



At stake →

Science of Climate Change

- Environmental Engineer by training
- PhD in Atmospheric Chemistry
- Science-Policy work
- Director of the Extreme Environments Research Laboratory focused on atmospheric processes in polar regions.



Main teaching assistants



Berkay Dönmez



Mihnea Surdu



Yolanda Temel



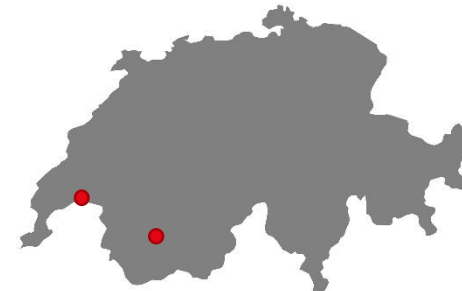
Michael Lonardi

EERL

eerl.epfl.ch



Associate Campus Sion
Alpine and Polar Environmental Research Center (ALPOLE)



- Type 1
 - We will use Point Solutions in class for polls and short exercises.
 - All answers are **anonymous**.
 - Please go to: responseware.eu
 - Enter as guest, do not provide any name or contact information.
 - Be aware, the data will go outside of Switzerland, but will be erased when the session is closed.
 - Let's try. Session ID is: **env410**

- Type 2
 - Discussion of media articles on climate change at the beginning of class.
Short reading tasks!

What is your background?

Go to: responseware.eu
Login: enter as guest
Session-ID: env410



- A. Engineering
- B. Economy
- C. Other science
- D. Other social science or humanities

For all assignments:
Work in teams of 4 with mixed
backgrounds.
Teach colleagues, ask colleagues,
challenge colleagues!

	No.	Date	Topics	Documents / Tentative
Basics	1.	11.09.2025	Introduction to the climate system	
	2.	18.09.2025	Climate System, Radiation	
	3.	25.09.2025	Earth's Energy balance, Greenhouse effect, Radiative transfer, aerosols & clouds	launch of first assignment
	4.	02.10.2025	Aerosols & clouds, Radiative Forcing, Feedback mechanisms	Launch of poster project
	5.	09.10.2025	Feedback mechanisms, Climate Sensitivity	
	6.	16.10.2025	Paleoclimate	submission of Poster proposal (graded)
Present and future Climate change	7.	30.10.2025	Climate variability	
	8.	06.11.2025	Paris Agreement, IPCC – report, Climate scenarios (RCPs, SSPs),	
	9.	13.11.2025	Tipping elements, 1.5 vs 2.0°C vs warmer, Emissions, Carbon budget, Emissions Gap	submission of Poster draft (graded)
	10.	20.11.2025	Carbon budget, Emissions Gap, Metrics	
	11.	27.11.2025	Metrics, Extreme Events	submission of assignment (graded)
Actions	12.	04.12.2025	Polar climate change	
	13.	11.12.2025	Mitigation measures	Poster Conference (graded)
	14.	18.12.2025	Climate engineering, questions and answers session	fill in Questionnaire in exercises (not graded)

- Lectures give you the general introduction to the topic
- Exercises will discuss content more in detail and partly quantitatively
- Project tasks help you develop your own research interests and presentation skills. You can work on projects and assignments together then and ask help from the teaching assistants.
- Grading (see also moodle):
 - 1 graded assignment: 25 %
 - Conference poster project: 25 %
 - Final written exam: 50 %
- The conference: 11 December in the afternoon
 - **Please make room in your schedules for the conference 3 – 5 pm (plus aperitif) → If you cannot make it, I will need a formal excuse by email until 28 November to arrange an alternative presentation date.**
- Online discussion forum Ed Discussions for yourselves (students).

Assignment and poster groups

- Groups of 4 student
- Same group for both assignment and poster
- Rules:
 - Minimum 3 different educational backgrounds (e.g., economy, life sciences, natural sciences)
- You organize yourselves
- Deadline: 25 September

- Enter your groups in this spreadsheet:
<https://docs.google.com/spreadsheets/d/12ciRsNRLwzOoqhVXWVJ32Xbm4dC3B1oPta-1aHIdE0I/edit?usp=sharing>
 - You'll also find the link on moodle

Impact of double deck work

- Lectures will take place in SG 0211 and on zoom
 - You can use room CM 1106 to log in via zoom
 - Being directly in class in SG 0211 is recommended
- Exercises and project work sessions will be done in CM 1106
 - No zoom streaming planned for now

ENV-410 learning outcomes

- Express the **basic physics and chemistry** of climate change
- Discuss the concepts of **climate variability** and **climate sensitivity**
- Reason why present day climate change is **different** from historical climate change
- Contrast climate change **scenarios**
- Apply simple **climate metrics**
- Interpret basic **climate data** and model output
- Critique mitigation, adaptation and climate intervention **options**

Lectures will provide the concepts.

Exercises will help you deepen your knowledge and apply it.

- Assess one's own level of skill acquisition, and plan their on-going learning goals.
 - → interactive sequences in lectures and exercises
- Plan and carry out activities in a way which makes optimal use of available time and other resources.
 - → see the schedule of deadlines and plan accordingly
- Communicate effectively with professionals from other disciplines.
 - → groups of four from various disciplines
 - → poster conference
- Give feedback (critique) in an appropriate fashion.
 - → groups of four from various disciplines
 - → poster conference
- Summarize an article or a technical report.
 - → assignments and poster conference
- Access and evaluate appropriate sources of information.
 - → assignments and poster conference



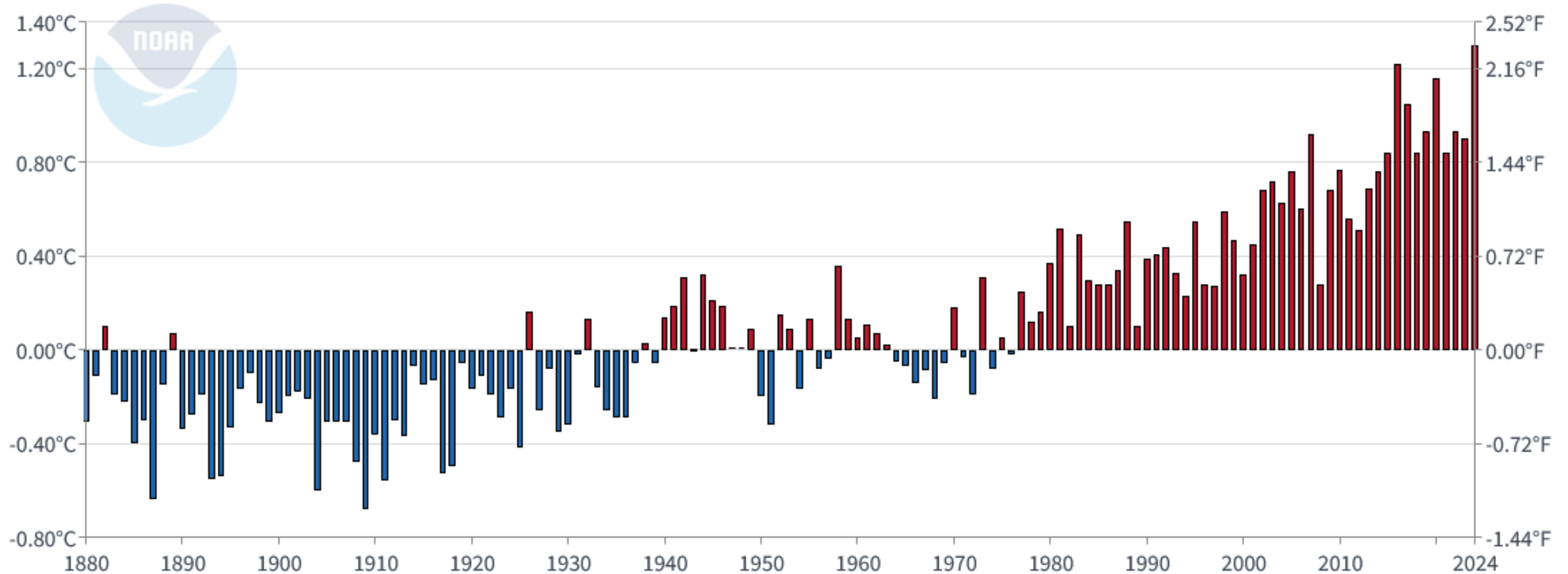
**More general
questions?**

Ready for the class?

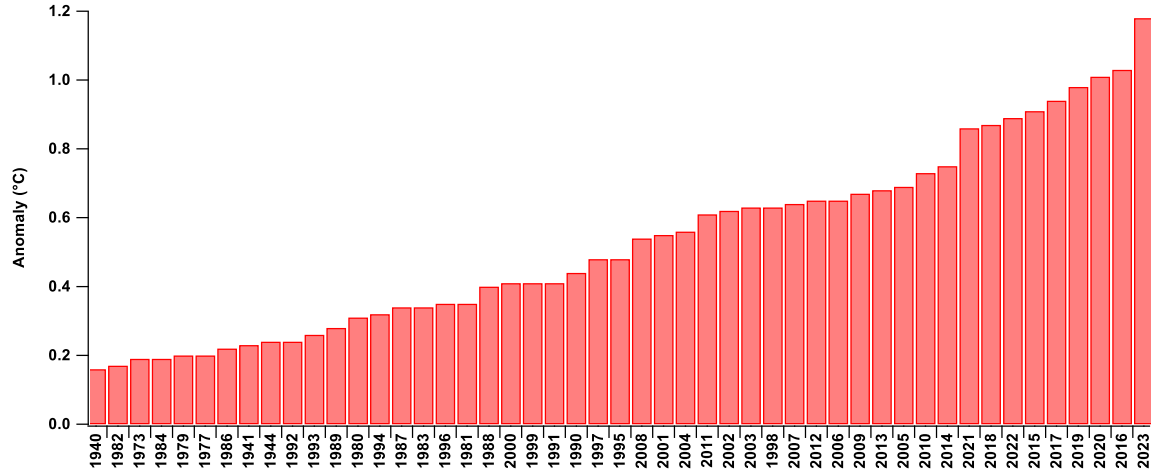
Global Land and Ocean

January Average Temperature Anomalies

Reference: 20th century average



How many hottest years were there in your lifetime?



- A. All were hottest years.
- B. All but ~2.
- C. All but ~5.
- D. More than 5.

Why Climate Emergency?



© picture-alliance/Pacific Press/E. McGregor

October / November 2024: Floods in Spain

Floods killed more than 200 people, displaced more than 400 people, and saw hundreds of thousands lose access to water and electricity. www.worldweatherattribution.org/

January 2025: Fires in California

The wildfires killed at least 30 people, forced more than 200,000 to evacuate, **destroyed more than 18,000 homes and structures, and burned over 23,000 ha of land in total.** Damage around \$250 billion.

www.worldweatherattribution.org/



March 2025: South Korean wild fires

> 70 people injured or dead
> 37'000 people displaced
www.worldweatherattribution.org/



April 2025: Heat Wave Central Asia

10°C hotter than normal. Many work hours lost in the agricultural sector (cf 230 million hours in Uzbekistan in 2023). Crop damage, Glacier loss.
www.worldweatherattribution.org/

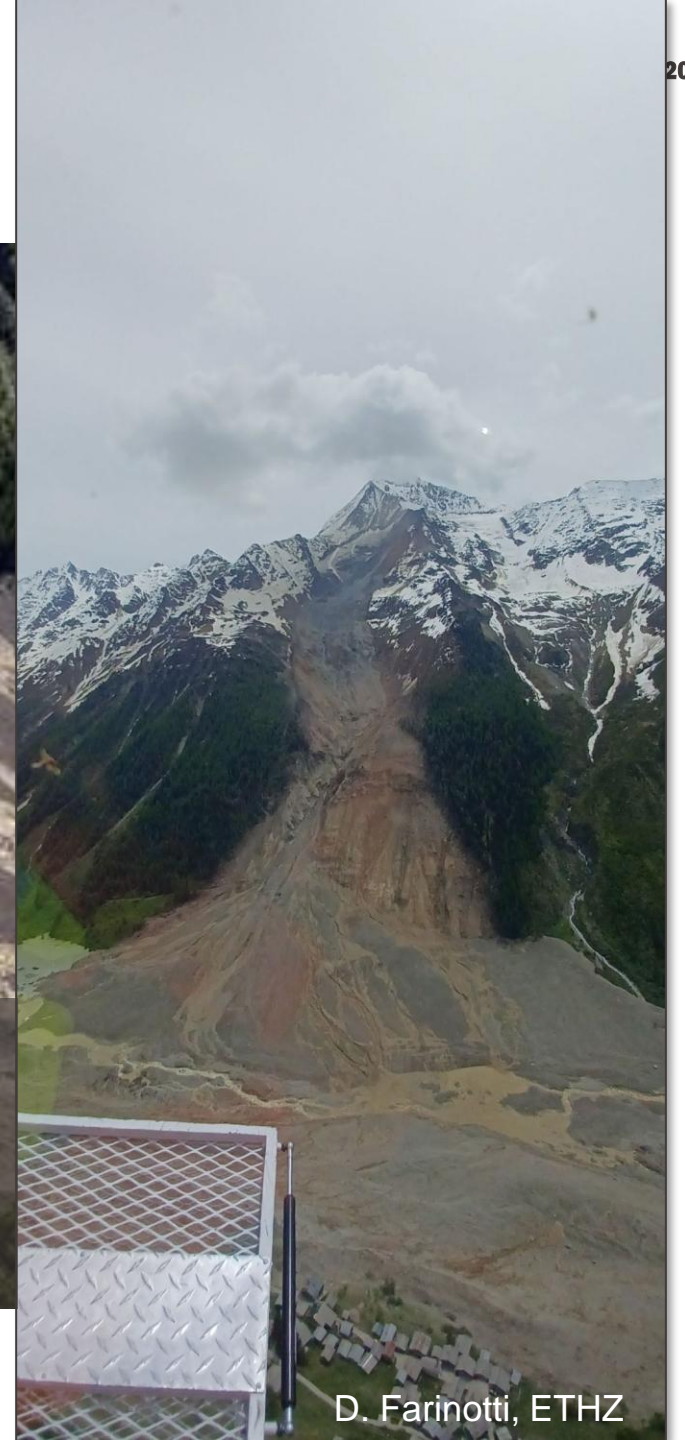




Source: SRF

Climate change had a contribution,
clear attribution remains to be
investigated:

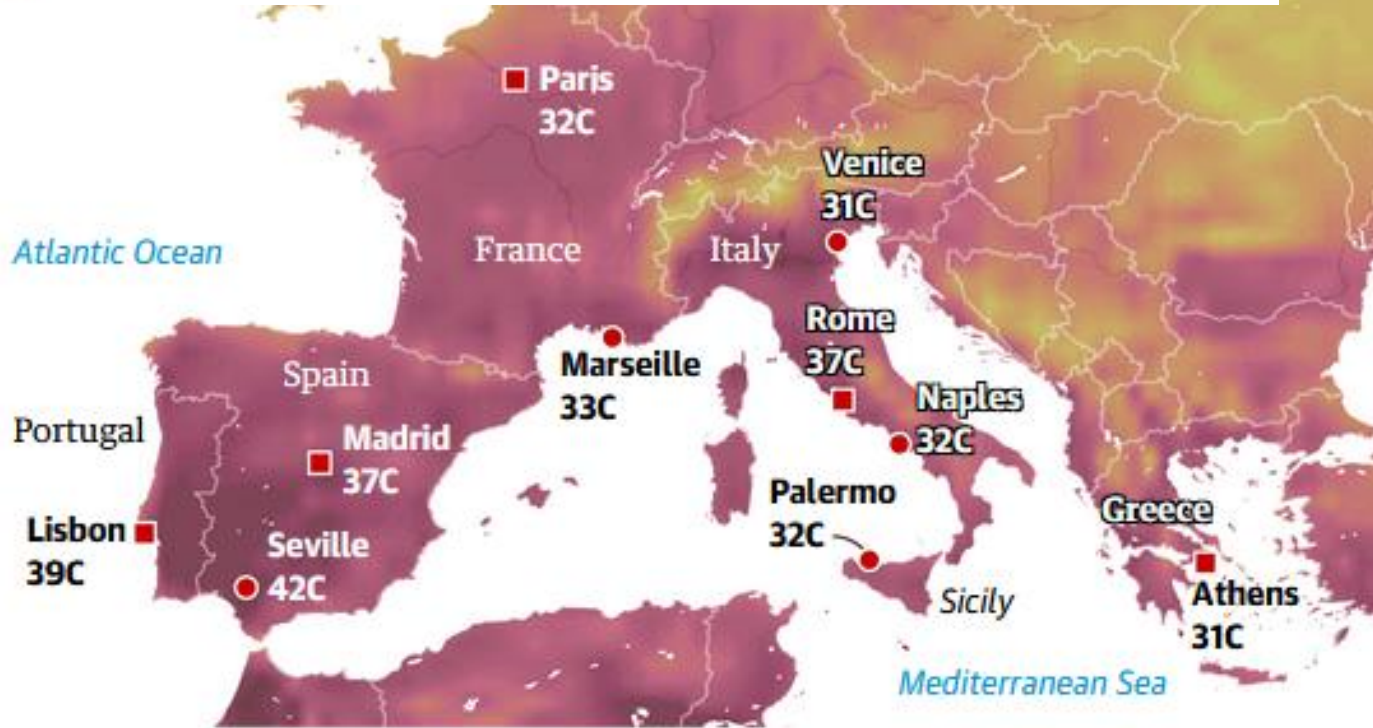
- Glacier melt
- Permafrost melt





June/July 2025 – heatwave in Europe

- Authorities issue warnings for extreme heat, wildfire, water resources and health



August 2025 - Glacial lake outburst in Alaska



- Melt and rain water fill the lake which then bursts
- Process has become more extreme with climate change
- In 2025 300 homes were flooded despite precautions

August 2025 – heatwave and wild fires in Spain



- More than 1000 deaths associated with event
- Hottest 10 consecutive days in Spain since 1950

All these events have become more likely because of climate change.

**Impacts are current reality.
Not a problem of the future. They come
thicker and faster than anticipated.**

The countries that could go extinct change may surprise you



The cost of the climate crisis? 20 million homeless every year



Over the past decade, extreme weather has displaced 20 million people a year Image: REUTERS/Marco Bello

WEF, 6 December 2019

Climate crisis made dead floods 'up to nine times r

Study reinforces the hard evidence that carbon
main cause of worsening extreme weather



for the flooding of the River Ahr in Rech in the Ahrweiler district of
mann Vogel/EPA

August 2021

Short summary
2021 – Floods
2022 – Heat waves
2023 – Cyclones,
Heat waves/fires
2024 – Floods, heat
waves, cyclones,
fires

Press release

One billion children at 'extremely high risk' of the impacts of the climate crisis - UNICEF

Children in the Central African Republic, Chad, and Nigeria are among the most at risk of climate
change, according to UNICEF's first child-focused climate risk index.

19 August 2021

UNICEF, 19 August, 2021

Deforestation in Brazilian Amazon hits highest annual level in a decade

Rainforest lost 10,476 sq km between August 2020 and July 2021,
report says, despite increasing global concern

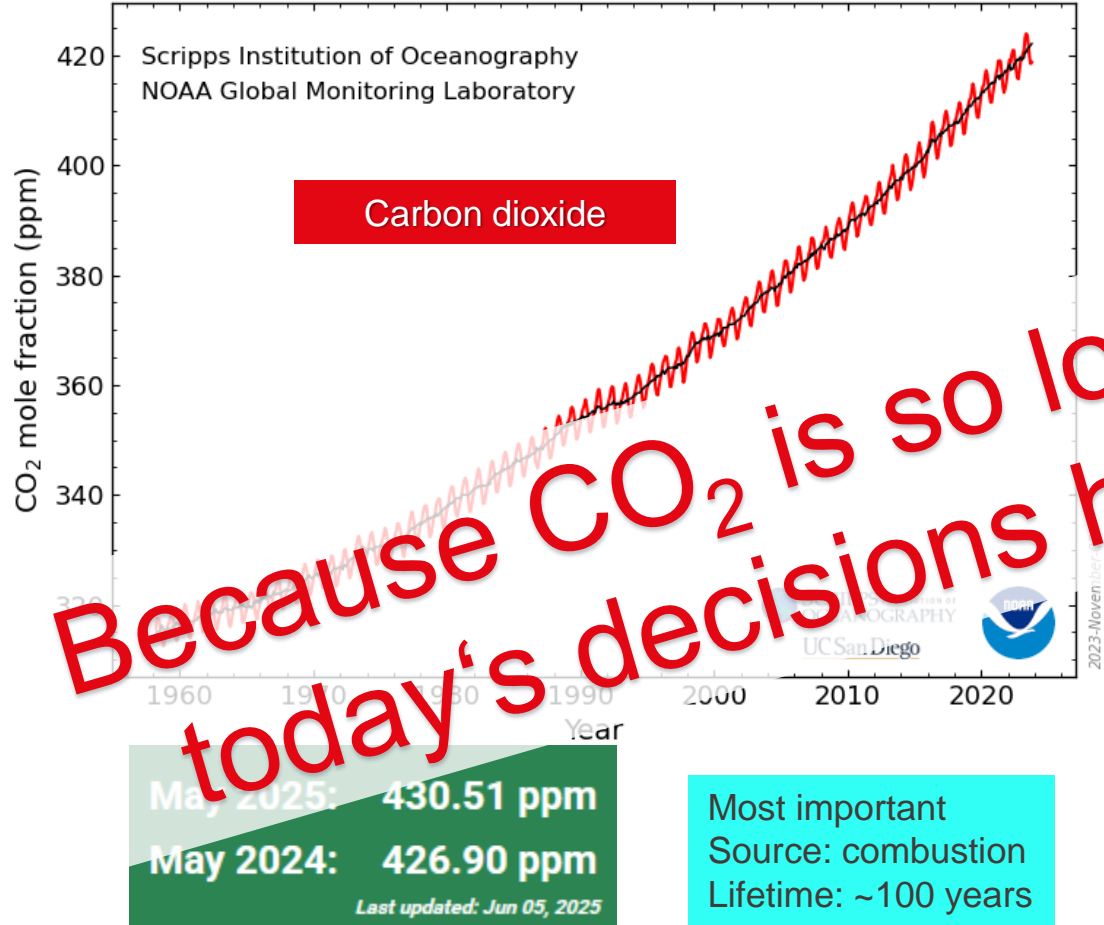


▲ 'Deforestation is still out of control,' Carlos Souza, a researcher at Amazon said. Photograph: Mayke Toscano/Mato
Grosso State Communication/AFP/Getty Images

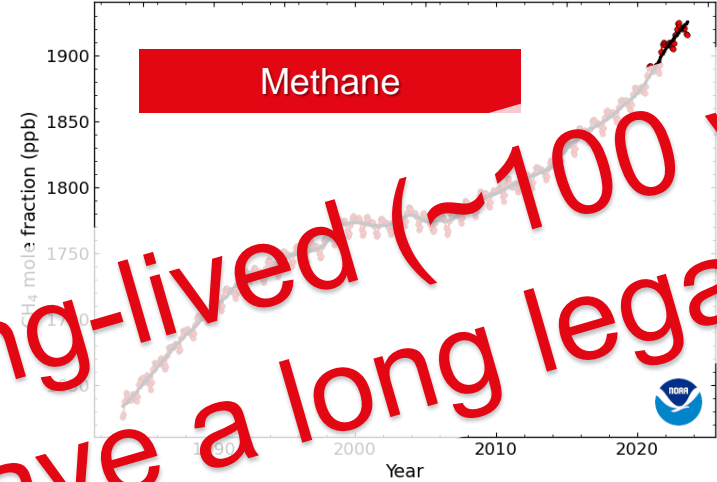
The Guardian, 20 August 2021

Trends of greenhouse gases in the atmosphere

Atmospheric CO₂ at Mauna Loa Observatory



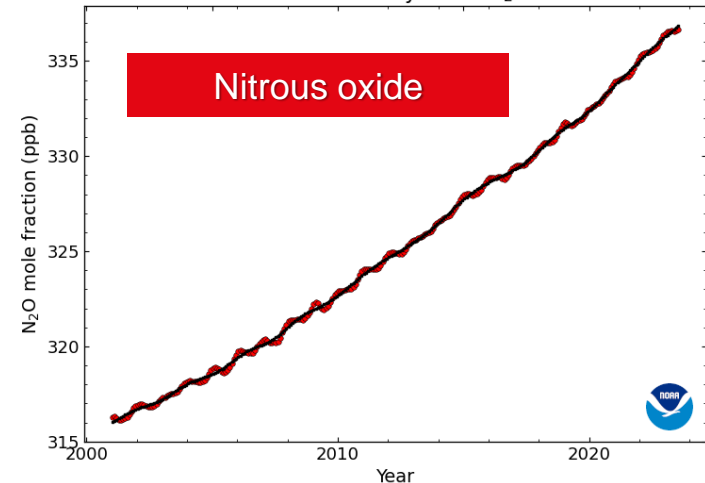
Global Monthly Mean CH₄



February 2025: **1933.97 ppb**
 May 2024: **1925.99 ppb**
Last updated: Jun 05, 2025

2nd most important
 Source: agriculture, energy, waste
 Lifetime: ~12 years

Global Monthly Mean N₂O



February 2025: **338.52 ppb**
 February 2024: **337.55 ppb**
Last updated: Jun 05, 2025

important
 Source: agriculture, waste
 Lifetime: >100 years

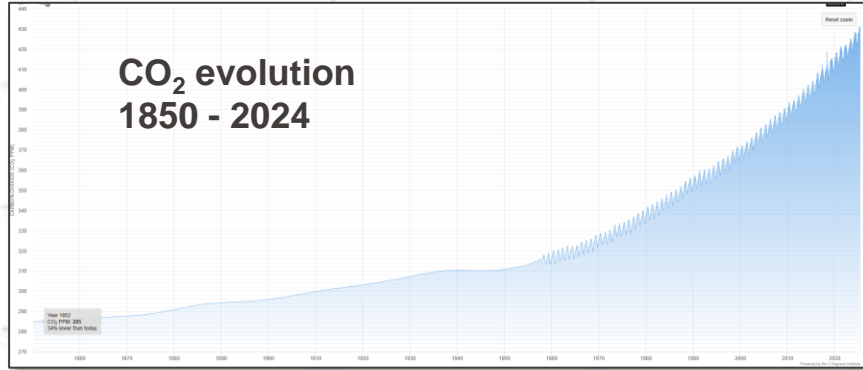
Global Average Temperature 1850 - 2024

Exact numbers of warming vary slightly between data products.

$1.62 \pm 0.06 \text{ }^\circ\text{C}$

Above average of 1850-1900

**Global
warming is
currently $1.3 \text{ }^\circ\text{C}$**



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

Global temperature anomalies relative to 1850-1900 average

Vertical lines indicate 95% confidence intervals

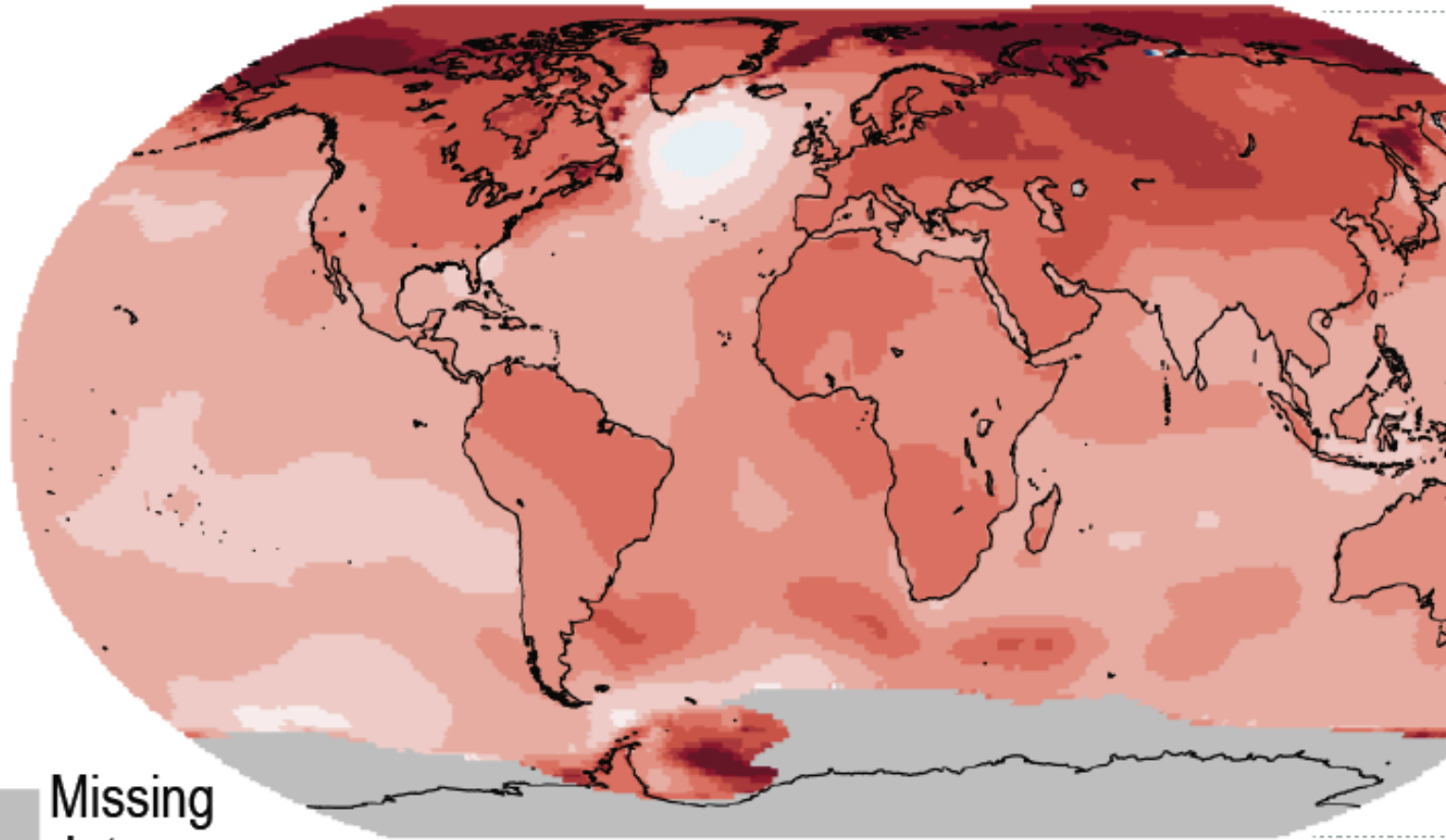
<https://berkeleyearth.org/global-temperature-report-for-2024/>

Global Temperature Anomaly ($^\circ\text{C}$)

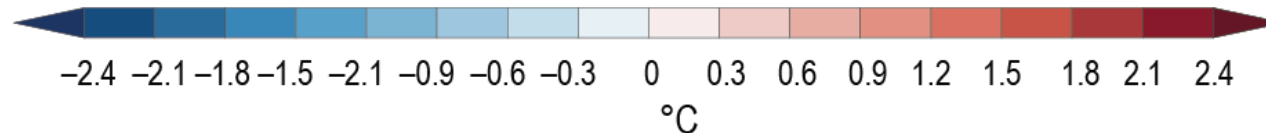
1860 1880 1900 1920 1940 1960 1980 2000 2020

1.6²⁷
1.4
1.2
1
0.8
0.6
0.4
0
-0.2
-0.4

Regional warming differences



Change in temperature at global warming level of 1 °C



- **Not all regions warm at the same speed.**
E.g., the Arctic warms up to 4 times faster than the global average.
- **Land warms roughly two times faster than the ocean.**
 - Average warming on land was $> 2^{\circ}\text{C}$ in 2023.
 - Average warming of the ocean was $> 1.0^{\circ}\text{C}$ in 2023.
- **Most of the warming has occurred since 1970.**

2024: hottest year on record

- Exceeded 1.5°C warming over the preindustrial era.
- 24% of the Earth's surface had a locally record warm annual average.

- Major population centers affected.
 - 3.3 billion people — 40% of Earth's population — experienced a locally record warm annual average in 2024.
 - Specifically: 2/3 of the population of China, and a majority of the populations of Brazil, Nigeria, Ethiopia, Mexico, 1/3 of the United States, and much of South and Central America, and Eastern Europe.

- New national record high annual averages for an estimated 104 countries.

*“The **Paris Agreement** central aim is to [...] **keep global temperature rise [...] well below 2°C above pre-industrial levels and to pursue efforts to limit the [...] increase [...] to 1.5 °C.**”*

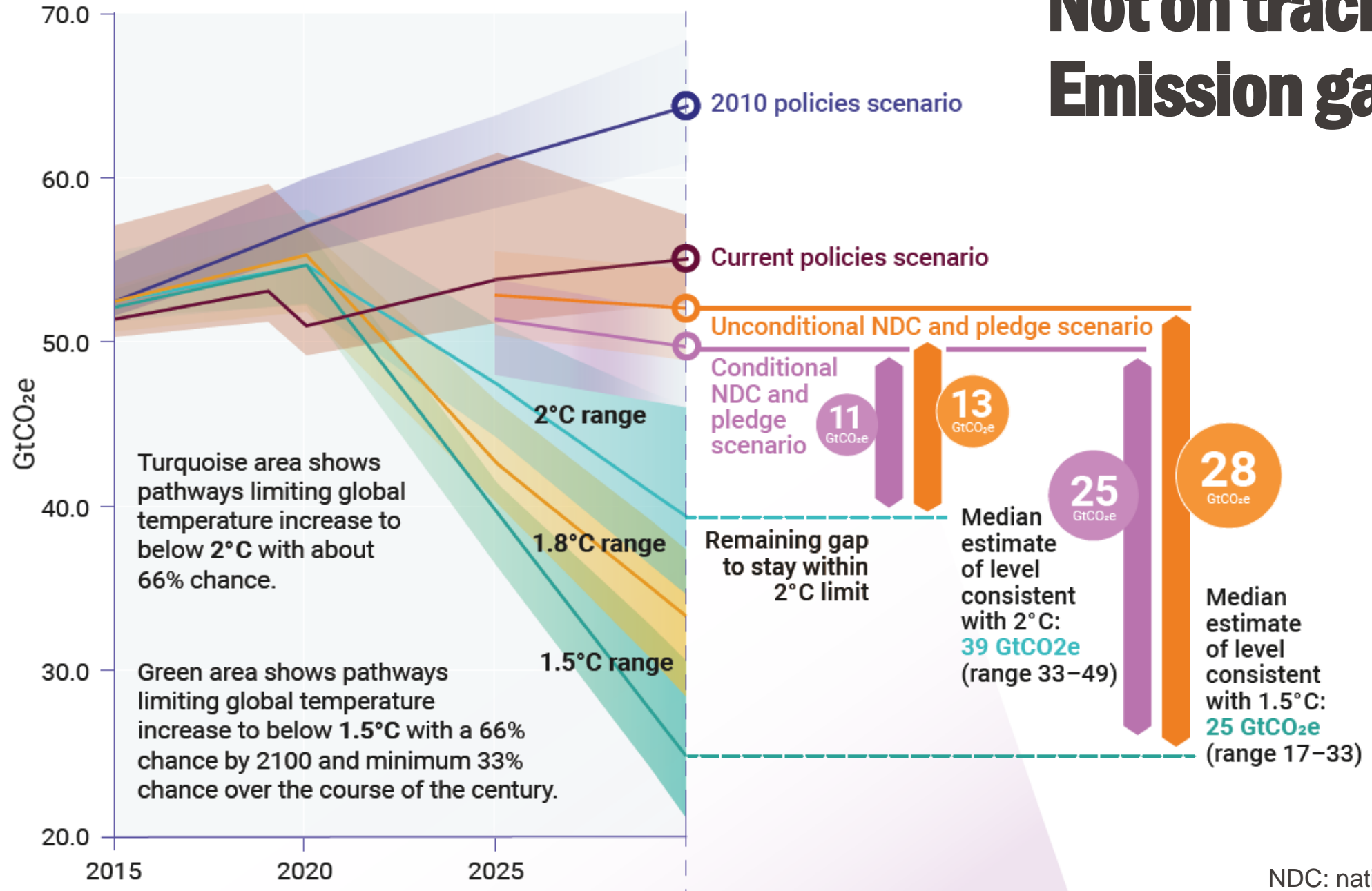
<https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>



«1.5°C vs warmer»

- Limitation of global warming to 1.5°C compared to 2°C allows to avoid substantial additional changes in **extremes** and their impacts:
 - Increase in **hot extremes** in most inhabited regions of the world
 - Heavier **precipitation** in several regions
 - Increased **drying** in some regions
- **Tipping points and irreversible impacts**
 - sea level rise,
 - extinction of animals, plants, coral
 - Loss of the cryosphere
 - ...

Not on track: Emission gap



NDC: nationally determined contribution

- Ignore
- Do a little bit and adapt
- Mitigate and adapt
- Climate interventions
- Other

Climate Emergency in a nutshell

1. We are extremely close to our global temperature target of 1.5/2.0°C for 2100.
2. Drastic emission reductions are needed now and net-zero needs to be achieved by 2050.
3. Humanity is faced with a technological, political and behavioral challenge never encountered before.



This is a very brief introduction. Do not forget to review the videos from the past years for more details.

The climate system

Definition of «climate» and «climate change»

- Climate is the **average weather** in a given area over a longer period of time. A description of a climate includes information on, e.g. the average temperature in different seasons, rainfall, and sunshine. Also a description of the **(chance of) extremes** is often included.
- The classical period used for describing a climate is 30 years, as defined by the World Meteorological Organization (WMO).
- Climate change is any **systematic change in the long-term statistics** of climate variables such as temperature, precipitation, pressure, or wind sustained over several decades or longer. Climate change can be due to natural external forcings (changes in solar emission or changes in the Earth's orbit, natural internal processes of the climate system) or it can be human induced.

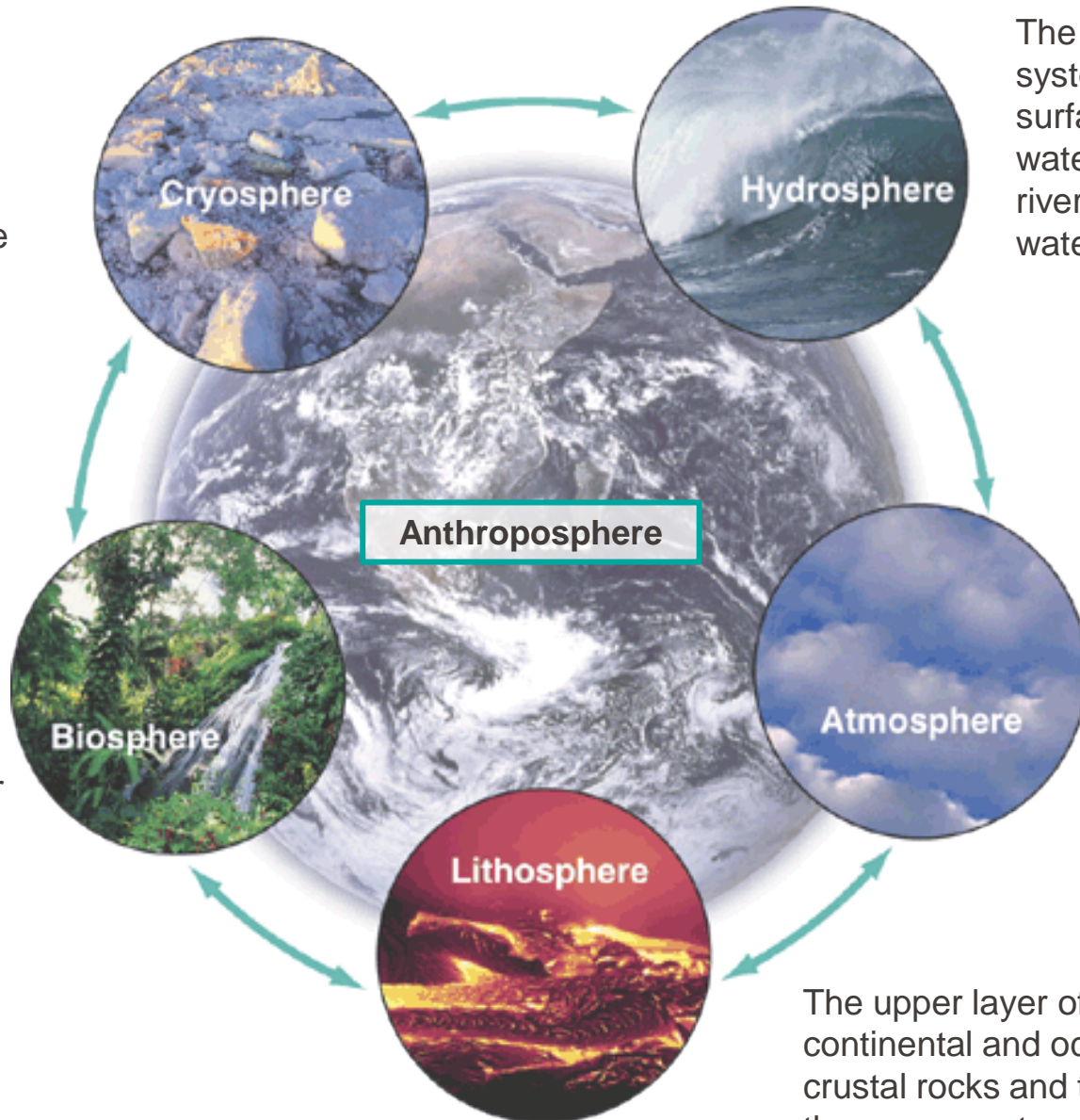
From the IPCC AR5 report:

“The climate system is the highly complex system consisting of five major **components**: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the **interactions** between them. The climate system **evolves in time** under the **influence** of its own **internal** dynamics and because of **external** forcings such as volcanic eruptions, solar variations and **anthropogenic forcings** such as the changing composition of the atmosphere and land use change.”

IPCC – Intergovernmental Panel on Climate Change, AR – Assessment Report, AR5 is from 2013.

Earth System Components

All regions on and beneath the surface of the Earth and ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers and ice sheets, and frozen ground (which includes permafrost).



The component of the climate system comprising liquid surface and subterranean water, such as oceans, seas, rivers, lakes, underground water, etc.

Anthroposphere represents activities of the **Anthropocene** epoch, the periods in which human activity has significantly affected Earth's biogeochemistry and climate. (not an official epoch)

The part of the Earth system comprising all ecosystems and living organisms, including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.

The gaseous envelope surrounding the Earth.

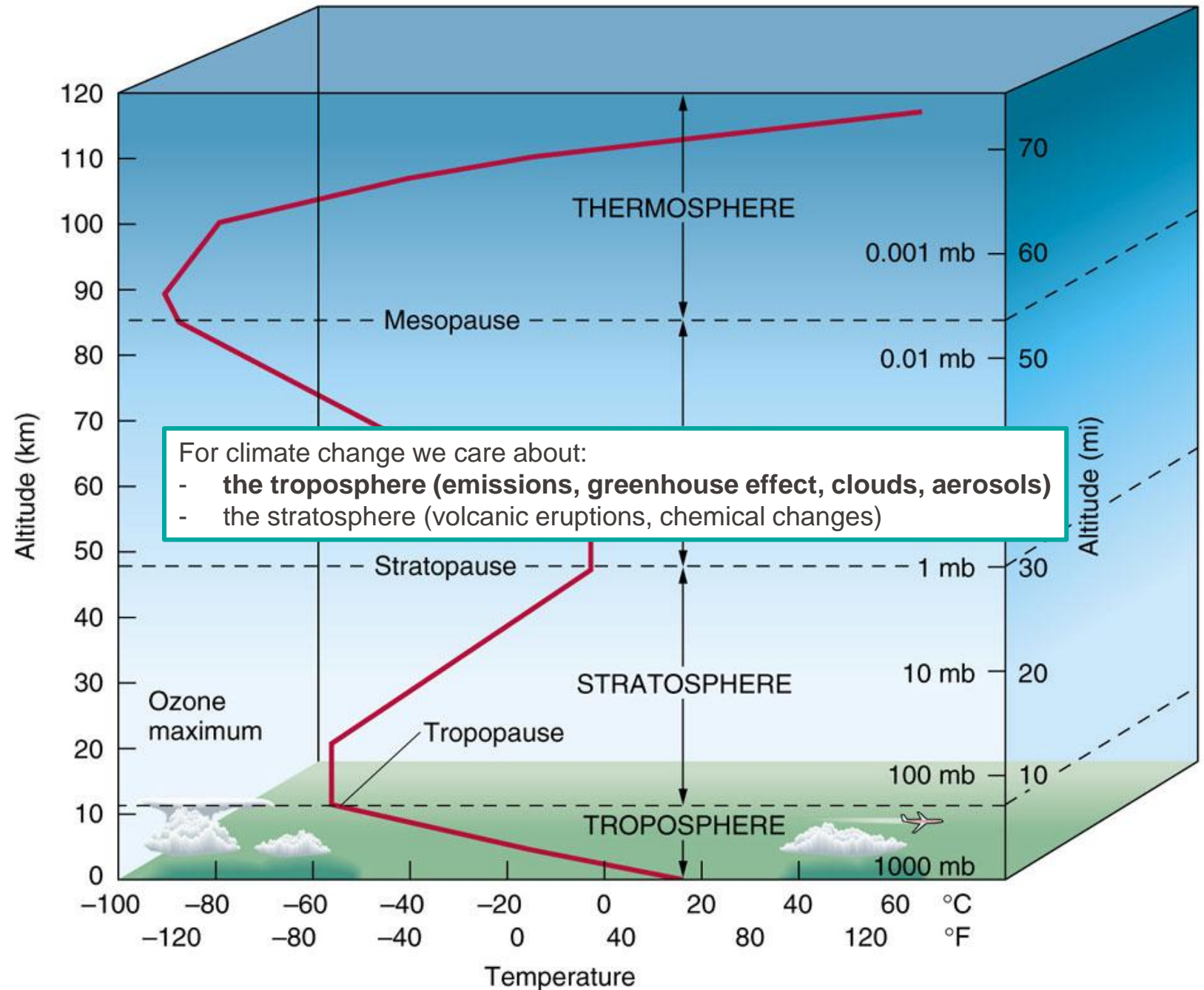
Recommended reading:
Wallace and Hobbs, chapter 2.1

The upper layer of the solid Earth, both continental and oceanic, which comprises all crustal rocks and the cold, mainly elastic part of the uppermost mantle.

EPFL Atmosphere

The vertical temperature profile provides basis for dividing the atmosphere into four layers:

- *Troposphere*: sun warms the surface, because atmosphere is mostly transparent to visible solar radiation, warm and moist air rises, cools and forms clouds, average **lapse rate** of $-6.5\text{ }^{\circ}\text{C km}^{-1}$.
- *Stratosphere*: dry and ozone-rich; ozone absorbs UV radiation, critical for life on Earth, receives warmth from solar radiation, inversion.
- *Mesosphere*: temperature decreases to a minimum at top, because much of the high energetic radiation is already absorbed by the thermosphere.
- *Thermosphere*: increase in temperature due to absorption of solar radiation and photodissociation of nitrogen and oxygen molecules.



Lapse Rate

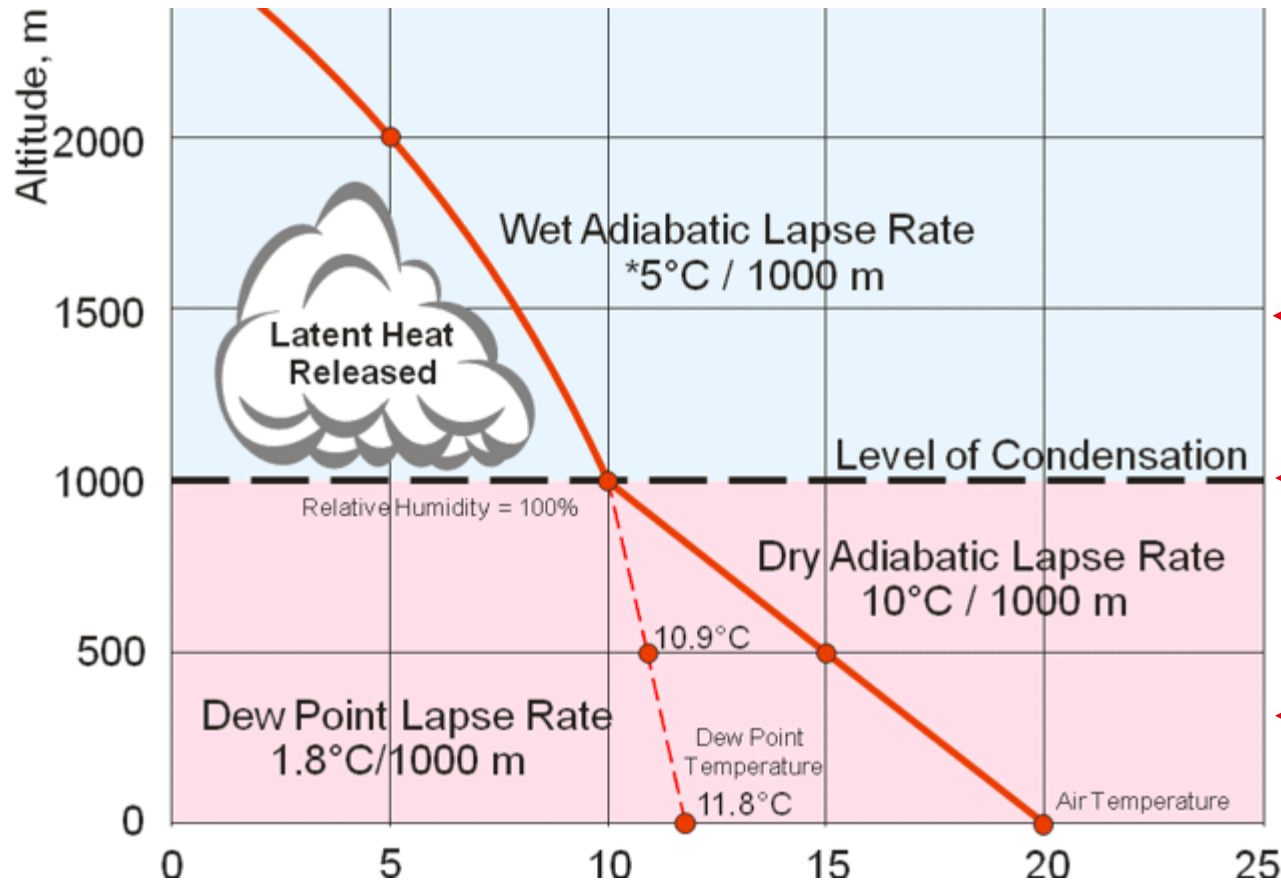
A critical climate feedback

Dew point temperature: temperature of air at which it will become saturated with water vapor (RH = 100%)

Adiabatic means, there is no heat or mass transfer between the air parcel and environment, only work is done (expansion).

Environmental lapse rate Γ is the rate at which temperature (T) decreases with height (z), it is roughly 6.5 degrees per 1000 m.

$$\Gamma = -\frac{dT}{dz} \quad (\text{K/m})$$



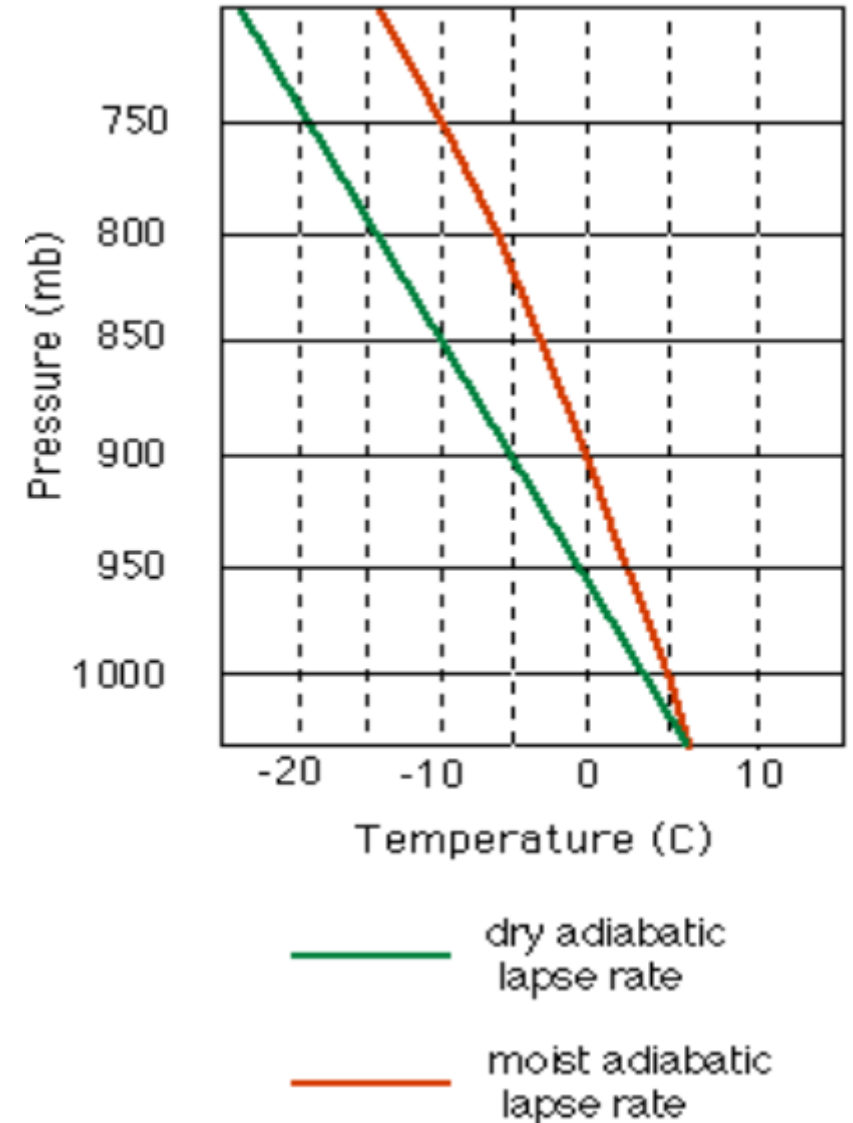
Because condensation is involved, we speak of the *wet* (moist) adiabatic lapse rate. Air parcels cool because heat is released as condensation heat.

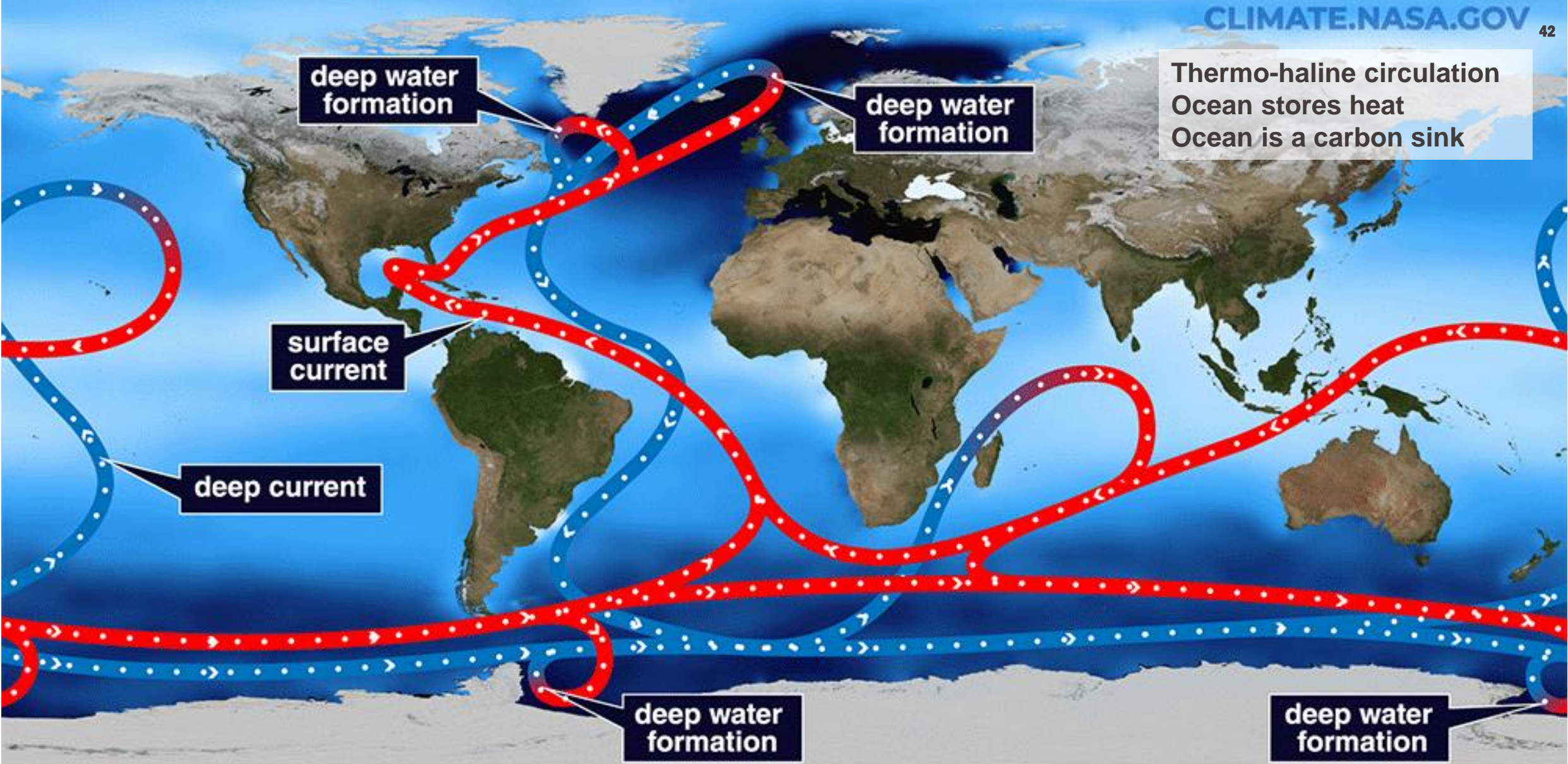
Air becomes saturated with water vapor and clouds can form through condensation (a process of latent heat release).

Pockets of warmer air rise, expand and cool and the cooler air compresses and falls until it is in equilibrium with the surrounding air. There is no condensation involved, hence *dry* adiabatic lapse rate.

Dry and moist adiabatic lapse rates

- The dry adiabatic lapse rate is constant with ~ 10 °C/km.
- The moist adiabatic lapse rate varies with pressure and temperature.
 - A moist air mass that rises will condense liquid water, which releases latent heat (in the same air parcel, hence 'adiabatic' still holds).
 - Consequently the rate of decrease in temperature in the further rising air parcel is reduced, since latent heat is added.



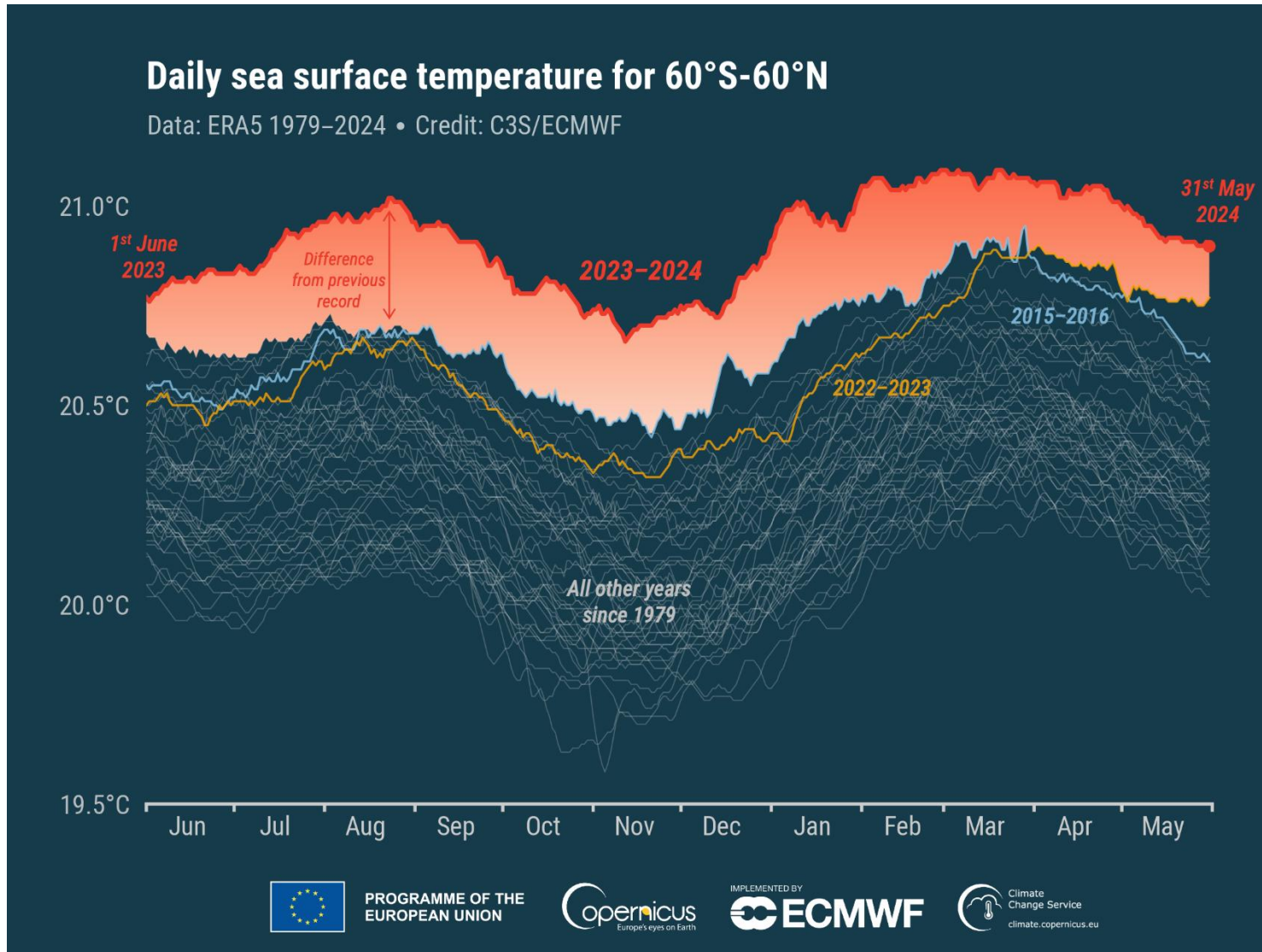


Thermo-haline circulation
 Ocean stores heat
 Ocean is a carbon sink



Sea Surface Density
 (kg per cubic meter)

Global Ocean Temperature Records in 2023

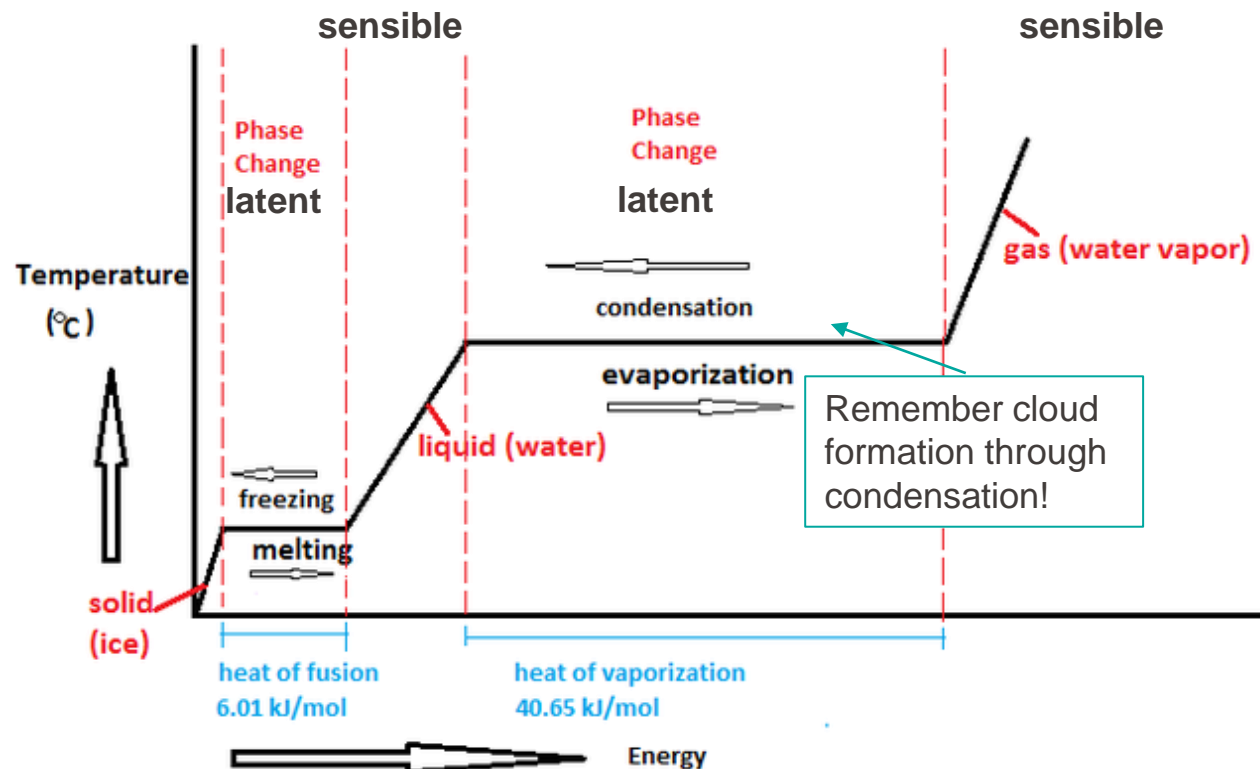


Latent and sensible heat

Both processes **transfer energy** in the climate system.

Latent heat: energy transferred in a process without change of the body's temperature, it is associated with the change of phase of atmospheric or ocean water: vaporization, condensation, freezing or melting.

Sensible heat: "sensed" or felt in a process as a change in the body's temperature, e.g., as increasing or decreasing air or water temperature.



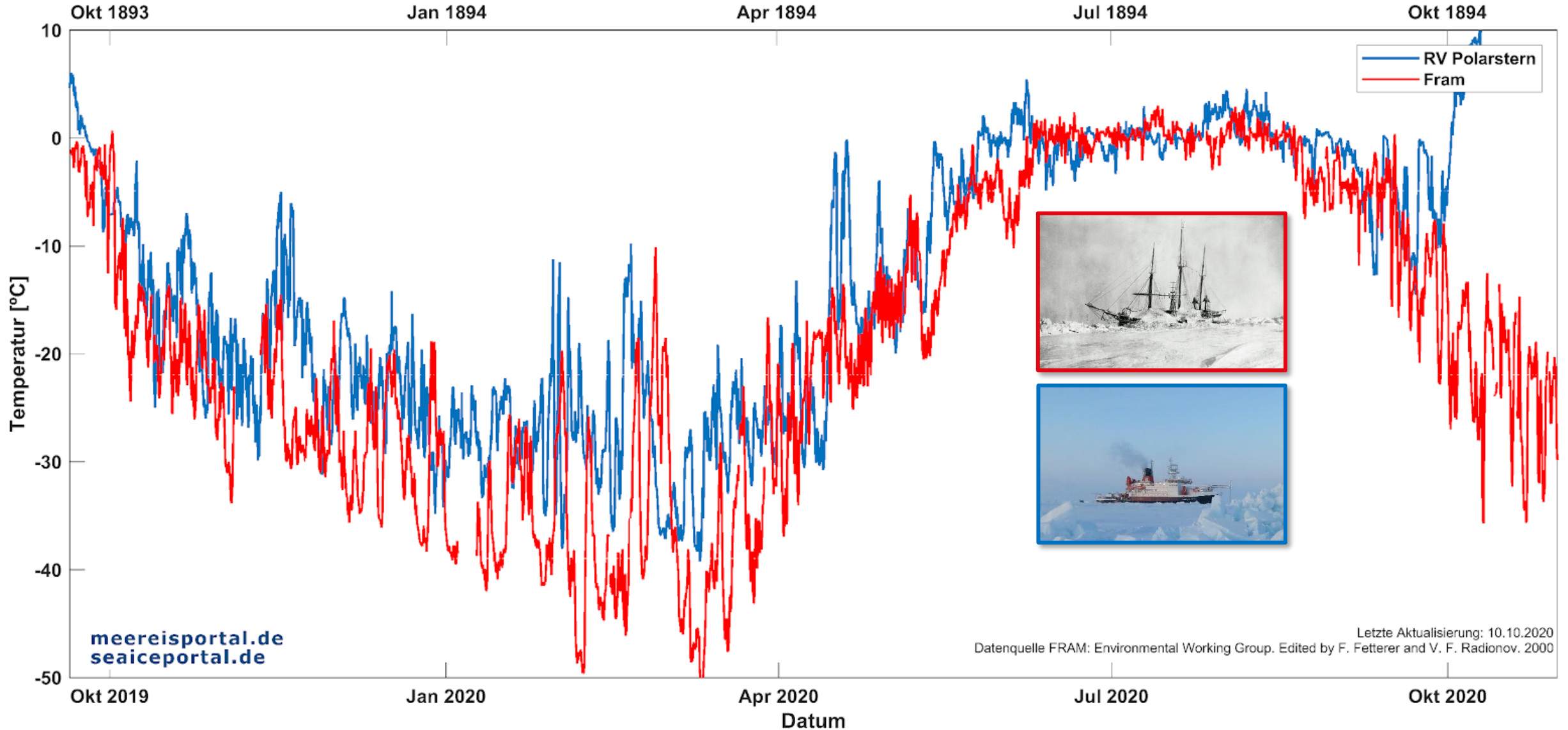
What will be the North Pole summer temperature in 2050?

- The Arctic warms about three times as fast as the global average.
- Currently summer temperature at the North Pole is around 0°C.
- With an estimated global average temperature increase of 0.1 °C per decade, what is the temperature at the North Pole in 2050?



North Pole, August 2018

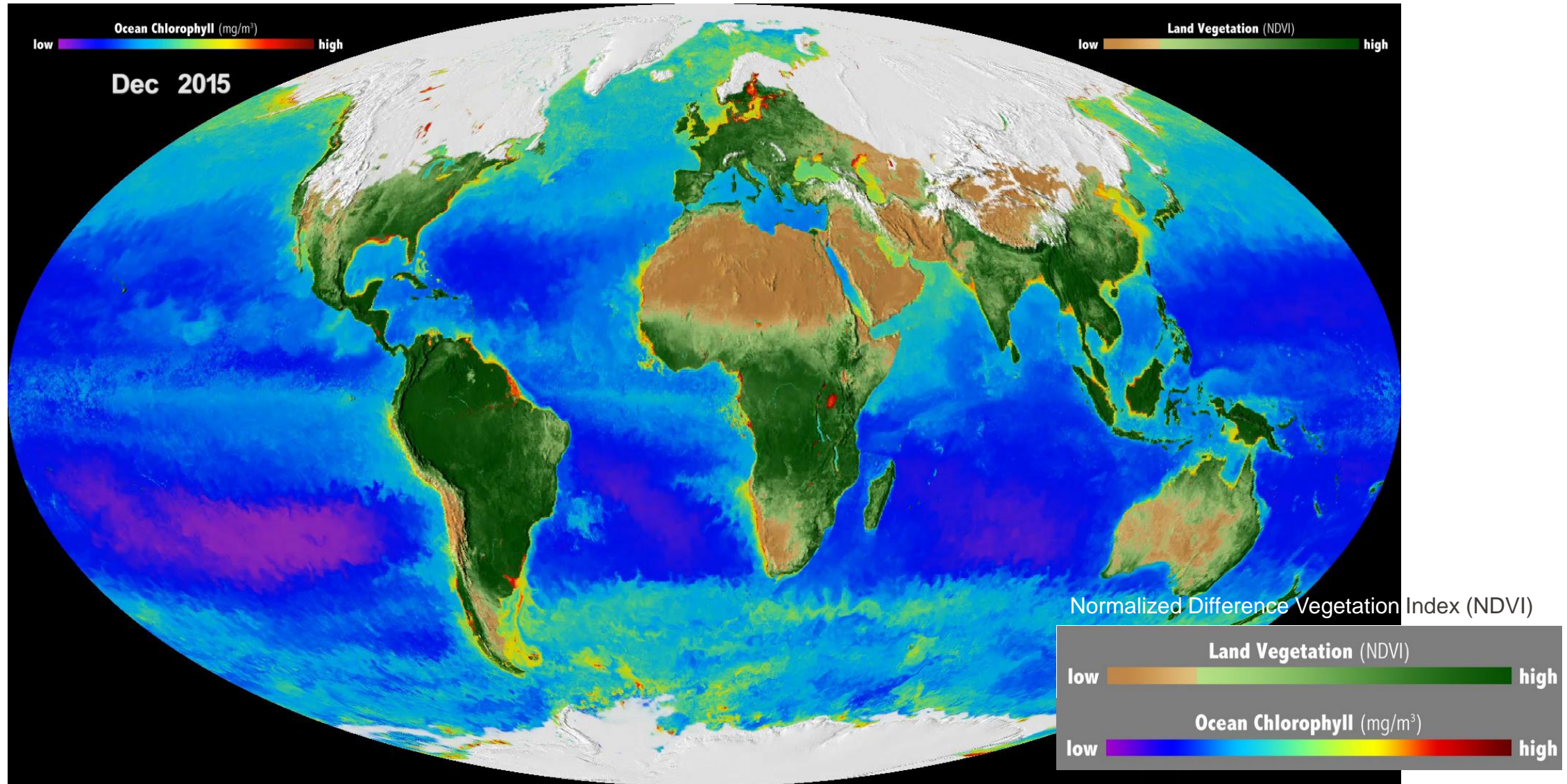
Arctic temperature change: 1893/94 vs 2019/20



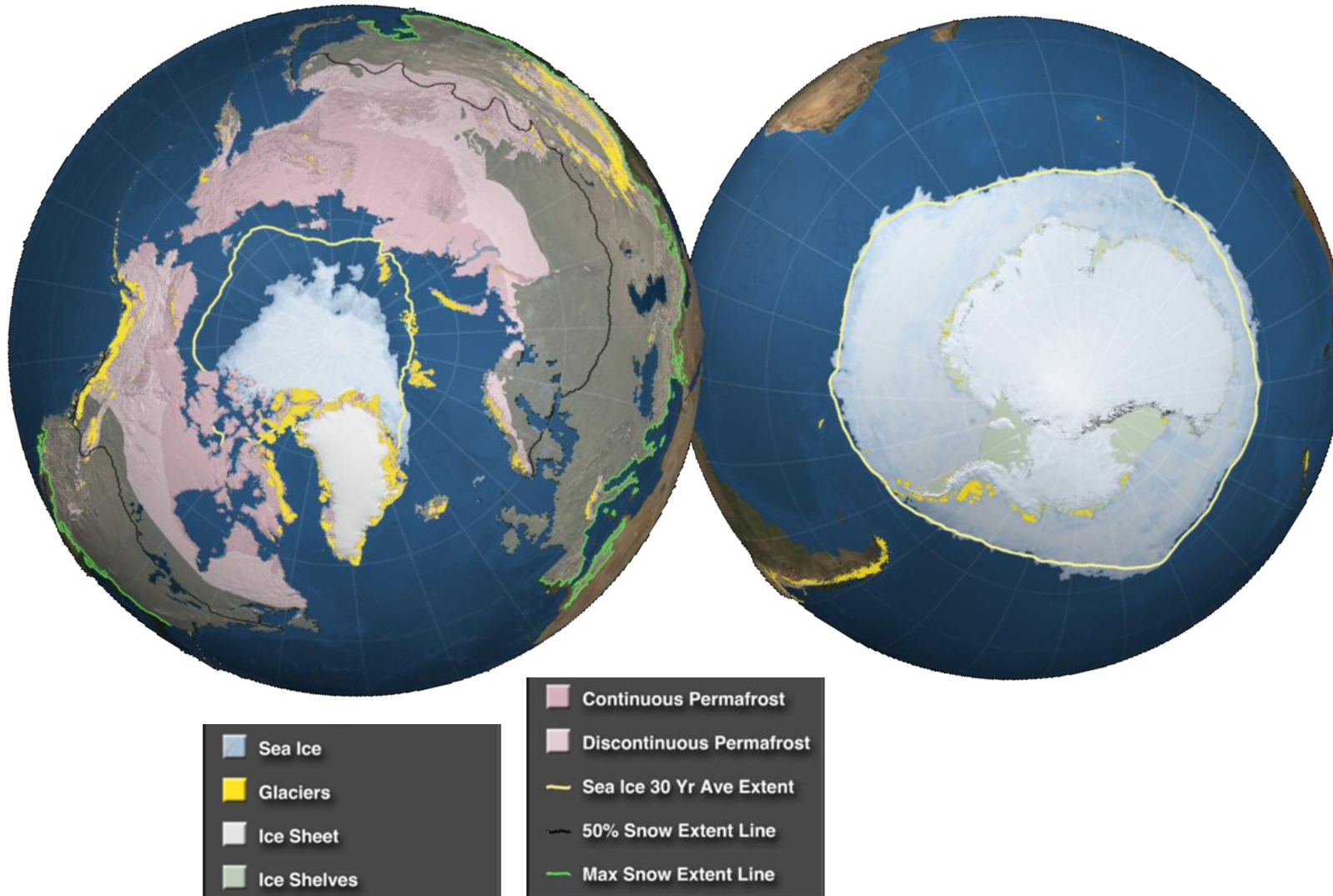
meereisportal.de
seaiceportal.de

Letzte Aktualisierung: 10.10.2020
Datenquelle FRAM: Environmental Working Group. Edited by F. Fetterer and V. F. Radionov, 2000

Biosphere (terrestrial and marine)



Cryosphere (terrestrial and marine)



Ice and seasonal snow strongly influence the **surface albedo** (reflectivity) and therefore the **radiation** budget, as well as the water cycle and the biosphere.

It is a key component of the **water cycle**.

99 % of the fresh water on Earth is in ice sheets. Greenland holds enough frozen water to raise the **sea level** by 6 m and Antarctica by 60 m.

Changes in sea ice extent, seasonality and thickness have potential impacts for **hemispheric-scale circulation**.

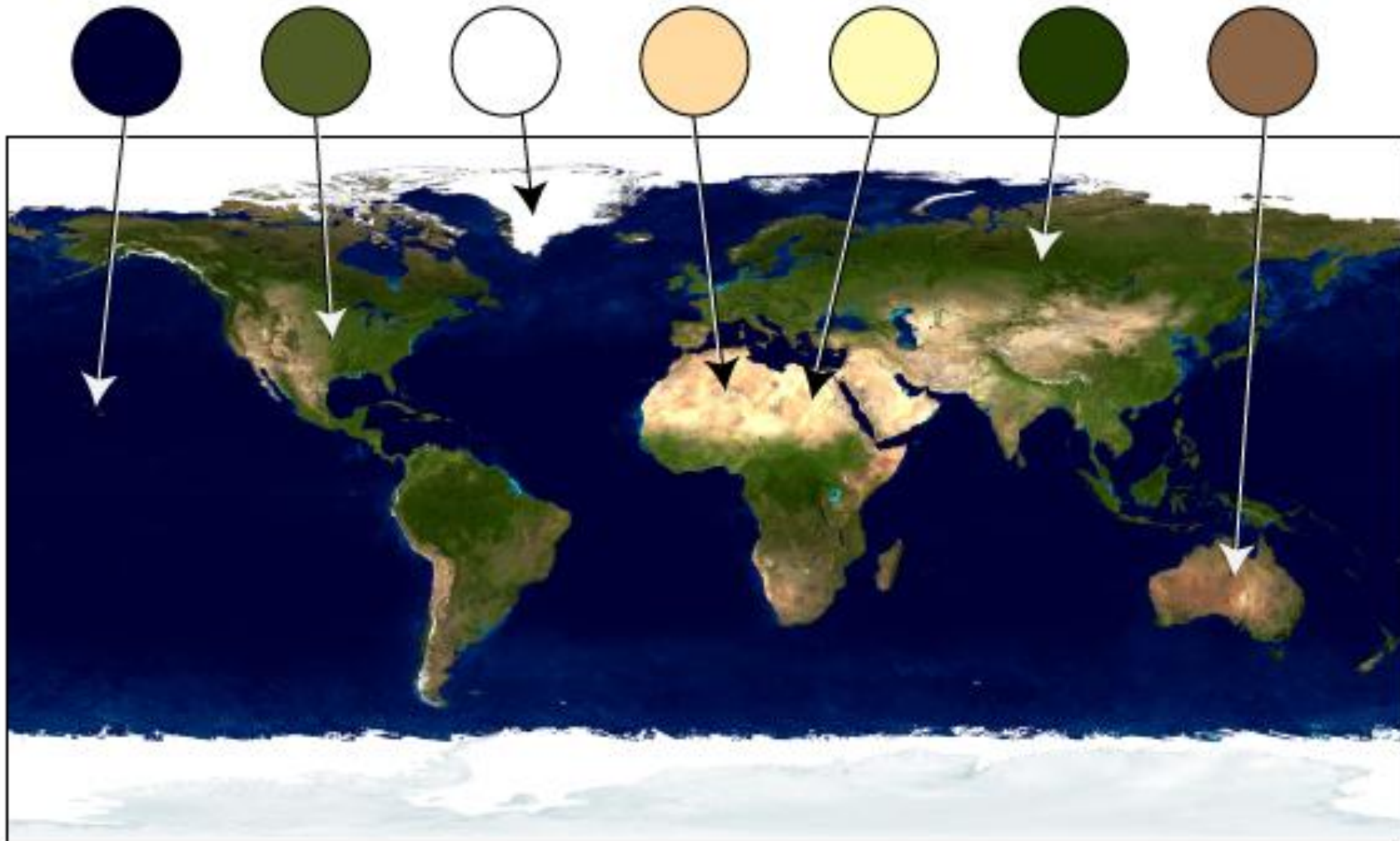
Changes in glacier mass balance contribute to changes in **sea level** but also have substantial implications for water supply for a substantial proportion of the global population.

Changes in permafrost and the seasonally thawed active layer have substantial implications in mid- to high latitudes (soil stability, natural hazards) and store large amounts of **carbon**

Albedo

A critical climate feedback

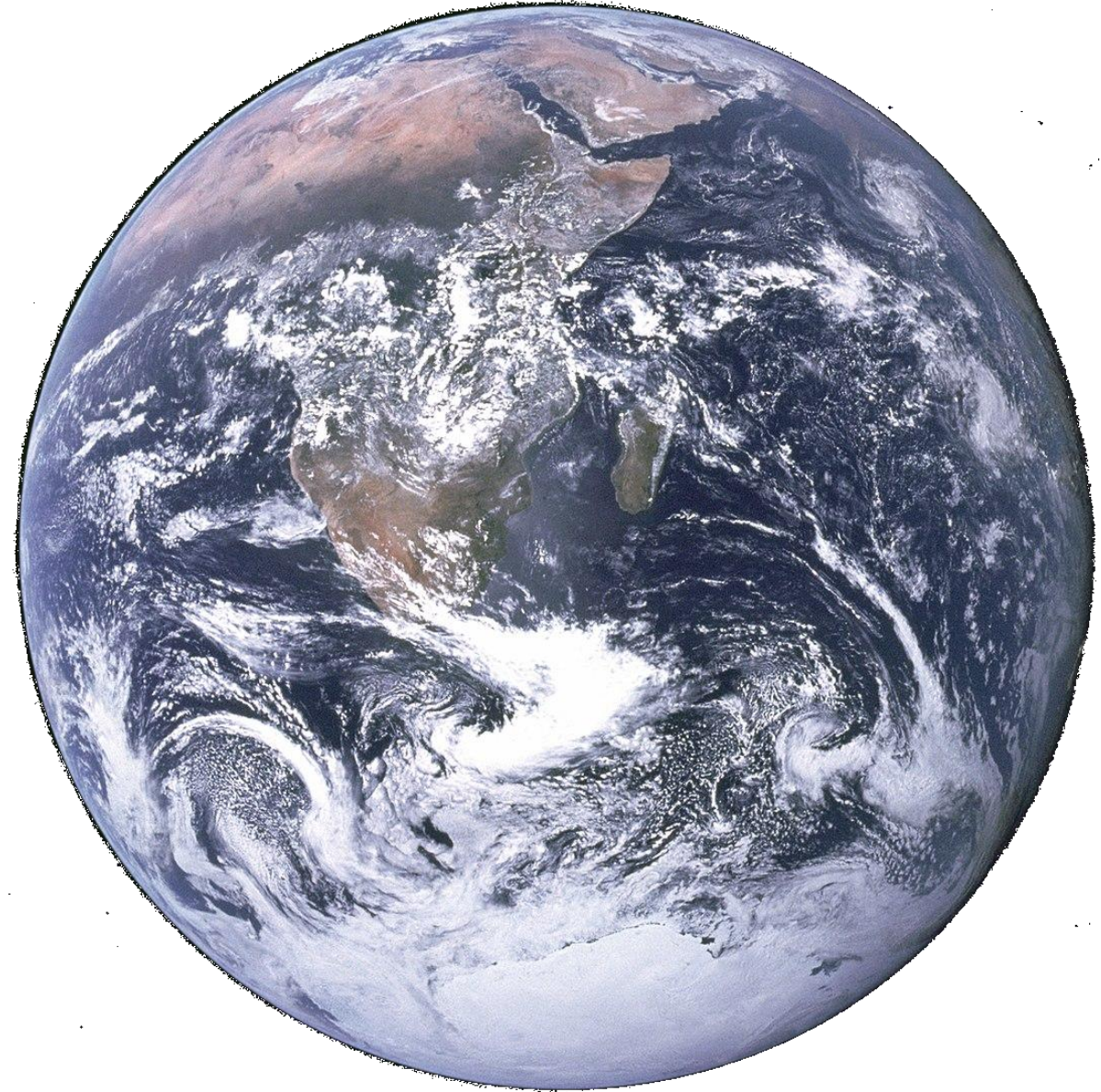
Reflectivity of a surface
1: fully reflective
0: complete absorption



Water (ocean), zenith angle: 45, 60, 70, 80°	0.05, 0.08, 0.12, 0.22
Fresh/worn asphalt	0.04/0.12
Conifer forest (summer)	0.08–0.15
Deciduous trees	0.15–0.20
Savanna	0.20–0.25
Green grass	0.25
Desert sand	0.30–0.40
New concrete	0.55
Ocean Ice	0.50–0.70
Old snow	0.45–0.80
Clouds	0.60–0.90
Fresh snow	0.80–0.90

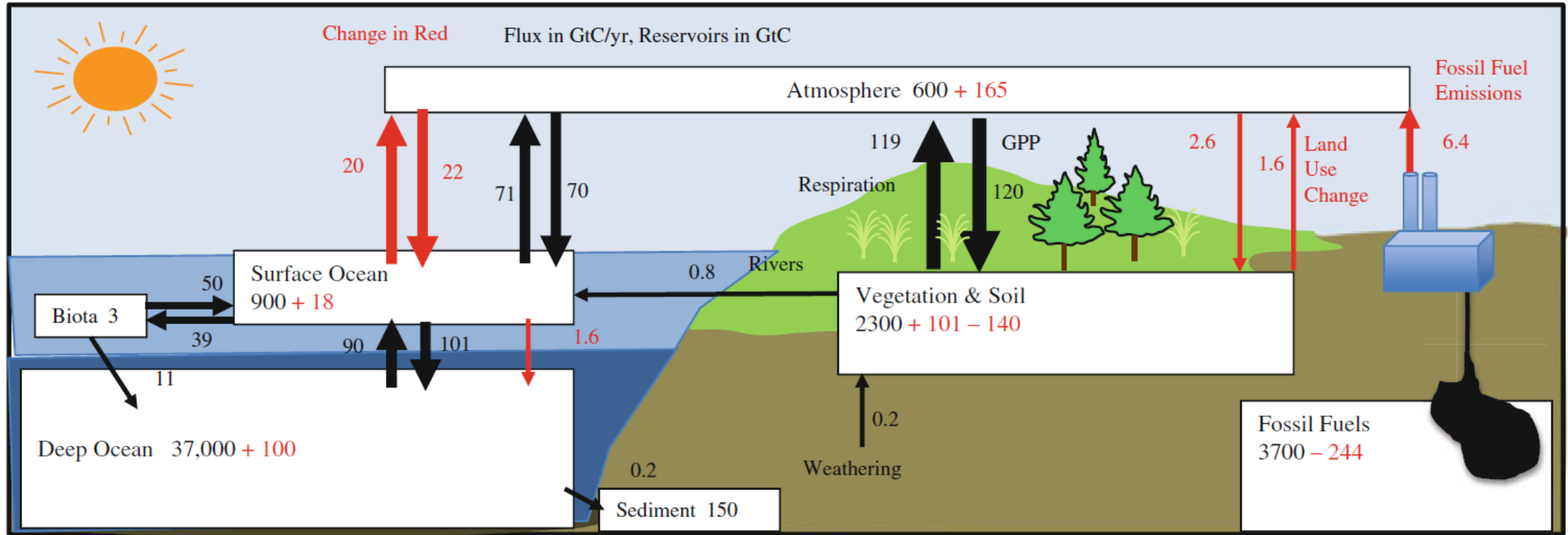
Planetary albedo, incl. atmosphere and clouds:

$\alpha \sim 0.3$





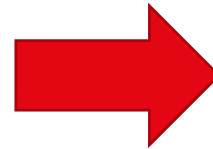
■ Narsaq, Southern Greenland 2022 (picture credit J. Schmale)



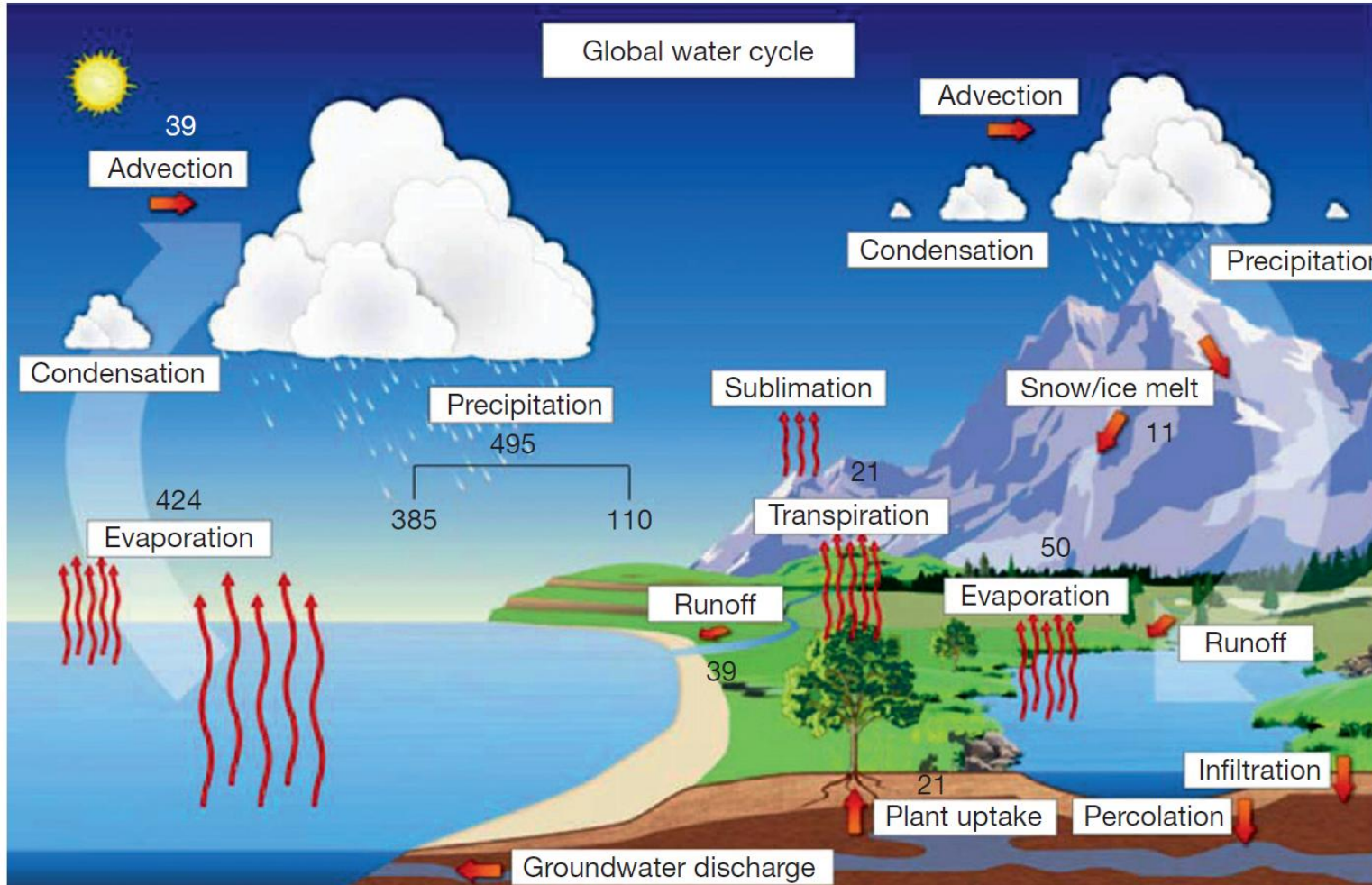
The largest climate system reservoirs for carbon include the deep ocean, soil and vegetation, surface ocean, and atmosphere. The approximate size of annual carbon fluxes is given by the width of the arrows; red arrows indicate perturbations by humans. Black arrows are natural exchanges. Quantities are in gigatons (10^9 tons) of carbon (GtC) for reservoirs and gigatons of carbon per year (GtC/yr) for fluxes.

Which compounds are included in the carbon cycle?

- Only CO₂.
- CO₂ and methane (CH₄).
- CO₂ and organic carbon.
- CO₂ and inorganic carbon.
- CO₂, CH₄ and aerosols.
- All of the above.



The carbon cycle comprises a large suite of compounds that contain carbon. In the atmosphere, there are not only **greenhouse gases** like CO₂ and CH₄ which influence climate, but also **other compounds** like volatile organic compounds and particulate carbon, specifically black carbon, which **interact with radiation** and contribute to **cloud formation**, and are hence relevant for climate change.



fluxes in (tera) $10^{12} \text{ m}^2 \text{ yr}^{-1}$

Advection: movement of solid, liquid, and gaseous water through the atmosphere.

Condensation: water vapor changes into water droplets (clouds).

Evaporation: water changes state from a liquid to vapor.

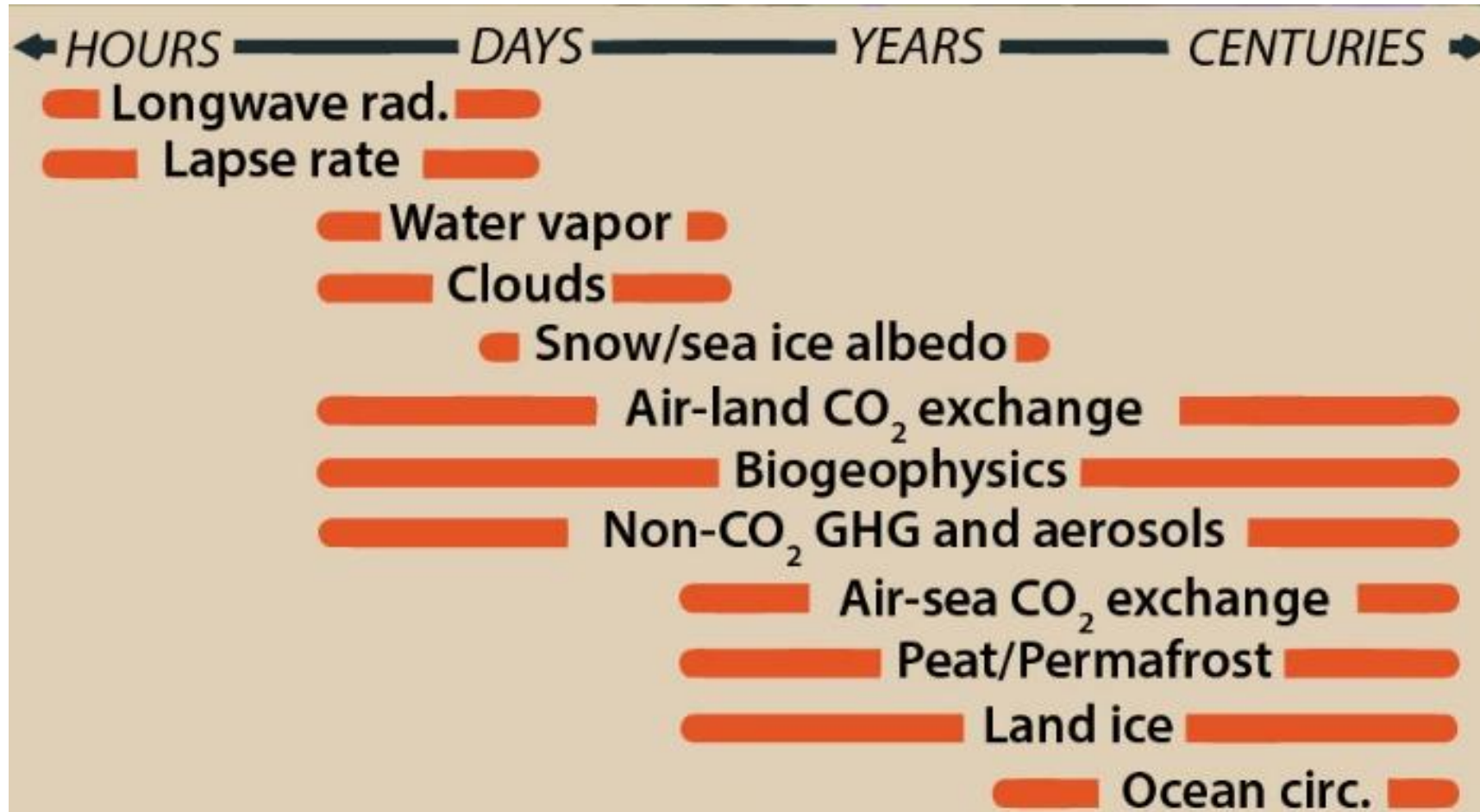
Infiltration: movement of water into the ground from the surface.

Percolation: movement of water past the soil and going deep into the groundwater.

Sublimation: ice and snow change into vapor without going through the liquid phase.

Transpiration: moisture from plants and trees evaporates into the atmosphere.

Water vapor is the most abundant greenhouse gas on Earth.



Biogeophysics: how plants, microbial activity and other organisms alter geologic materials and affect geophysical signatures

Climate relevant processes occurring within and between «spheres» have different time scales. There are processes which occur on even longer time scales than shown here (e.g., continental movement).

Summary: Climate system

- Earth's climate system is driven by the **sun**.
 - The **atmosphere mediates the flow of energy** between the sun and the Earth, through the action of clouds and greenhouse gases.
 - There are several different components of the Earth's climate system, "**spheres**": atmosphere, terrestrial surface, ocean, cryosphere, biosphere and anthroposphere (the sphere of human effects).
 - In addition to energy, several **critical substances flow through the Earth system**. Two of the most important are **water and carbon**. They are important for climate, and they are important for life.
 - In the atmosphere water vapor and carbon dioxide are **greenhouse gases**.
Exact discussion of mechanism follows.
 - **Transformation of water** is a mechanism for **moving heat** from where it evaporates and releasing it on condensation. Exact discussion of mechanism follows.
 - Climate relevant processes occur on different **time scales**.
 - There are **climate feedback mechanisms** which slow or accelerate change.
Exact discussion of mechanism follows.
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