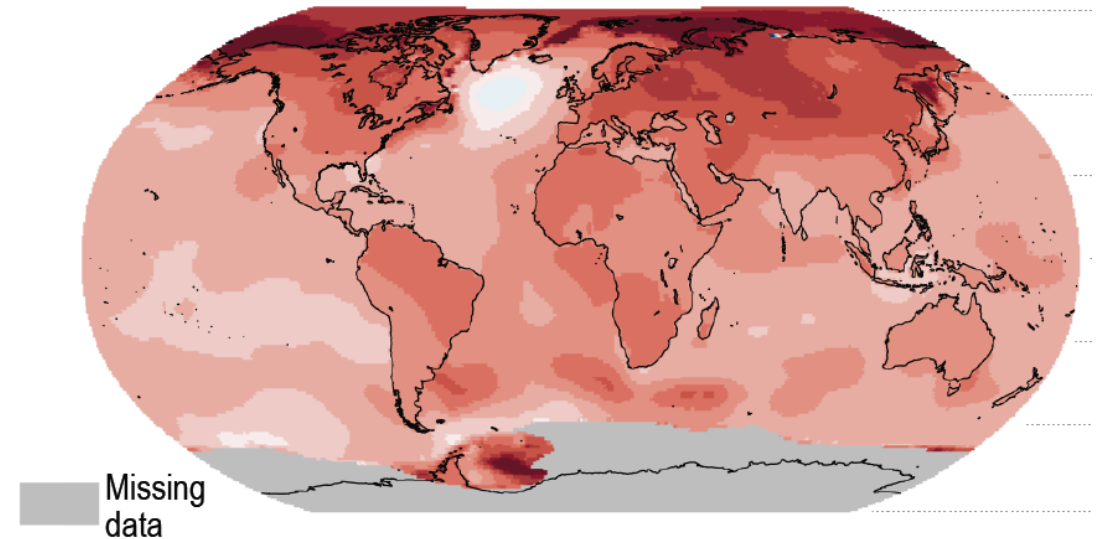


# Recap from last lecture

- What are anomalies and how are they calculated?
- Paris agreement: keep global temperature rise below  $1.5^{\circ}\text{C}$  above preindustrial levels
- Warming is heterogeneous



	No.	Date	Topics	Deadlines / tentative
Basics	1.	11.09.2025	Introduction to the climate system	Questionnaire (not graded)
	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)

# Lapse Rate

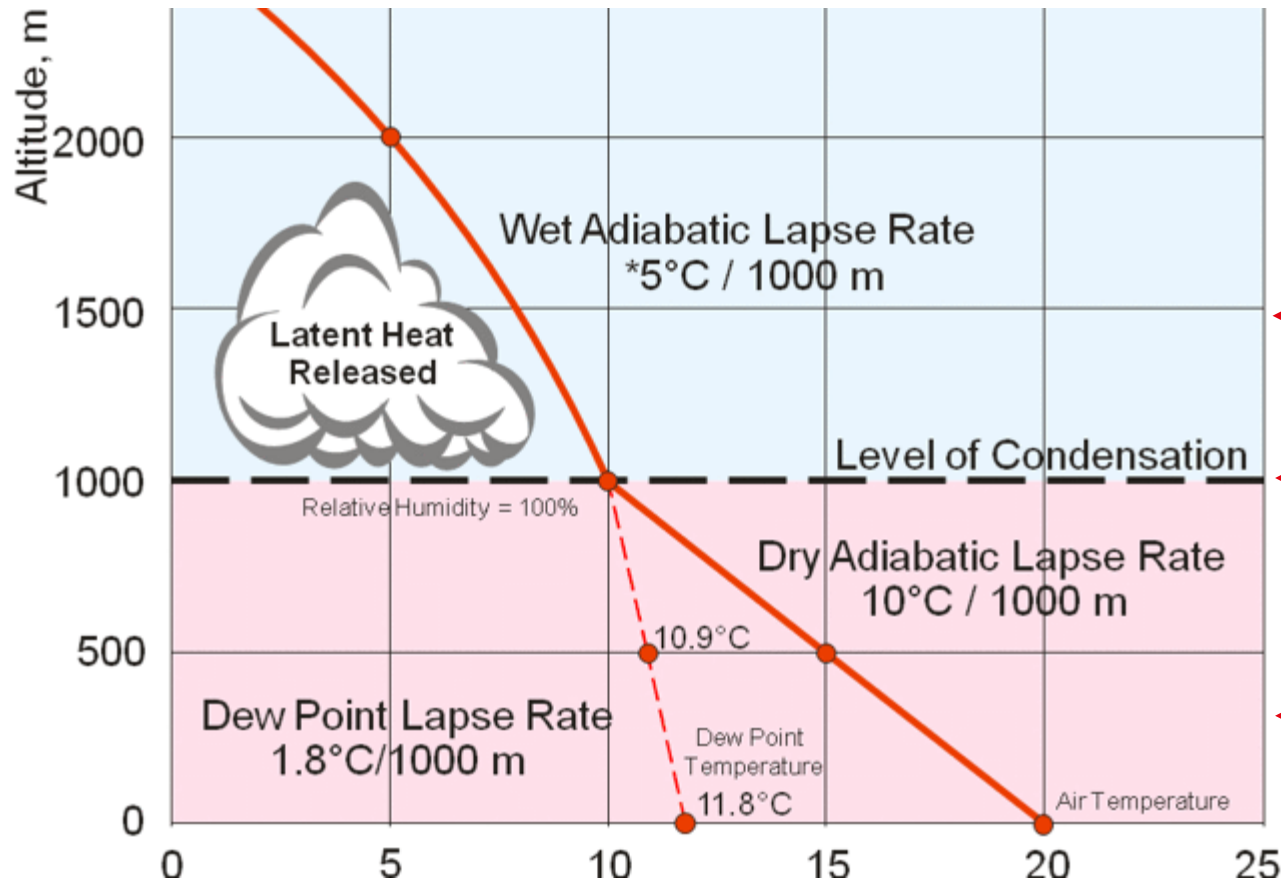
## A critical climate feedback

**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**  $\Gamma$  is the rate at which temperature (T) decreases with height (z), it is roughly 6.5 degrees per 1000 m.

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



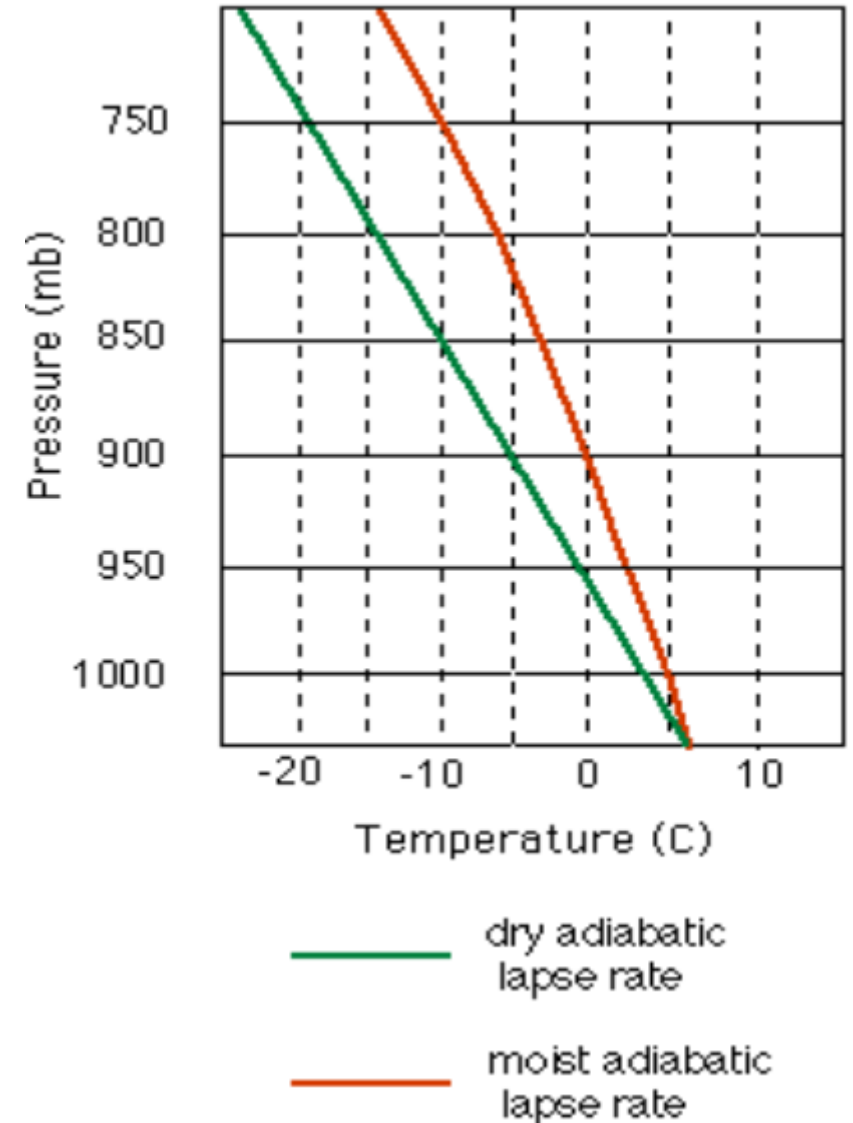
Because condensation is involved, we speak of the *wet* (moist) adiabatic lapse rate. Air parcels cool because heat is released as condensation heat.

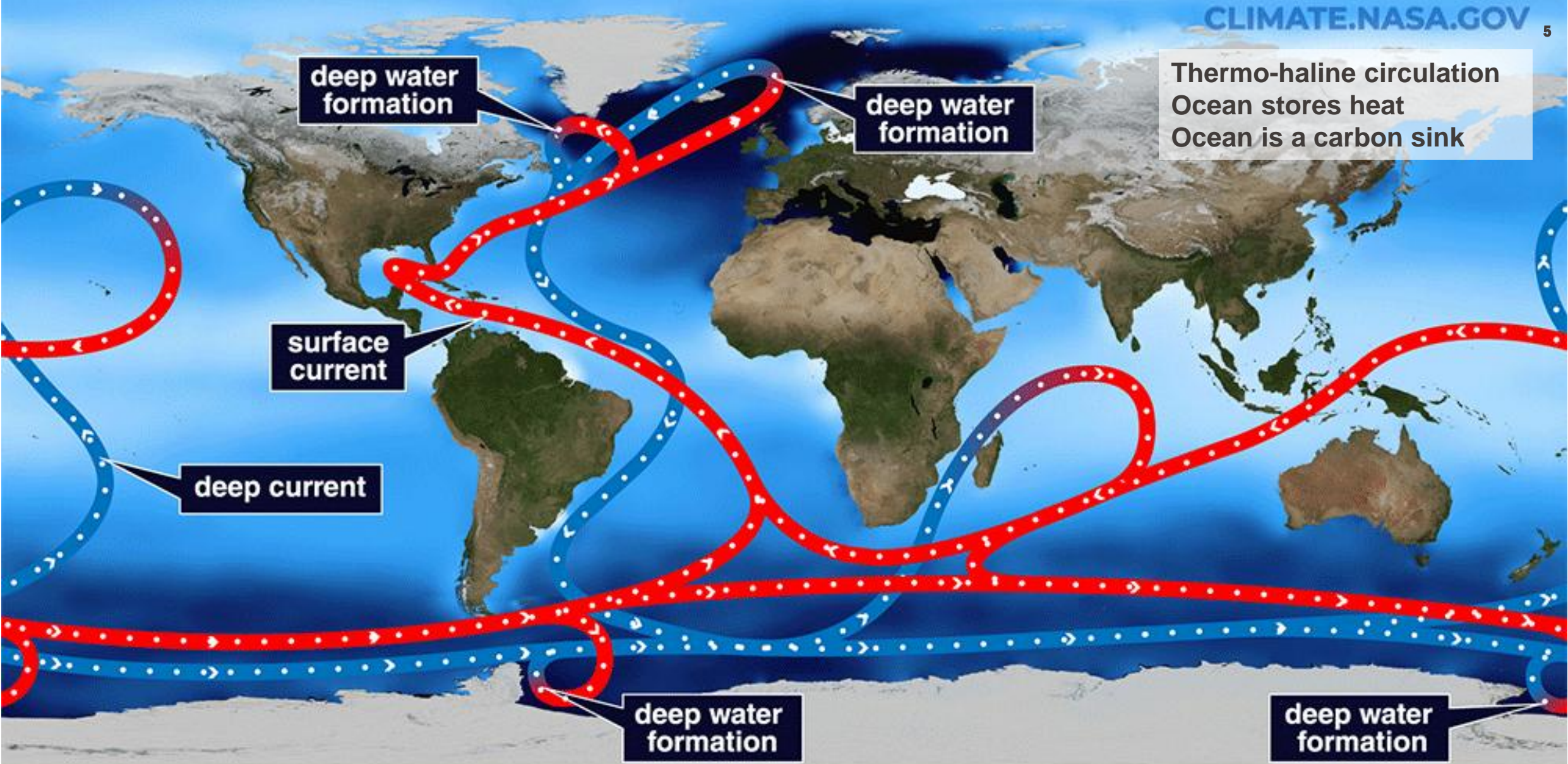
Air becomes saturated with water vapor and clouds can form through condensation (a process of latent heat release).

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  $\sim 10$  °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

deep water formation

deep water formation

surface current

deep current

deep water formation

deep water formation



**Sea Surface Density**  
 (kg per cubic meter)

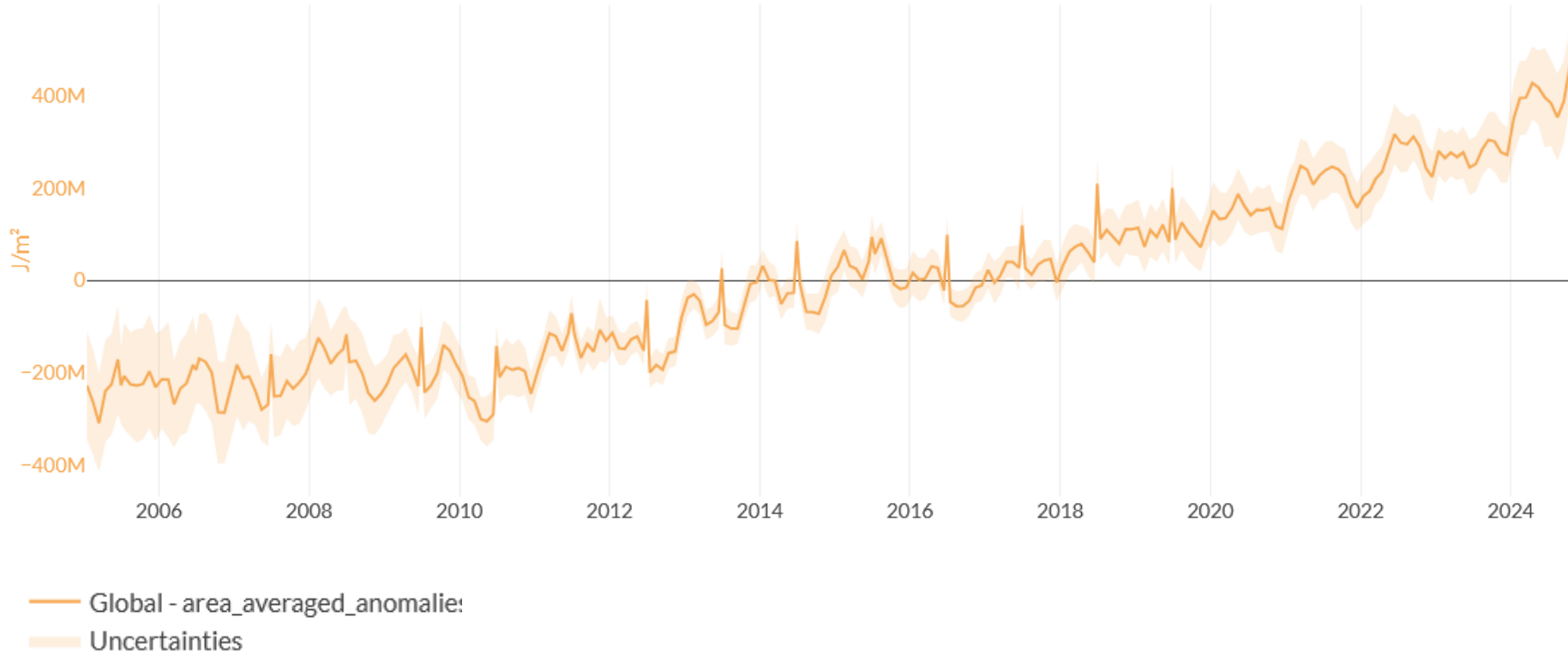
1002      1003      1006      1012      1020      1028



## Ocean Heat Content

Assessing the surplus heat in Earth's system from climate change - of which about 90% is stored in the ocean - from the sea surface, down to 2000 metres of depth.

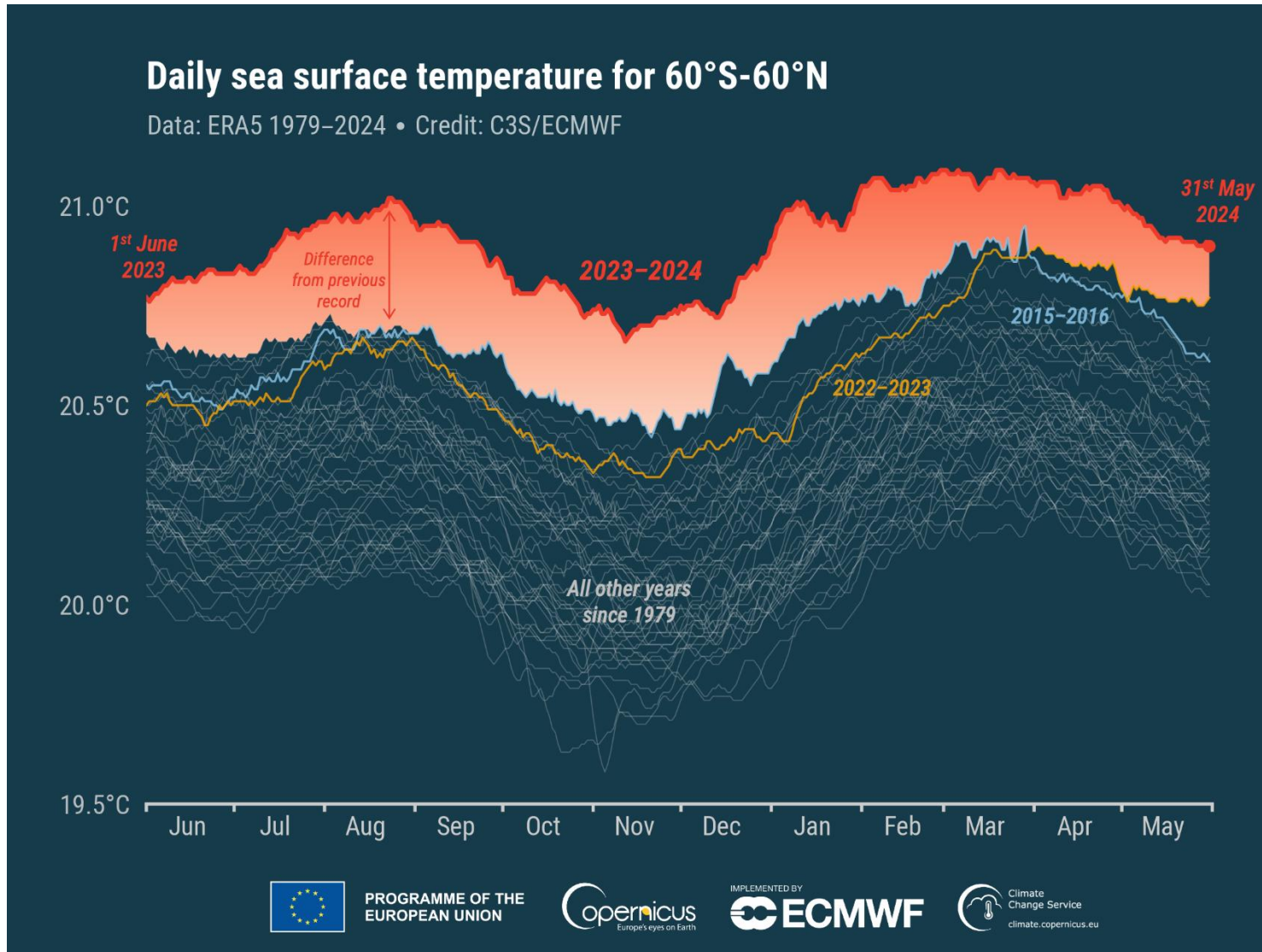
Global Ocean Heat Content (J/m<sup>2</sup>)



- Nearly **90% of the heat** from human-generated global warming is stored in the ocean
- It is highly certain that the global upper ocean (0–700 m) has warmed since the 1970s and extremely likely that human influence is the main driver<sup>1</sup>
- Over the last 15 years, the accumulated heat in the ocean has risen by nearly 50% in comparison to the amount accumulated over the last 50 years<sup>2</sup>
- Ocean warming is responsible for about 30-40% of contemporary global mean sea level rise - water expands when it is heated

- Ocean warming: **irreversible ocean warming**, and its associated sea level rise, is considered irreparable, as the ocean takes hundreds to thousands of years to respond to changes
- **Decreased marine biodiversity**: ocean layers down to about 2000 metres, are home to a large diversity of marine life. These layers bear the brunt of warming, with negative effects on marine ecosystems
- **Disruption of marine food systems**: decline in fisheries productivity and subsequent loss of livelihoods and food security
- **Ocean stratification**: reduced ocean mixing and distribution of the nutrients on which marine primary producers are highly reliant
- **Weather patterns and severe events**: warmer ocean temperatures can impact weather patterns, such as tropical cyclones and flooding
- **Ocean circulation**: ocean warming can potentially impact the thermohaline circulation and upwelling processes
- **Deoxygenation**: warmer water holds less oxygen, leading to a loss of oxygen in the ocean
- **Carbon Cycle**: ocean warming can reduce the capacity of the ocean and marine ecosystems to absorb carbon<sup>5</sup>
- **Sea ice melting**: heat absorbed by the ocean can cause ice shelves and sea ice to melt, which affects the crucial role of polar regions in ocean circulation and our climate system

# Global Ocean Temperature Records in 2023

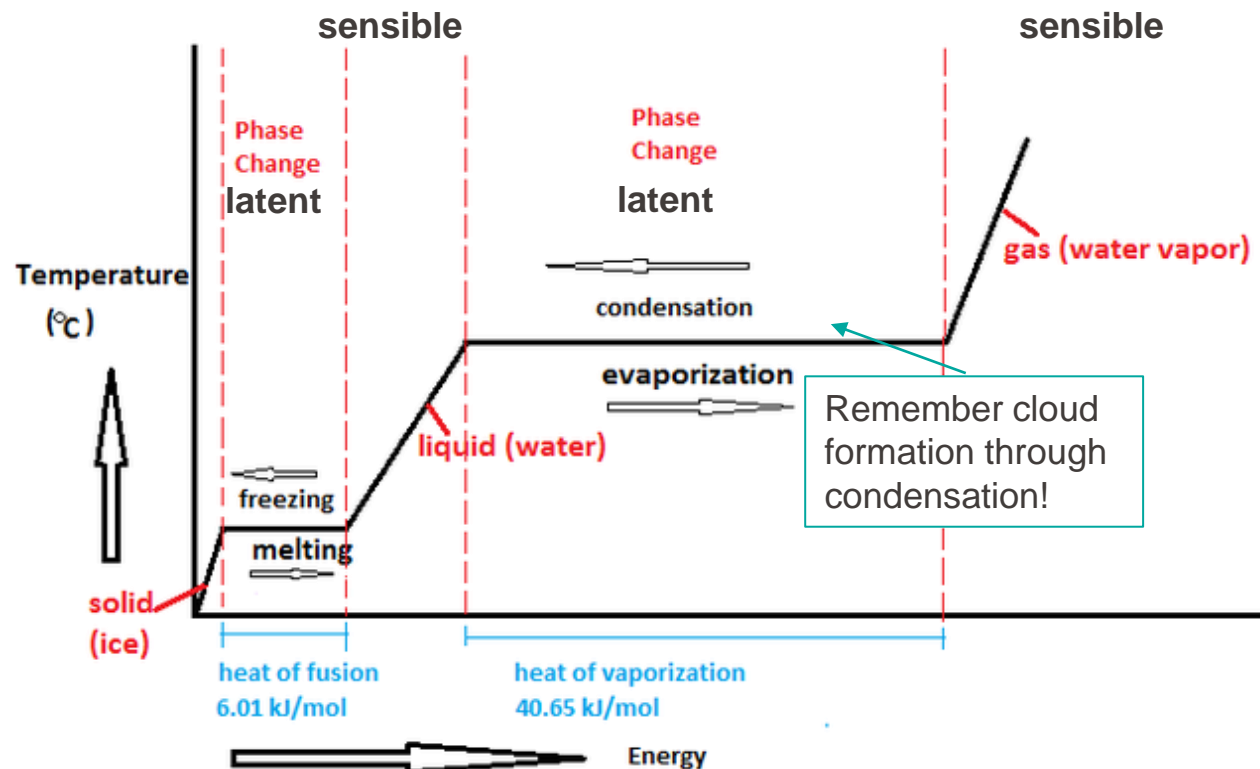


# Latent and sensible heat

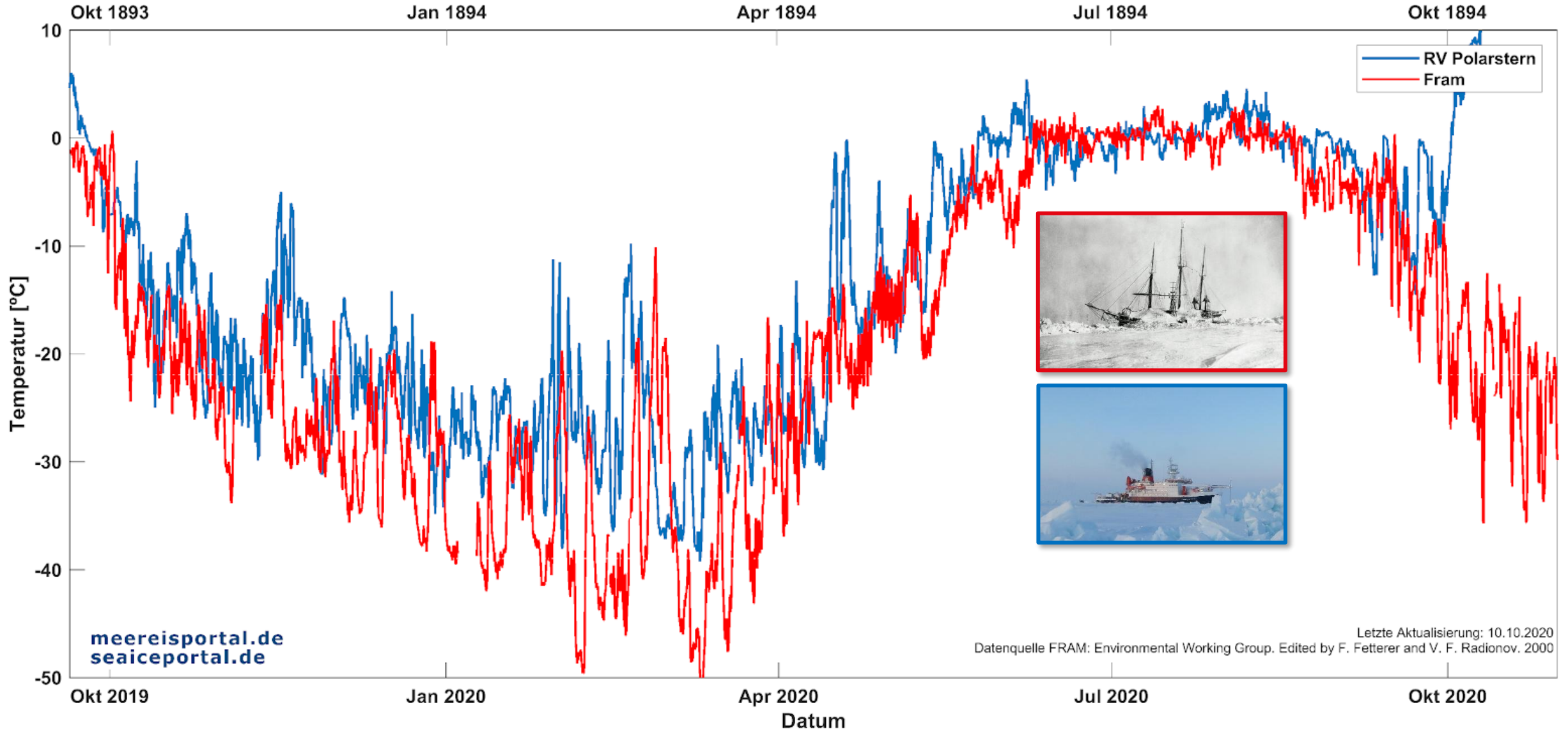
Both processes **transfer energy** in the climate system.

**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.



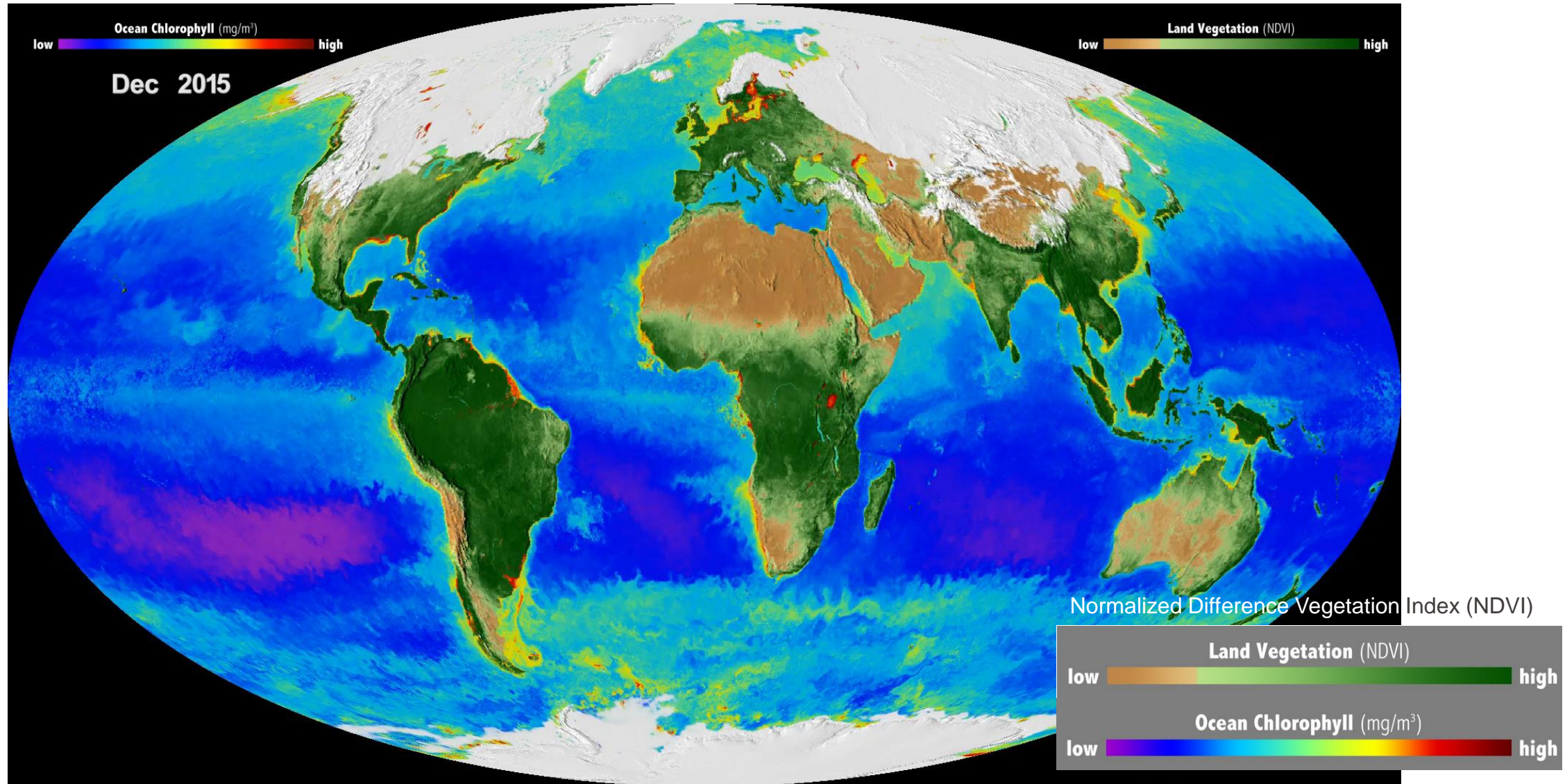
# Arctic temperature change: 1893/94 vs 2019/20



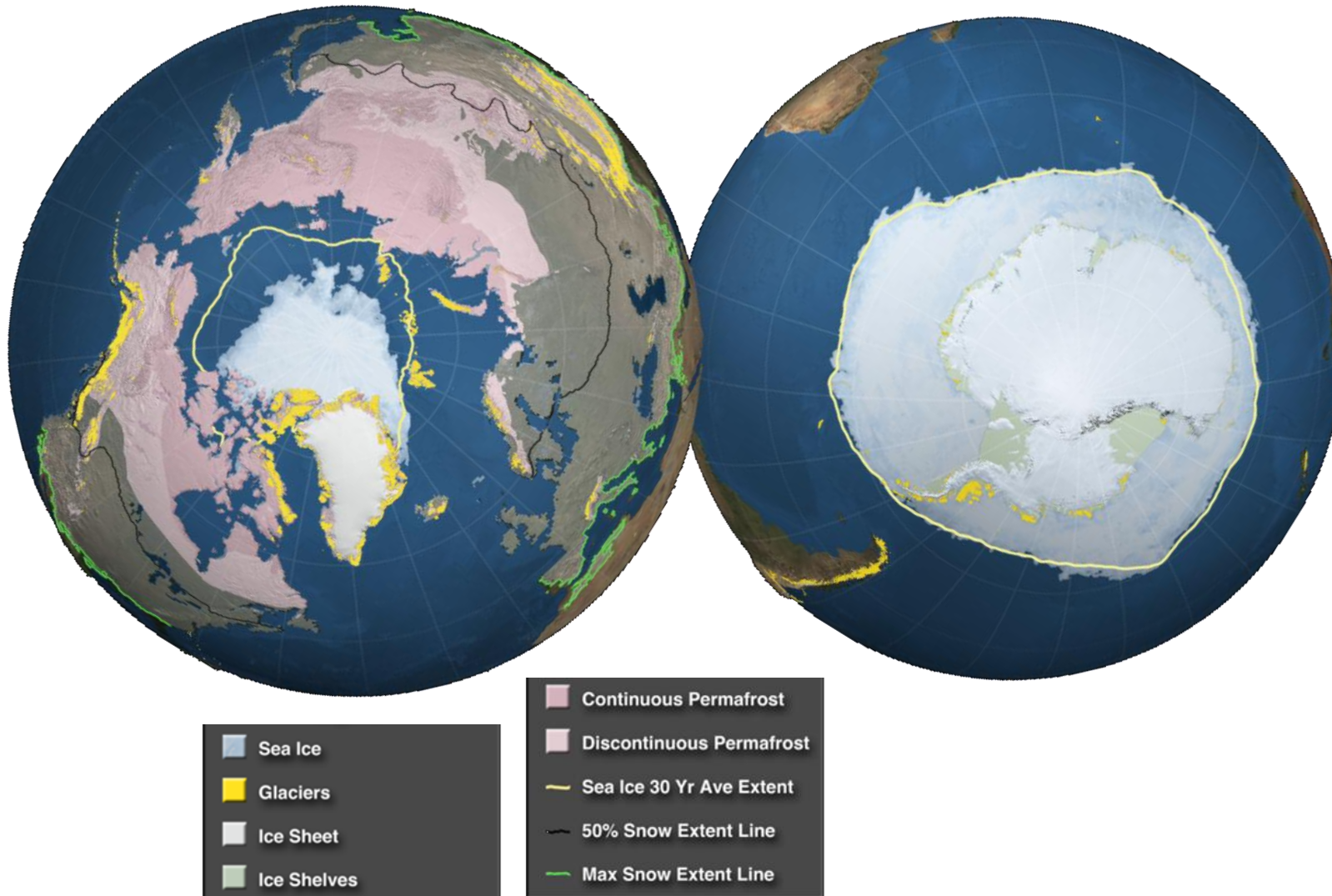
meereisportal.de  
seaiceportal.de

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.

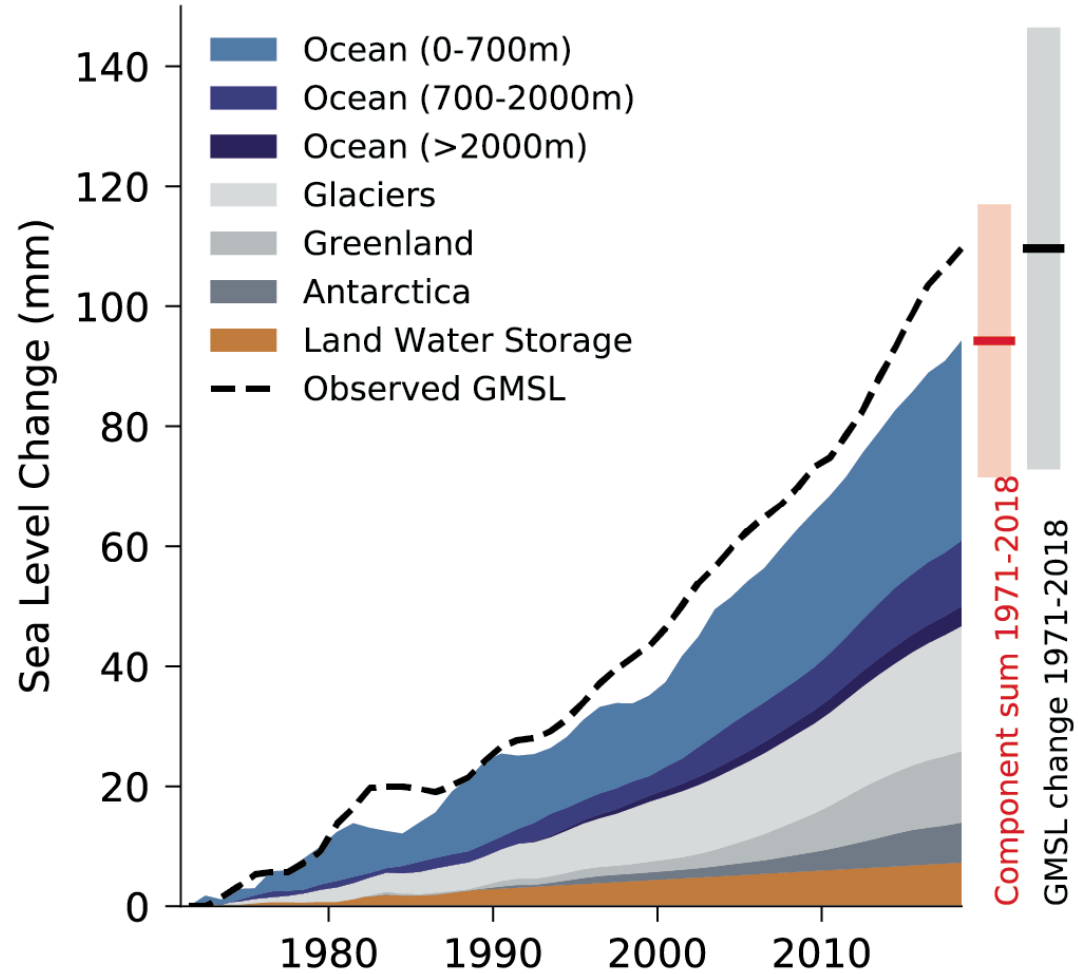
Changes in sea ice extent, seasonality and thickness have potential impacts for **hemispheric-scale circulation**.

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**

# Contribution of the cryosphere to sea level rise

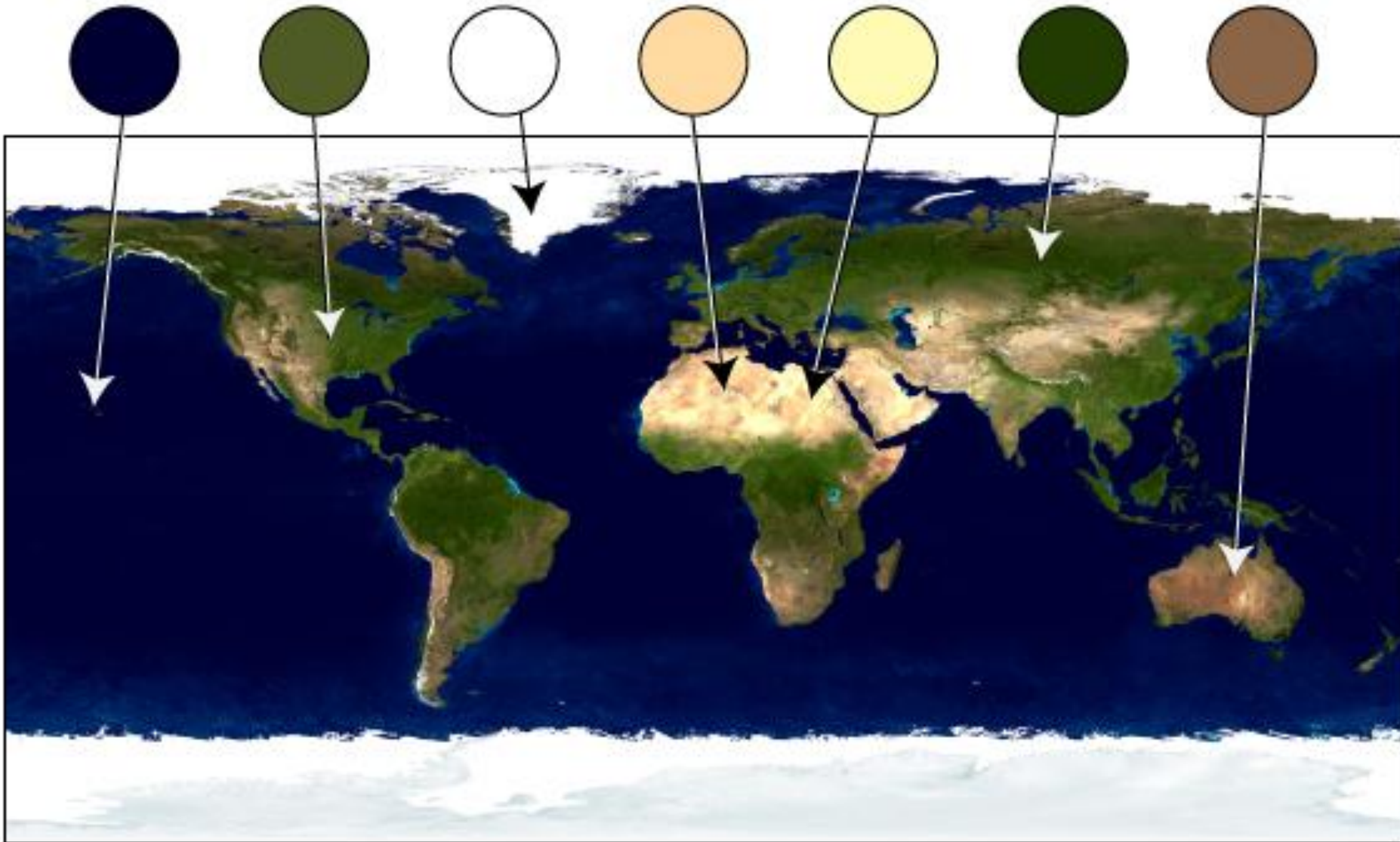
(b) Global Sea-Level Budget



# Albedo

A critical climate feedback

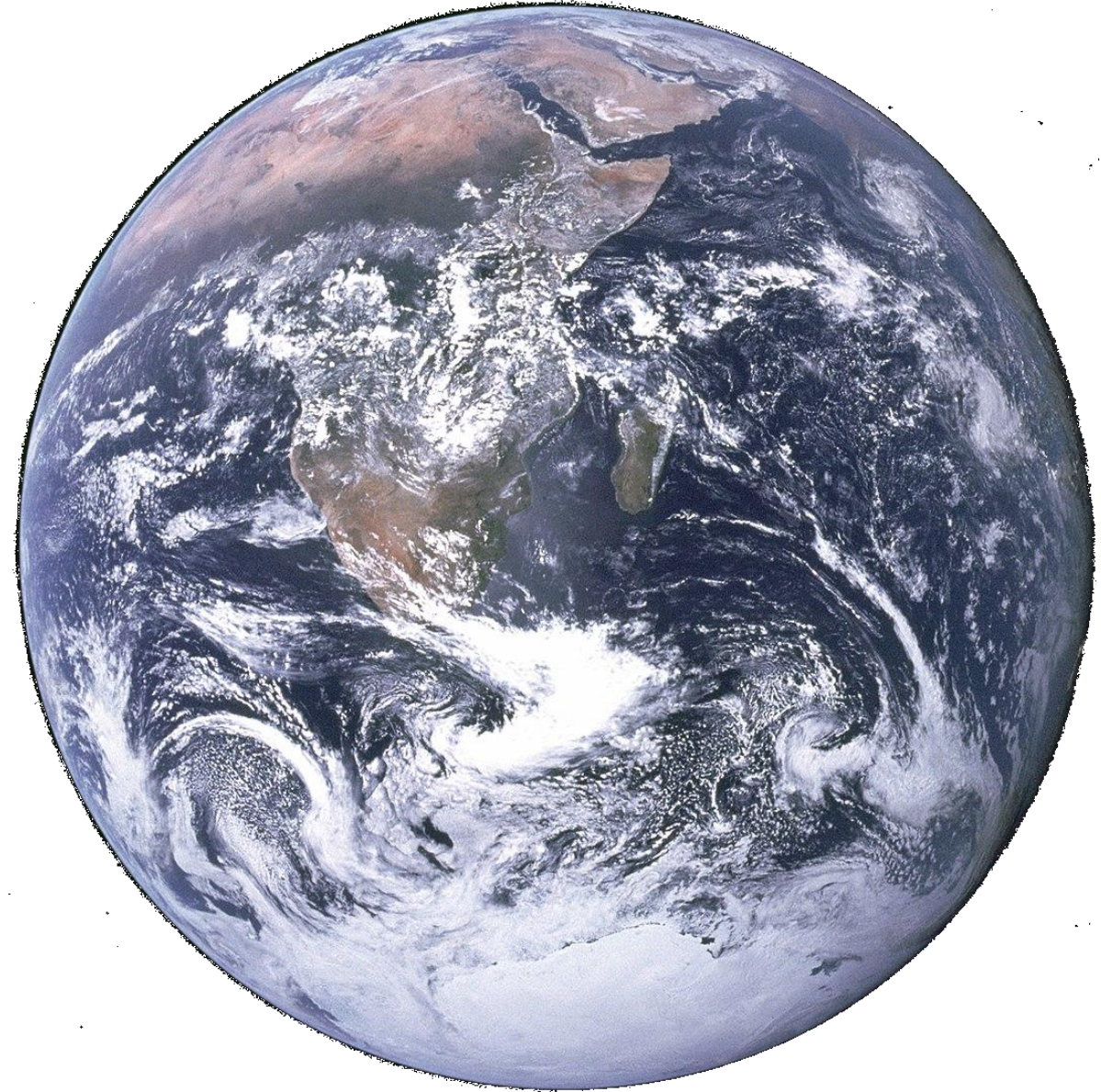
Reflectivity of a surface  
1: fully reflective  
0: complete absorption



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

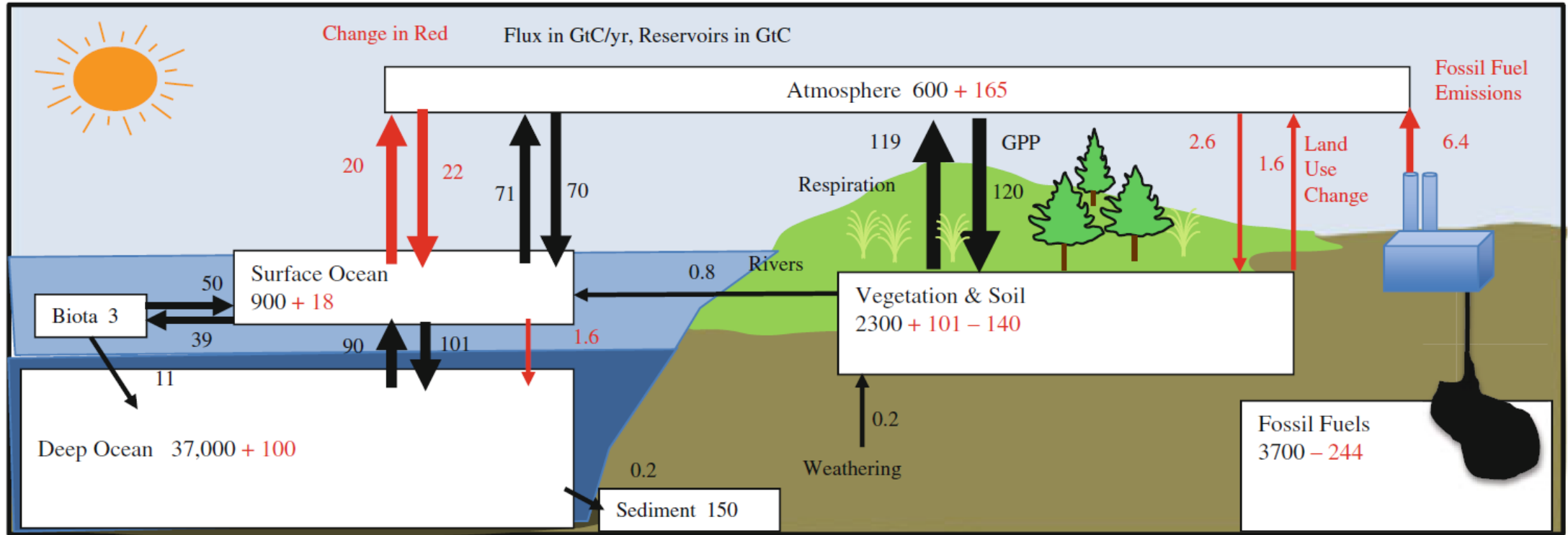
Planetary albedo, incl. atmosphere and clouds:

$$\alpha \sim 0.3$$



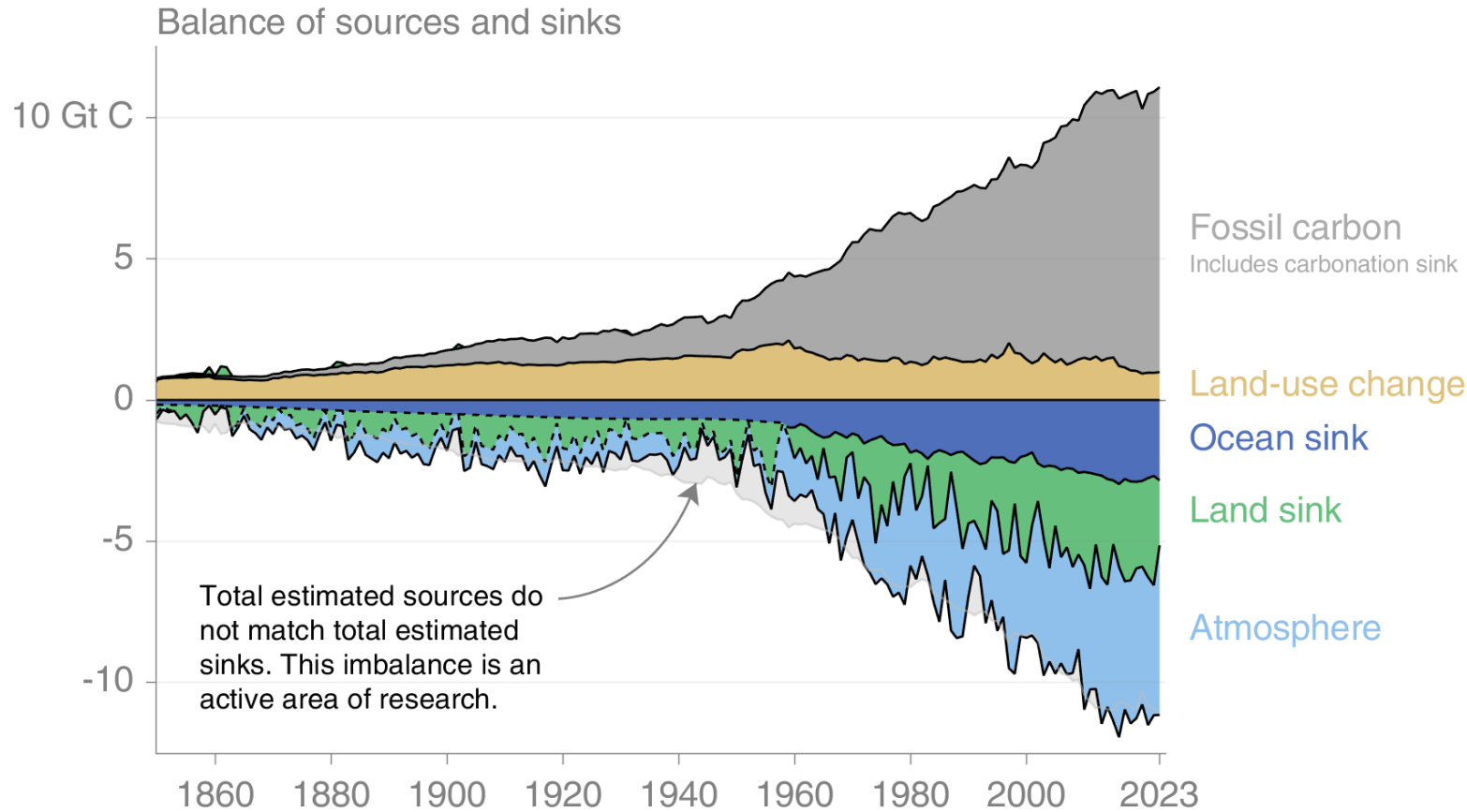


■ Narsaq, Southern Greenland 2022 (picture credit J. Schmale)



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.

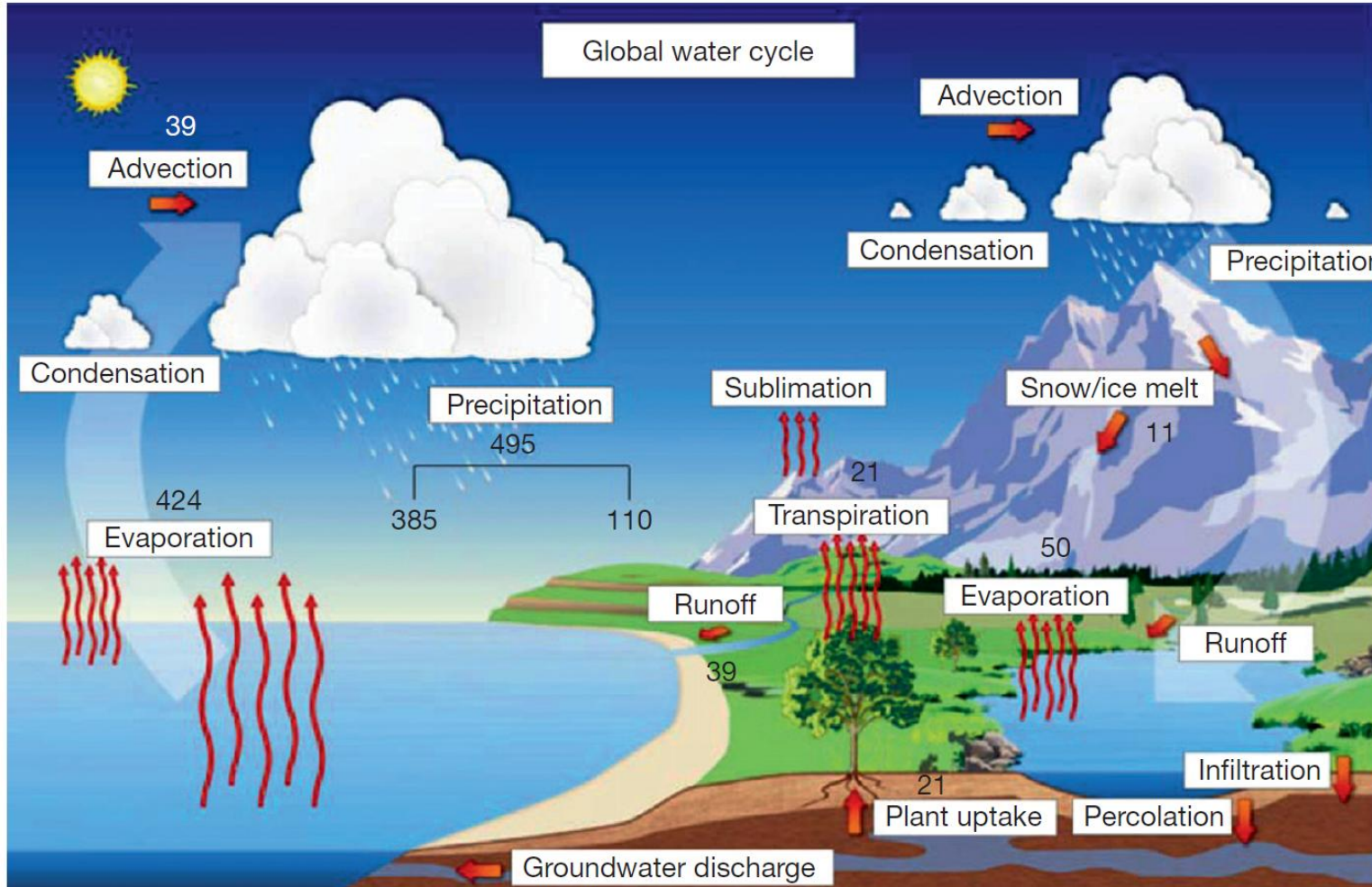
Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean  
 The “imbalance” between total emissions and total sinks is an active area of research



Warm oceans have a long legacy effect.

This is an ecosystem service.  
But for how long?

Results in quick response of Earth's temperature (global warming).



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.

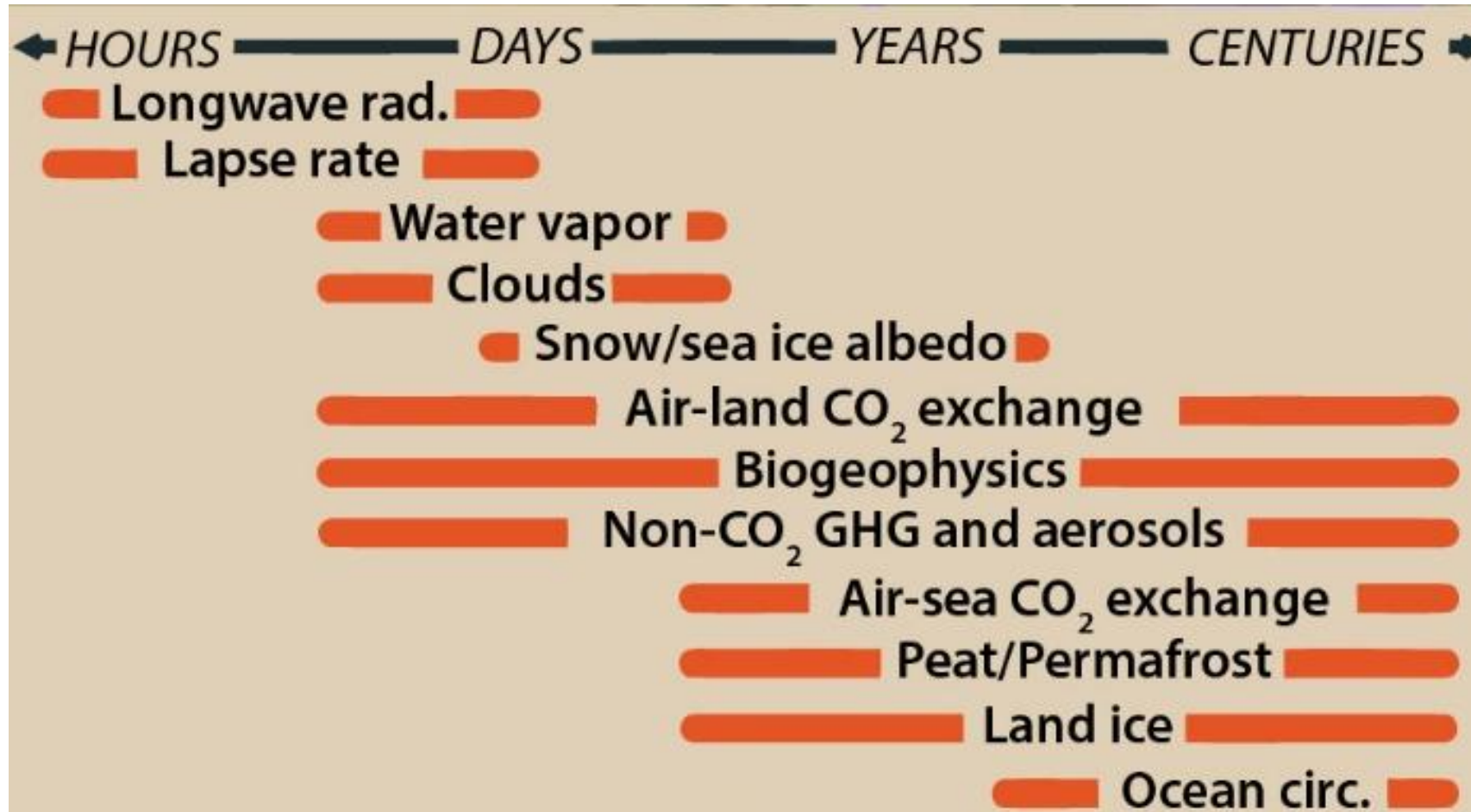
Percolation: movement of water past the soil and going deep into the groundwater.

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.**

**For each  $1^\circ\text{C}$  warming, the atmosphere can hold 7% more water vapor.**



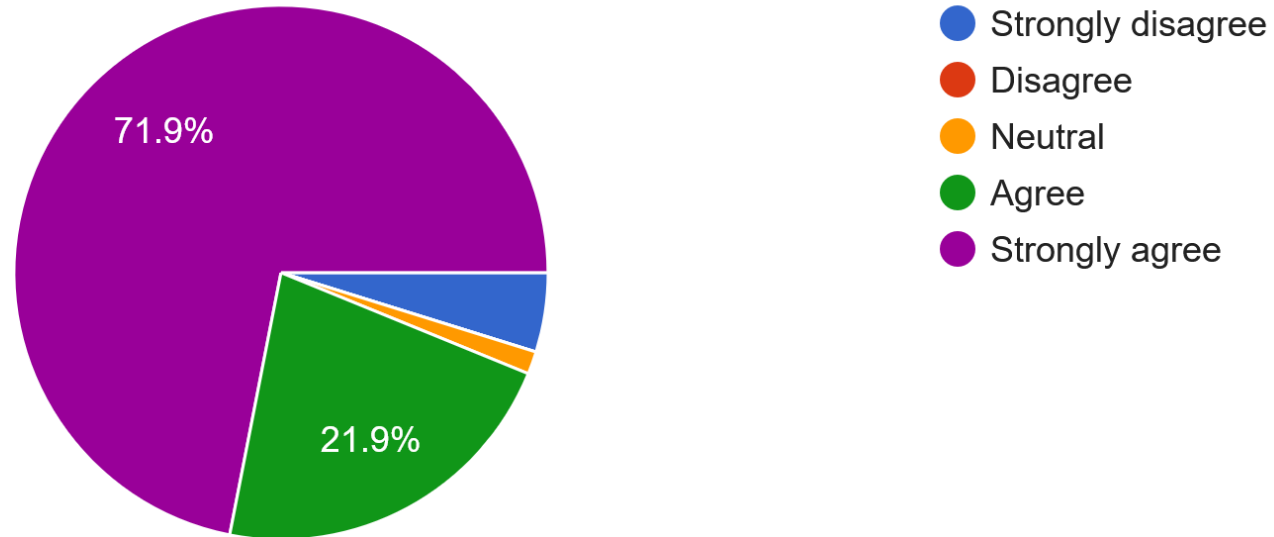
Biogeophysics: how plants, microbial activity and other organisms alter geologic materials and affect geophysical signatures

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).

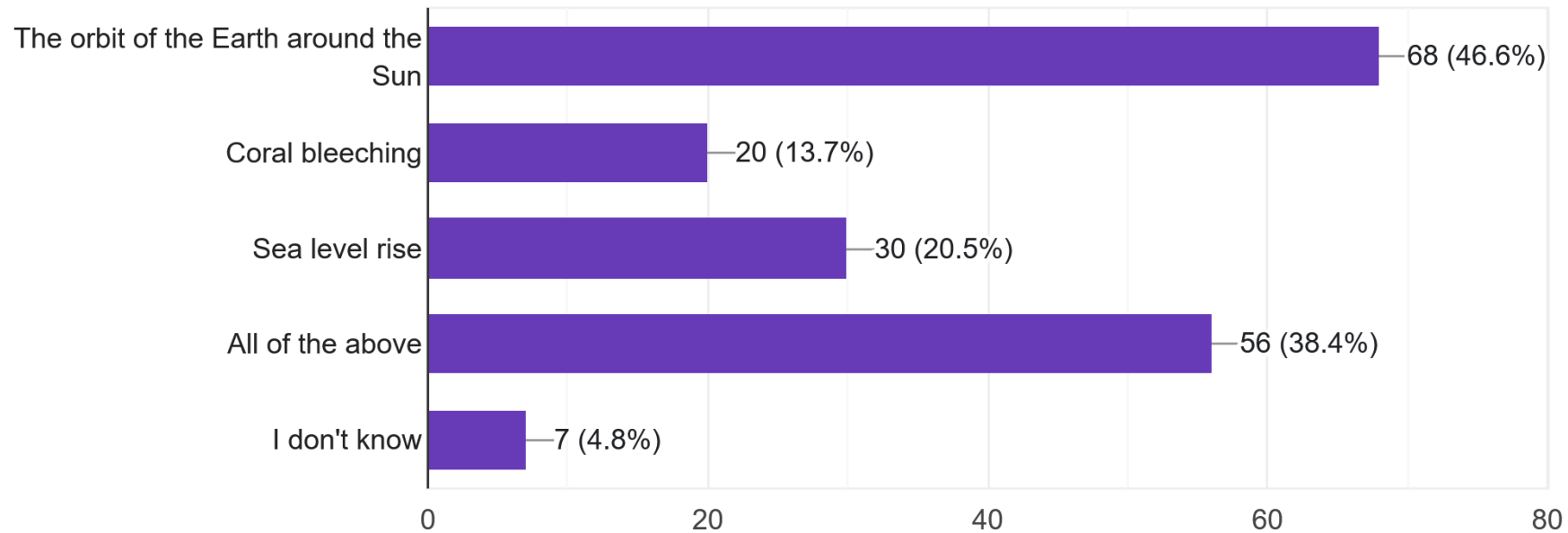
# Summary: Climate system

- 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.
-

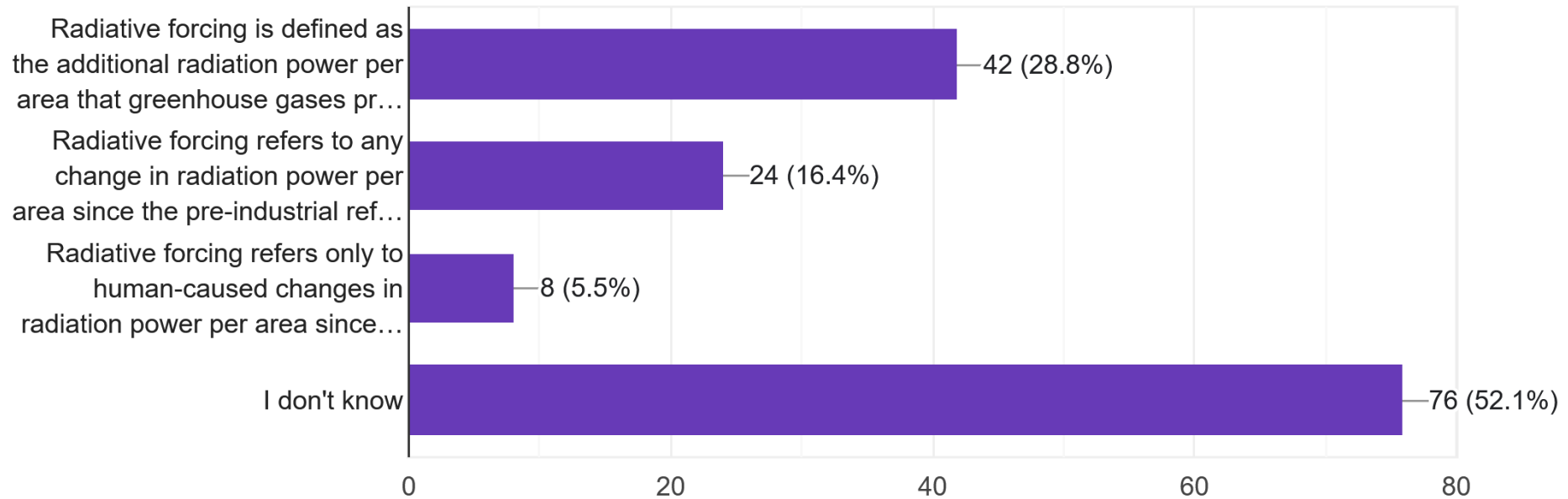
# I am very interested in learning more about climate change



# Which of these natural events have a direct climate effect?



# What is radiative forcing?



# Your topics of interest

- Thank you for all the suggestions!
  - There are about 3 pages of topics
- We will address most of them.
- If you are specifically interested in solutions and energy questions, please consider to also take the course ENV-421 'Sustainability, climate and energy'
- You can find a short summary of the survey on moodle under this week.