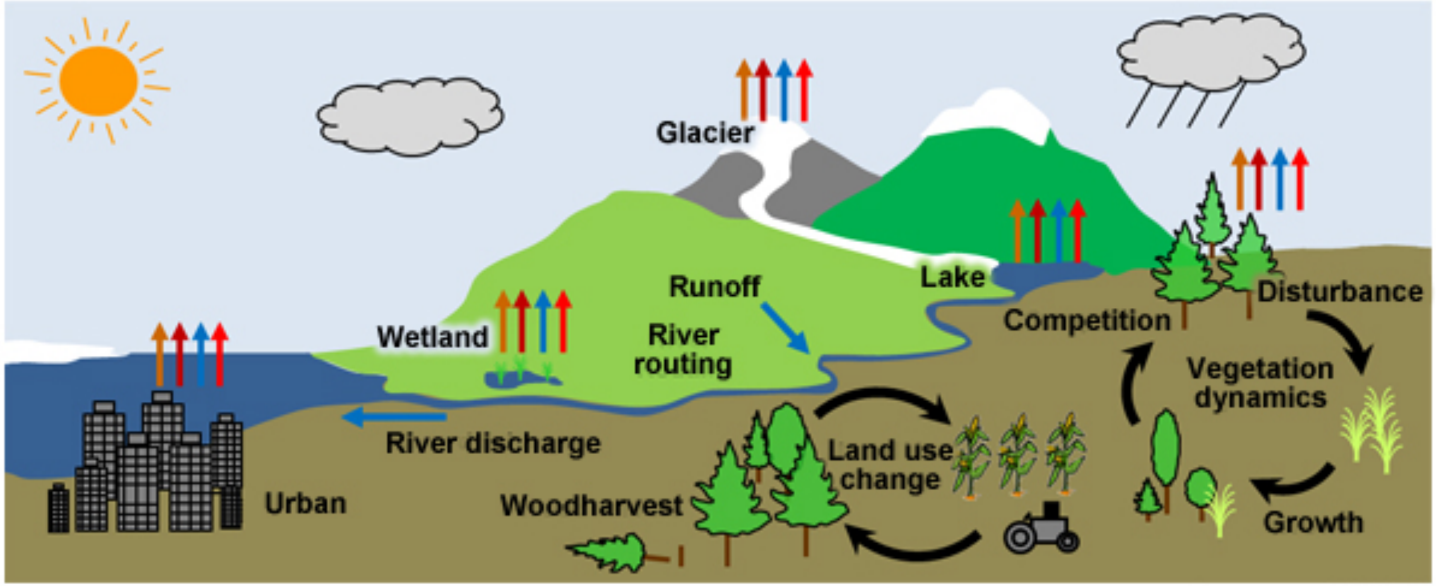
Land processes play a key role in the climate system, determining the exchange of **energy**, **moisture** and **carbon** with the **atmosphere** and the **ocean**.

Climate model components: Land model [2]

Early land models were quite simple, but have increased in complexity over the past 20 years.

Modern land models consider:

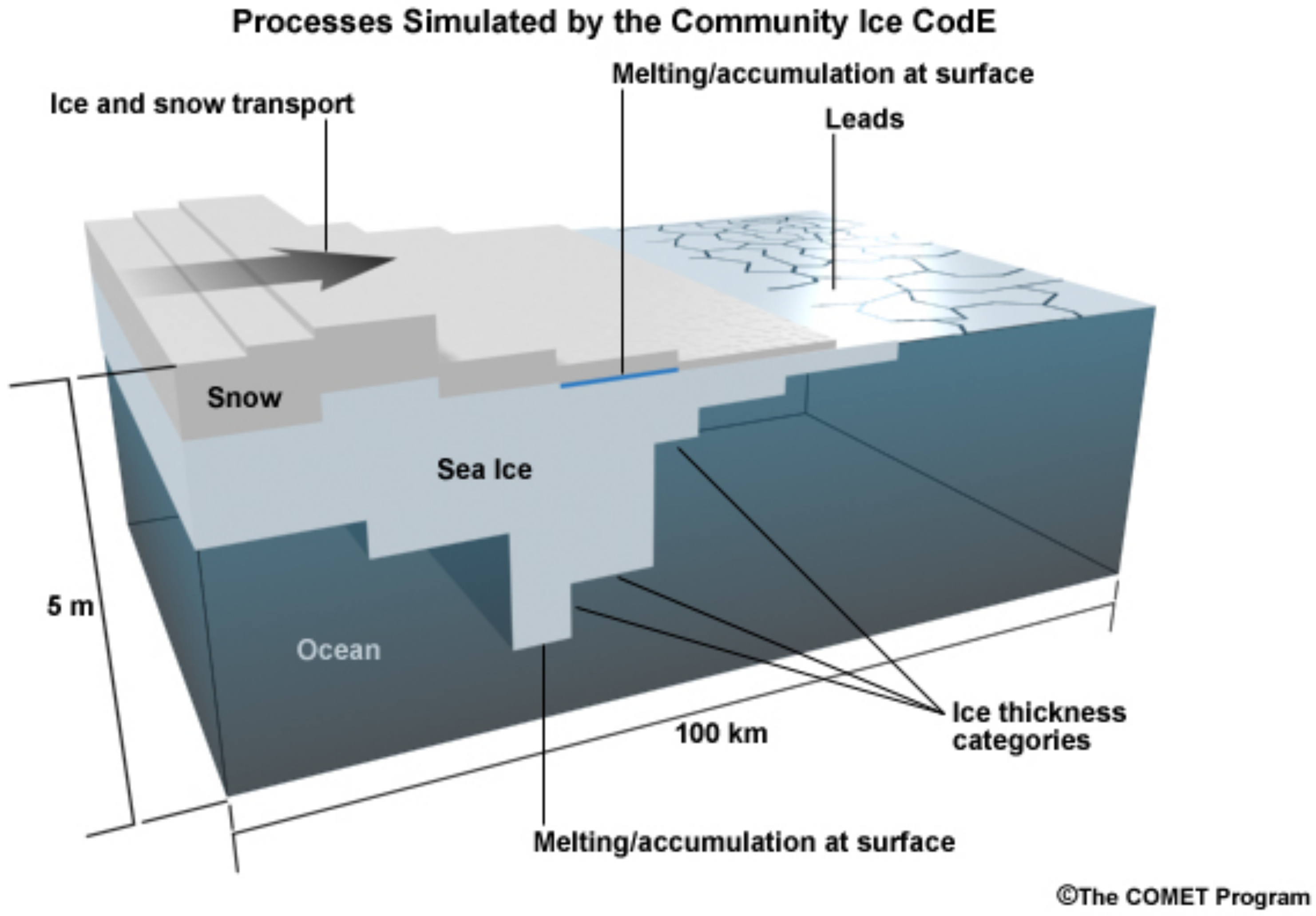
- **Energy** and **water** exchange between different **vegetation** types
- **Vegetation effects** on wind flow
- **Interactive ecosystems** that evolve with changing climate conditions
- A complete **water cycle**
- **Water**, **carbon** and **nitrogen** exchanges between **soil**, **vegetation** and the **atmosphere**
- **Freshwater runoff** in the ocean



Processes Simulated by the Community Land Model 4.0

Lawrence et al. 2011

Climate model components: Ice model



Ice is of paramount importance to the climate system, due to its high albedo.

Climate model components: Ice model

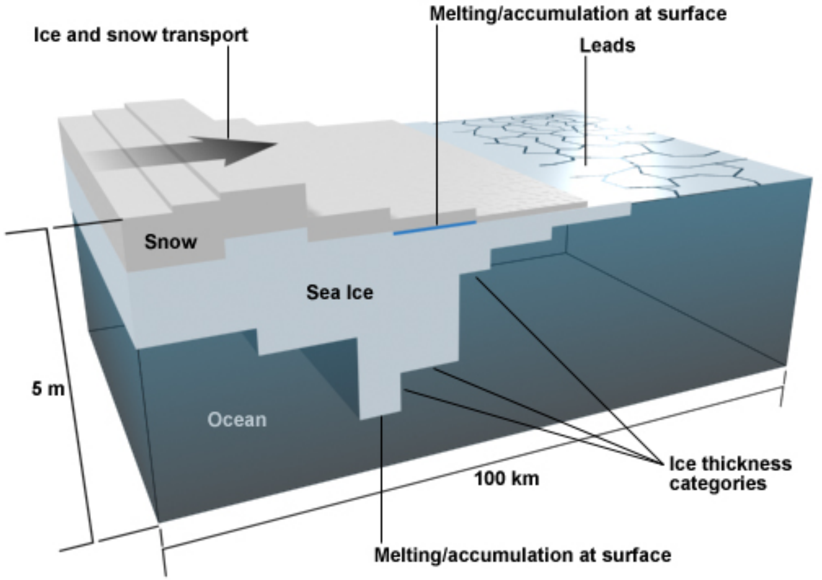
Sea-ice forms from the freezing of seawater:

- **Albedo** effect
- **Barrier** between liquid ocean and the atmosphere
- **Moisture** flux effects
- **Latent** and **sensible** heat flux effects
- Cold, **saline water** formation

Sea-ice models simulate:

- **Heat fluxes** from freezing and melting
- **Motion**
- Formation of **ridges**, **leads** and **melt ponds**
- **Aerosol** deposition

Processes Simulated by the Community Ice CodE



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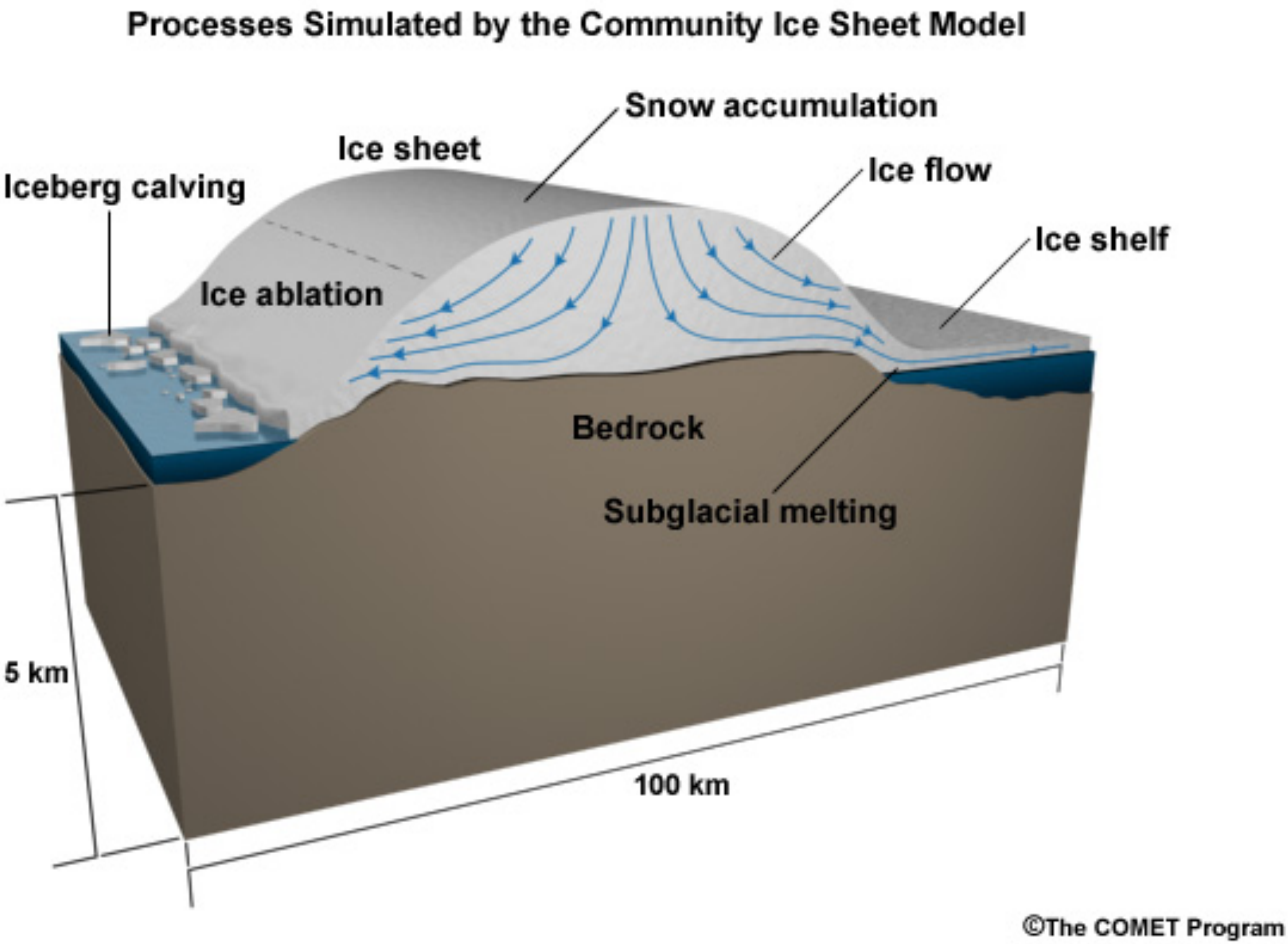
Climate model components: Ice model



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Dynamical ice sheet models are employed for simulating **land ice**.

Model tuning

A climate simulation is **meaningful** when there is **no intrinsic drift** in global climate.

Under **constant boundary conditions**, the simulated global climate:
- must **not warm nor cool**
- reach a **steady state**, resulting from the balancing of the energy coming in and out of the climate system

To achieve the **steady state** under **constant** boundary conditions, climate models need to be properly **tuned**.

Model tuning example

By adjusting the relative humidity thresholds for cloud formation, we can determine the amount of incoming solar radiation that is reflected back to space. Reducing cloud cover, we warm the system; increasing cloud cover, we cool the system.

In either of the cases, the simulated climate will reach a new balance, which will however be warmer or cooler. Tuning is about removing this warming/cooling effect, by means of adjusting cloud properties to reproduce a realistic energy balance.

Model evaluation

Once a climate model is tuned, its performance needs to be **evaluated**:

- **Compare** model **results** against concurrent **observations**.
- Quantify **model bias**.

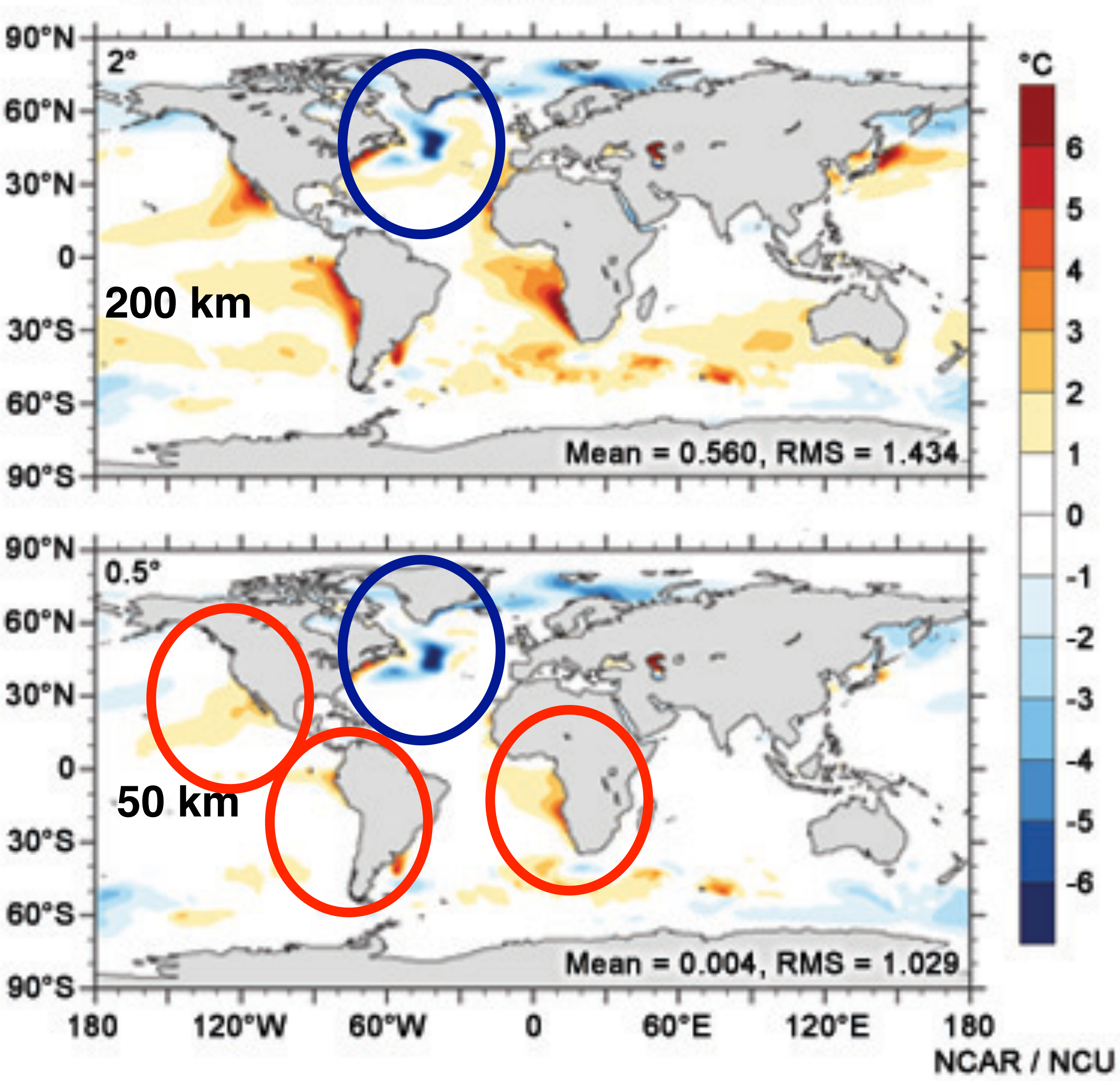
Most often, model evaluation is based on the so-called **hindcast simulations**:

- The model is driven by **re-analysis data**, simulating climate for a period of at least **10-15 years**.
- Re-analysis data are considered to be what is called “the **best estimate** of the state of the atmosphere”.
- Hindcast simulations are, hence, a “**perfect boundary conditions**” experiment.
- Comparing the outcome of hindcast simulations against observations, allows for quantifying **model biases**.

Model biases are of **paramount importance** and must be taken into account, especially when future climate projections are considered.

Model biases: SST

Difference between the SST in observations and 2° run (top) and 0.5° run (bottom) of CCSM4 for 1990-1999



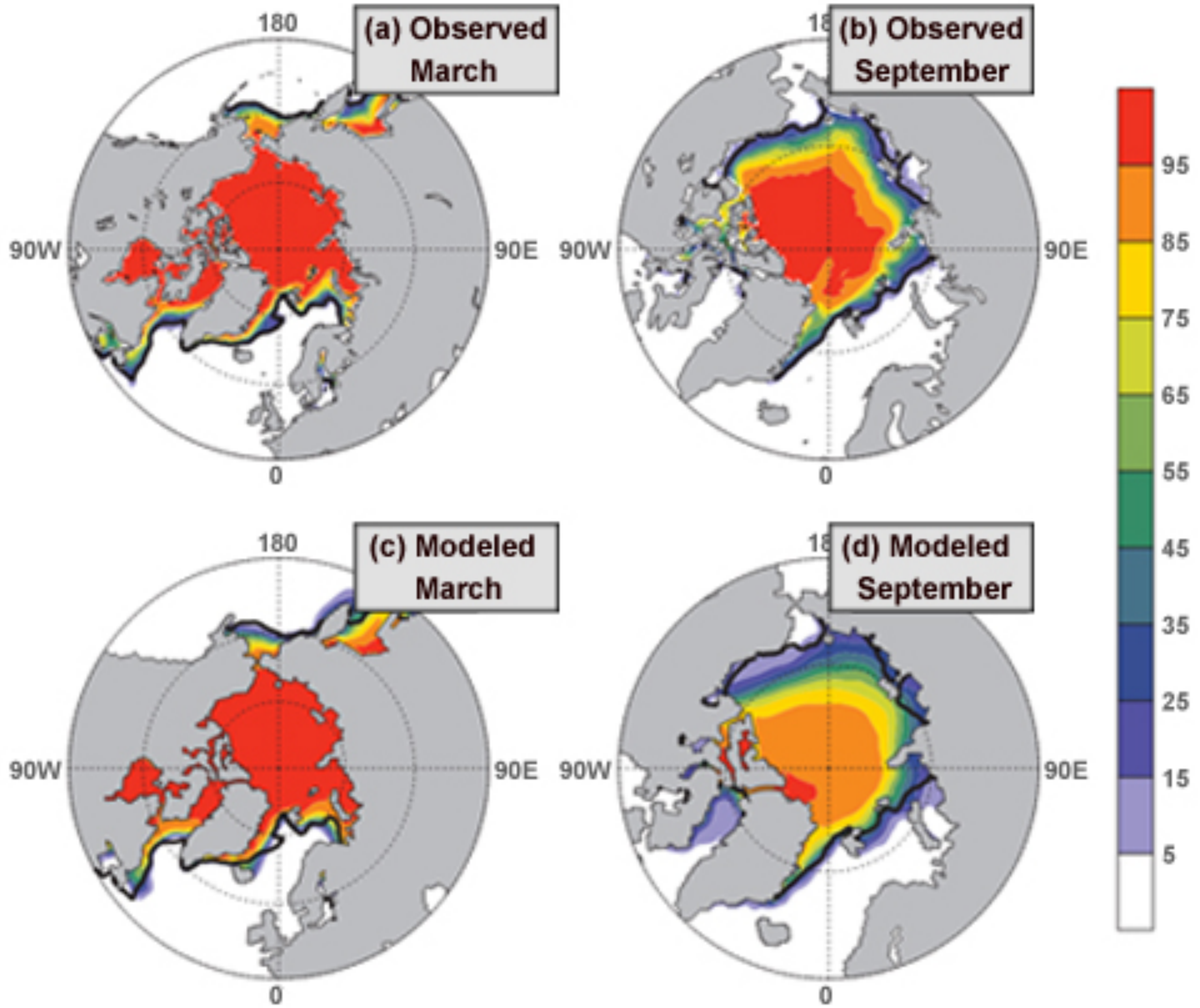
NCAR / NCU

Warm biases reduced when the resolution increased:

- Increased temperature gradients
- Increased surface wind
- Enhanced cold water upwelling

Model biases: Sea-ice

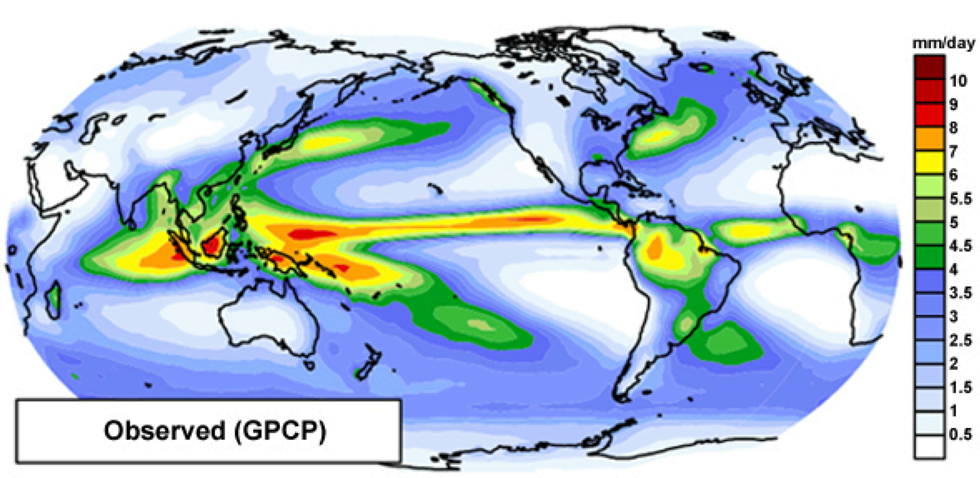
Sea Ice Concentration (%) for 1981-2005.
Top (a-b): Observed Climatology from SSM/I/SSMR Satellites.
Bottom (c-d): Ensemble Mean from CCSM4 Model.
Black Line: Ice Edge from SSM/I/SSMR Data.



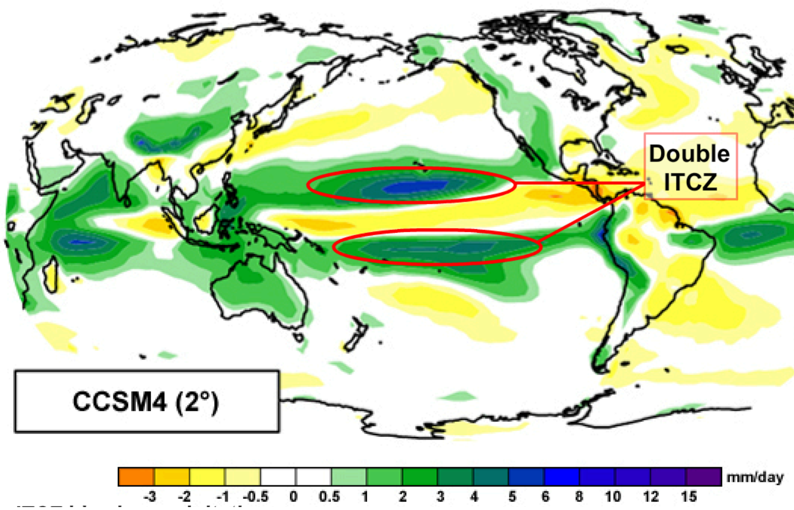
Jahn et al. 2011

Model biases: Precipitation

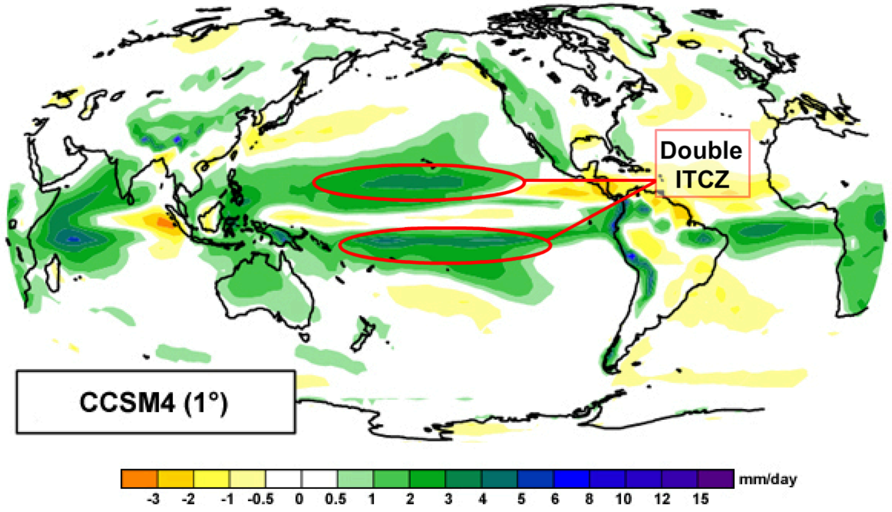
Average Annual Observed Precipitation (GPCP, 1979-2003)



Average Annual Precipitation Bias



Average Annual Precipitation Bias



Double ITCZ bias:

- **Excessive precipitation** in the tropics.
- **Less precipitation** in equatorial Pacific.

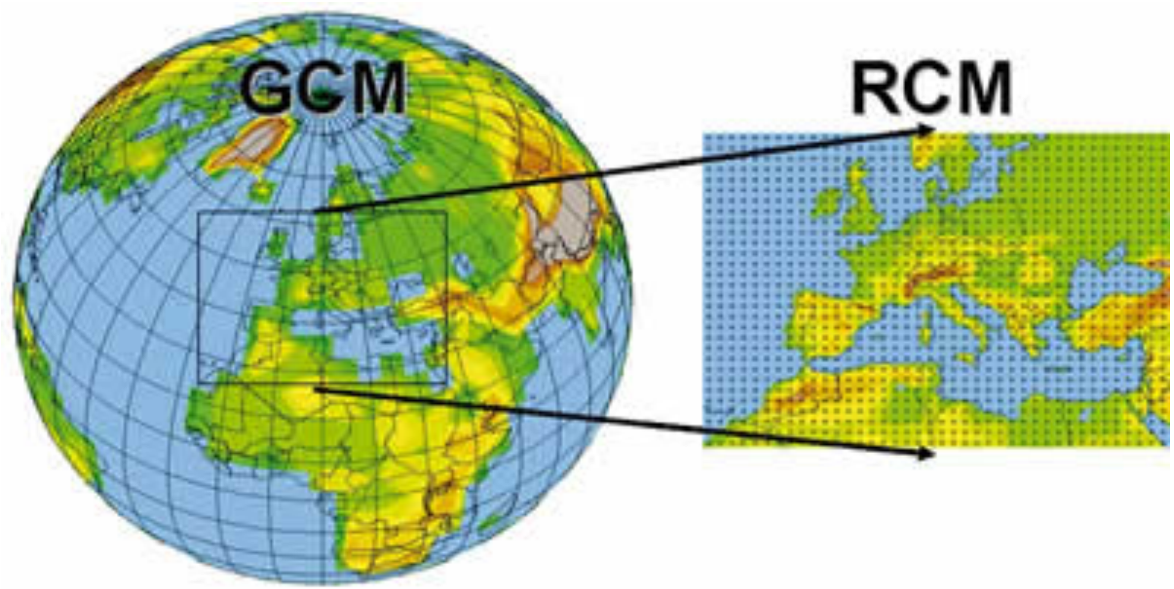
Regional climate models

Global climate models (**GCMs**) simulate **global climate**, taking into account **as many as possible** components of the climate system.

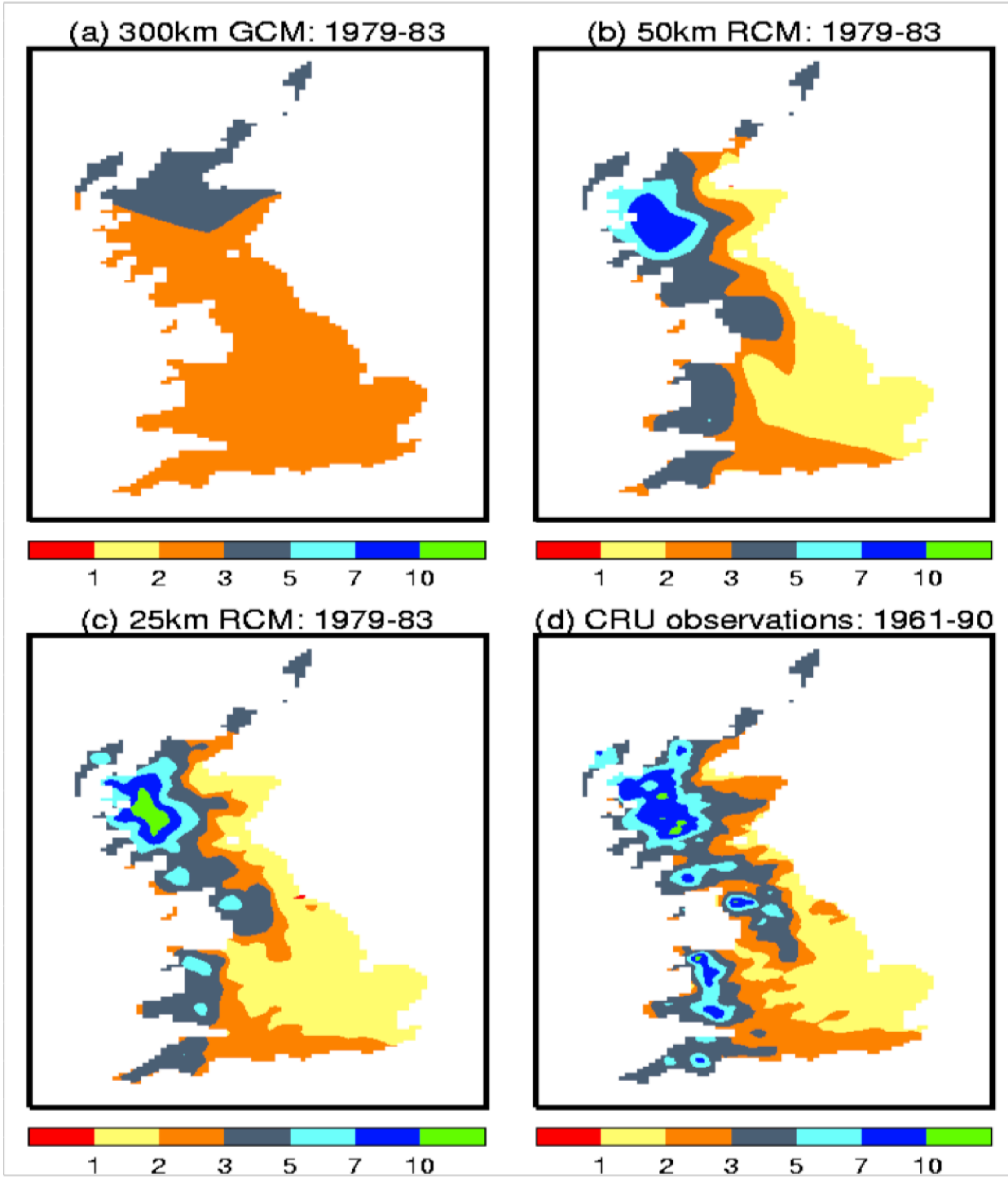
- Coarse resolution (**30 - 50 km**).
- **Cannot** be used for assessing climate at the **regional/local scale**.

Solutions:

- Run the GCM at **higher** horizontal and vertical **resolution**.
- **Statistical** downscaling.
- Dynamical downscaling (**regional climate modelling**).



Regional climate models: The added-value



- Computationally **cheaper** to run at the same resolution of a GCM.
- **High-resolution** RCMs are able to reproduce **smaller-scale atmospheric processes** (e.g. turbulence, mesoscale cyclones).
- Topography, vegetation cover and other **terrestrial fields** are **better represented** at high-resolution.
- Better evaluation against **regional observations**.
- More **complex** parameterisations.
- **Regional** tuning.

Regional climate models: Applications

Model development and validation

- “Perfect boundary conditions” experiments.
- Over 20 RCMs available worldwide.
- Wide range of regional domains and resolutions (10 - 100 km).

Studies focusing on processes w.r.t. climate

- Land-atmosphere interactions, cyclogenesis.
- Tropical storms, hurricanes.
- Regional hydrologic and energy budgets.

Climate change

- Regional signals, variability and extremes.

Regional climate models: How they work?

Regional climate simulations are conducted by **driving** a high-resolution RCM with:

- **Initial** conditions.
- Time-dependent **lateral** meteorological **boundary conditions**.
- **Surface boundary** conditions.

Driving data can be derived by either a **GCM** or **analysis/re-analysis** data, and can also include **greenhouse gases** and **aerosol** forcing.

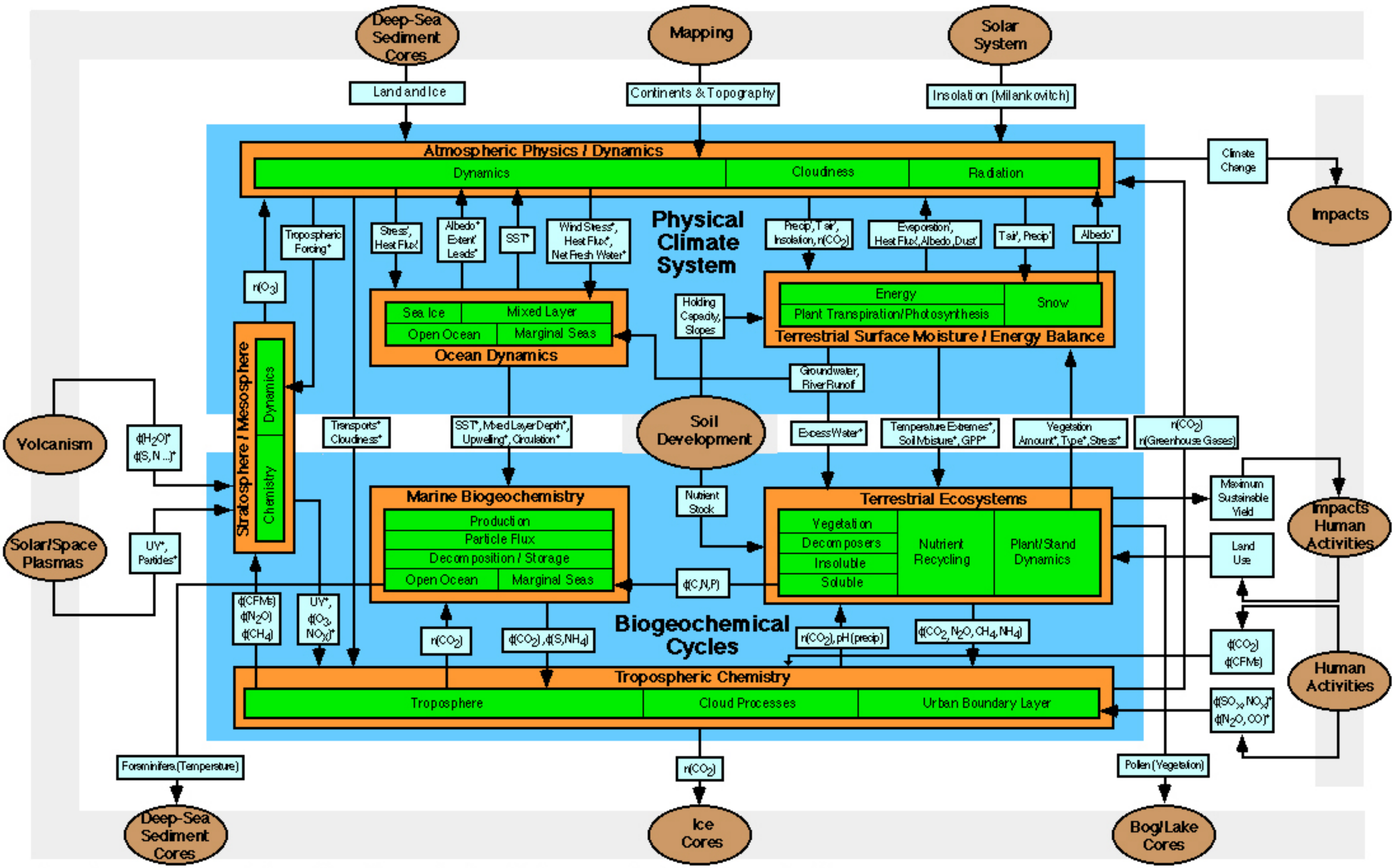
RCM simulations operate in **1-way nesting** mode: **no feedback** back to the driving model.

The **ultimate goal** of RCM is to:

- Account for **sub-GCM grid-scale forcing** in a physically-based way.
- Enhance the simulation of atmospheric simulations and climatic variables at **fine resolutions**.

Future directions

Conceptual Model of Earth System Processes Operating on Timescales of Decades to Centuries



' = on timescale of hours to days   * = on timescale of months to seasons   ϕ = flux   n = concentration

NASA

Final summary

Climate models aim at simulating changes in climate statistics due to external forcing; In climate modelling, boundary conditions matter.

Boundary conditions are prescribed and influence the warming and cooling of the simulated climate. They include solar radiation, atmospheric composition and land use.

Climate models simulate both resolved and unresolved processes; the latter are represented with parameterisations.

Climate model components: atmosphere, ocean, land, ice sheets and sea-ice.

Tuning and evaluation of climate models are important procedures.

Regional climate models allow for enhancing the simulation of climate at finer resolutions.

Thank you very much for your attention

Questions;

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