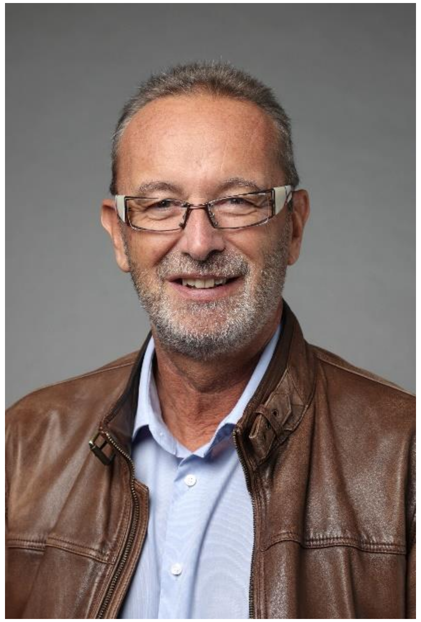
Sustainability, climate and energy

ENV-421
Jérôme Chappellaz, Jonas Schnidrig

Who are we?

In charge



Jérôme Chappellaz
Full Professor

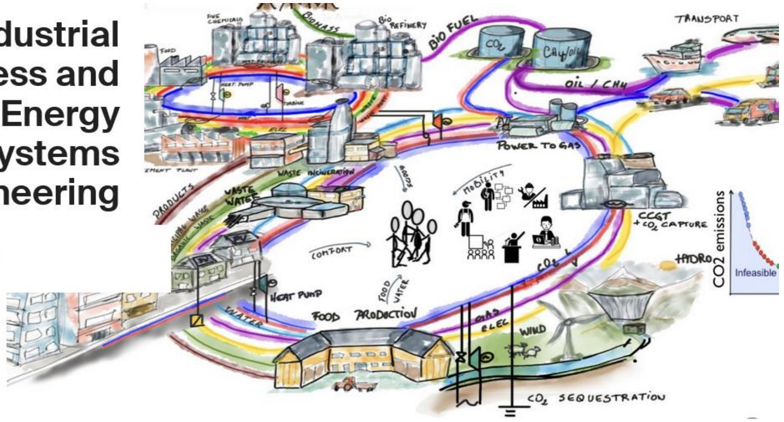
Jonas Schnidrig
Collaborator
Lecturer

Smart Environmental Sensing in Extreme Environnements – SENSE

sense.epfl.ch

Industrial Process and Energy Systems Engineering

Vision de l'IPESE



ipese.epfl.ch

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

Interactive sequences

- We will use the PointSolutions app in class for polls and short exercises.
- All answers are **anonymous**.

- Please go to: **responseware.eu**

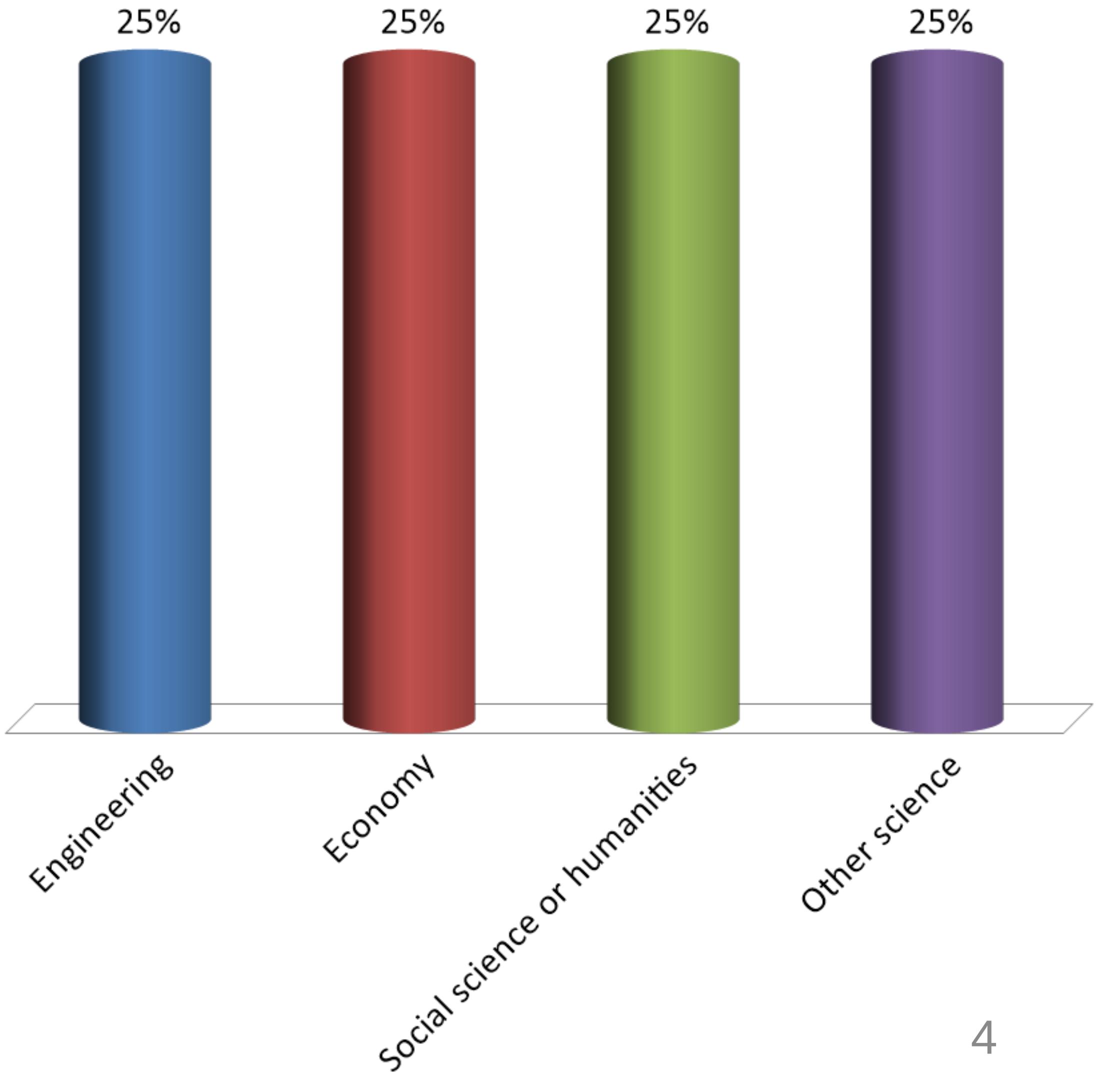
- Enter as guest, do not provide any name or contact information.
- Be aware, the data will go outside of Switzerland, but will be erased when the session is closed.

- Let’s try. Session ID is: **env421**

What is your background?

A. Engineering
B. Economy
C. Social science or humanities
D. Other science

Go to: **responseware.eu**
Login: **enter as guest**
Session-ID: **env421**

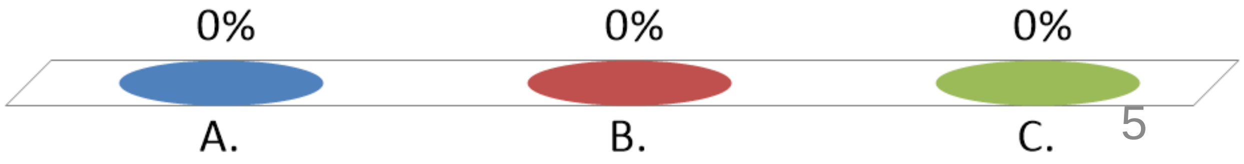


Have you studied climate change already ?

A. Not at all.

B. Previous classes addressed part of it.

C. I had specific classes on climate change science *(like ENV-410 by Julia Schmale)*.

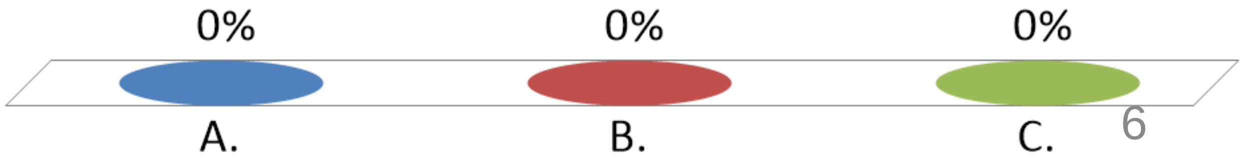


Have you studied the energy systems already ?

A. Not at all.

B. Previous classes addressed part of it.

C. I had specific classes on energy system science *(like ME-409 by François Maréchal)*.



EPFL

General outline

No.	Date	Topics	Remarks
1.	18.02.2025	Introduction to the climate system. Earth energy balance. Greenhouse gases and aerosols	
2.	25.02.2025	Introduction to energy systems. Energy balance fundamentals	
3.	04.03.2025	Radiative forcing. Feedback mechanisms. Climate sensitivity	
4.	11.03.2025	Overview of energy technologies	
5.	18.03.2025	Climate archives: geological to millennial time scales	Conf. Michael Sigl + QCM evaluation (graded)
6.	25.03.2025	Climate variability. Climate change scenarios. Carbon cycle feedbacks.	
7.	01.04.2025	Technologies' impacts	Conf. Alexis Quentin
8.	08.04.2025	Tipping points. Extreme events. Regional climate change	
9.	15.04.2025	Climate change impacts on renewable energy systems. Impact of RES on climate	J. Castella (Watted) : PowerPlay game
10.	29.04.2025	Field visit : floating solar platform + dam (Romande Energie)	
11.	06.05.2025	Intro to systemic approach on local scale climate/energy engineering	Start of group work
12.	13.05.2025	Group work on chosen case study	
13.	20.05.2025	Group work on chosen case study	
14.	27.05.2025	Presentation of group reports	Reports are graded

Basics (1.–9.)

Applications (10.–14.)

Exam session between 16.06.2025 and 05.07.2025

Additional information

- Lectures give you the general introduction to the topic
- Exercises will discuss specific content more in detail and partly quantitatively
- Group work: you will be assigned to groups of 5 (we will use Moodle)
- Grading :
  - Exercises in Week 5 : 20 %
  - Group project: 30 %
  - Final written exam: 50 %

- Online discussion forum Ed Discussions

Groups

- Groups of 5 students
- Rule:
  - 2 students per group who already followed ENV-410
- You organize yourselves
- A spreadsheet will be made available on Moodle.

ENV-421 learning outcomes

- Discuss the concepts of climate variability at different time scales and climate sensitivity
- Draw the energy balances of an energy conversion system
- Describe the climate limitations to energy conversion scenarios
- Interpret climate data and model outputs

Lectures will provide the concepts.
Exercises will help you deepen your knowledge and apply it.

ENV-421 transversal skills

- Plan and carry out activities in a way which makes optimal use of available time and other resources.
  ➔ Plan according to exams and report

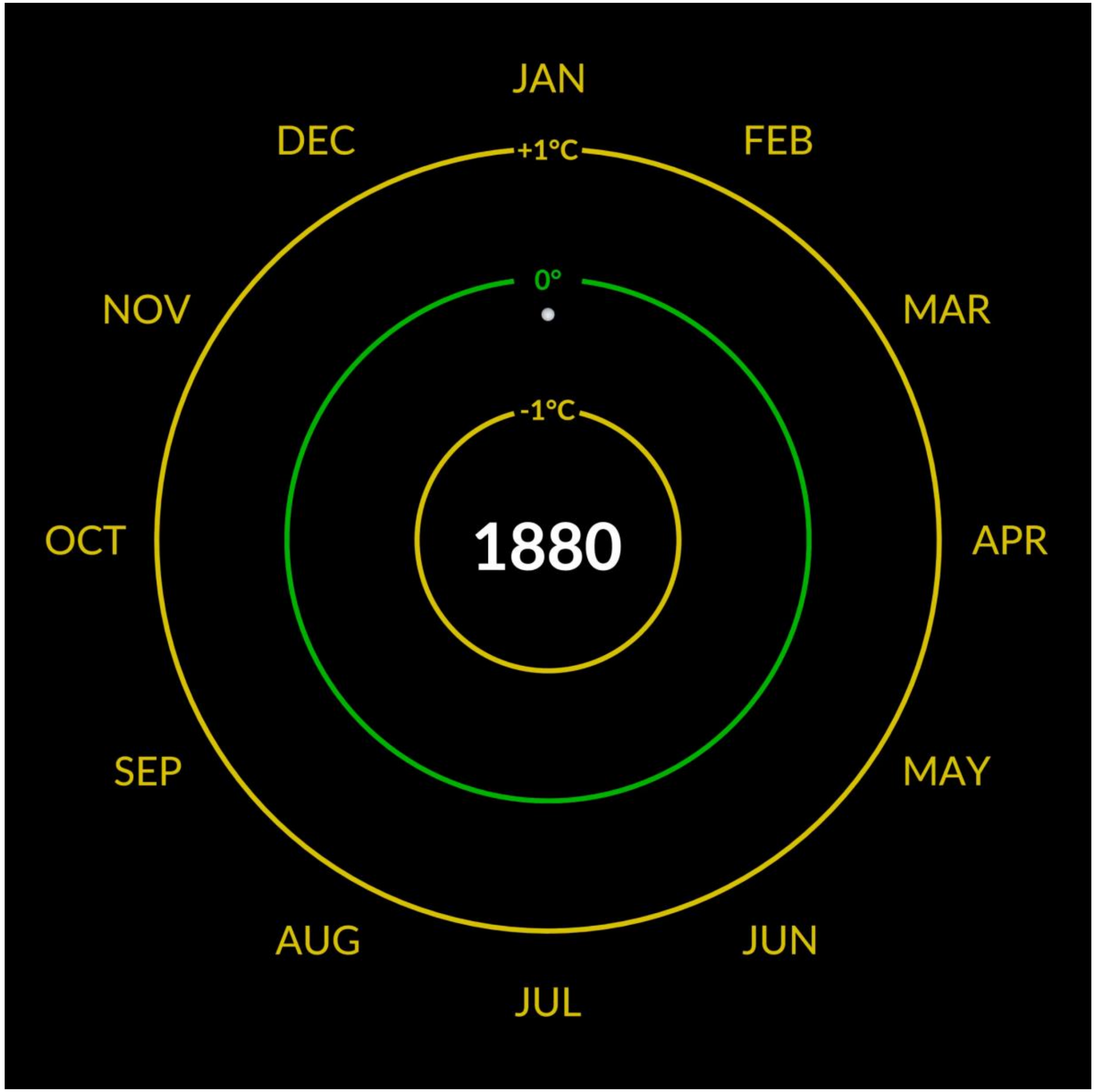
- Communicate effectively with professionals from other disciplines.
  ➔ Different background in groups + seminars + field visit

- Summarize an article or a technical report.
  ➔ specific exercises

- Access and evaluate appropriate sources of information.
  ➔ specific exercises

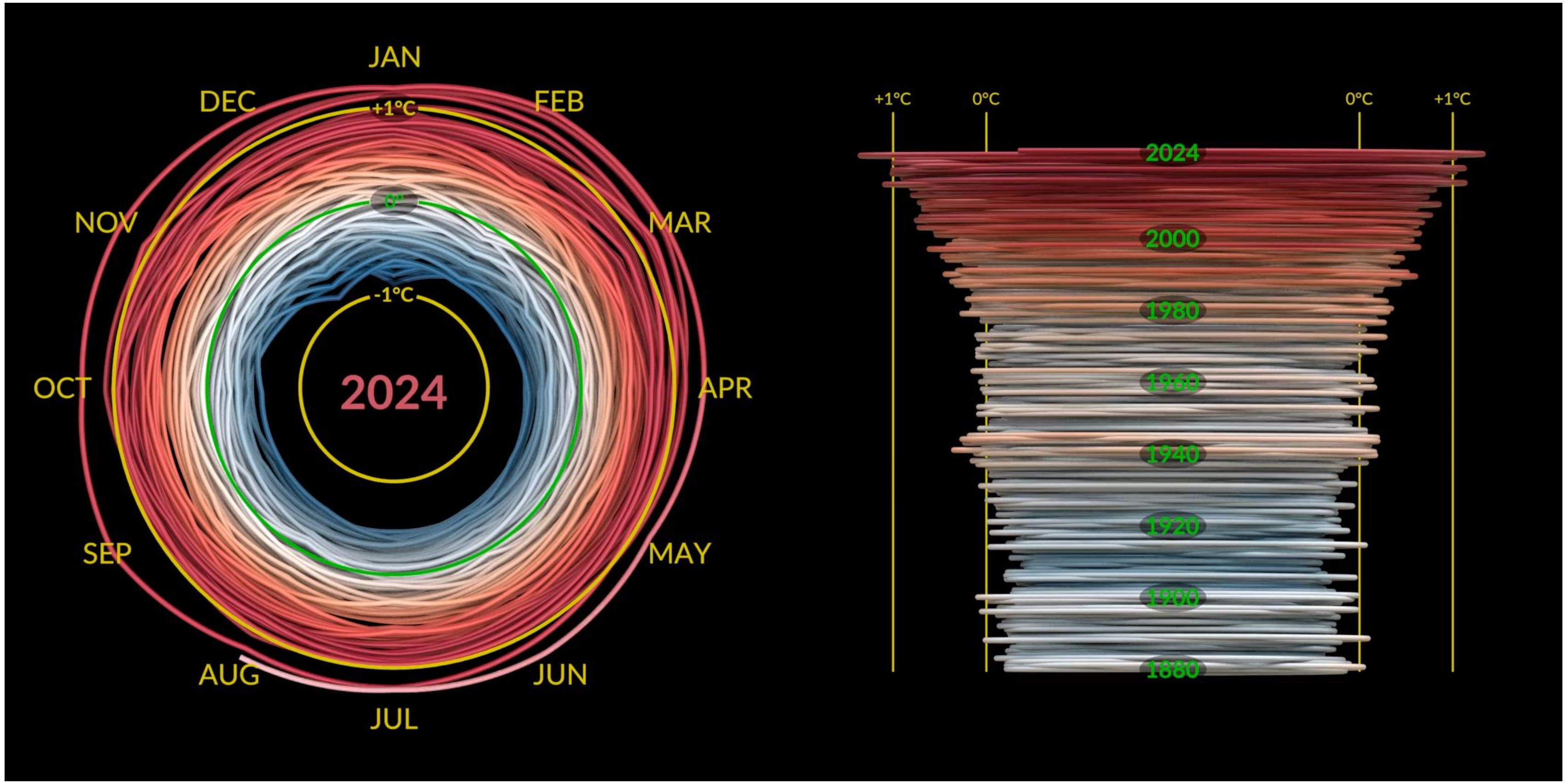
Questions?

Why should we matter about climate and energy together ?



Source : NASA scientific visualization studio
https://svs.gsfc.nasa.gov/5190/

Why should we matter about climate and energy together ?



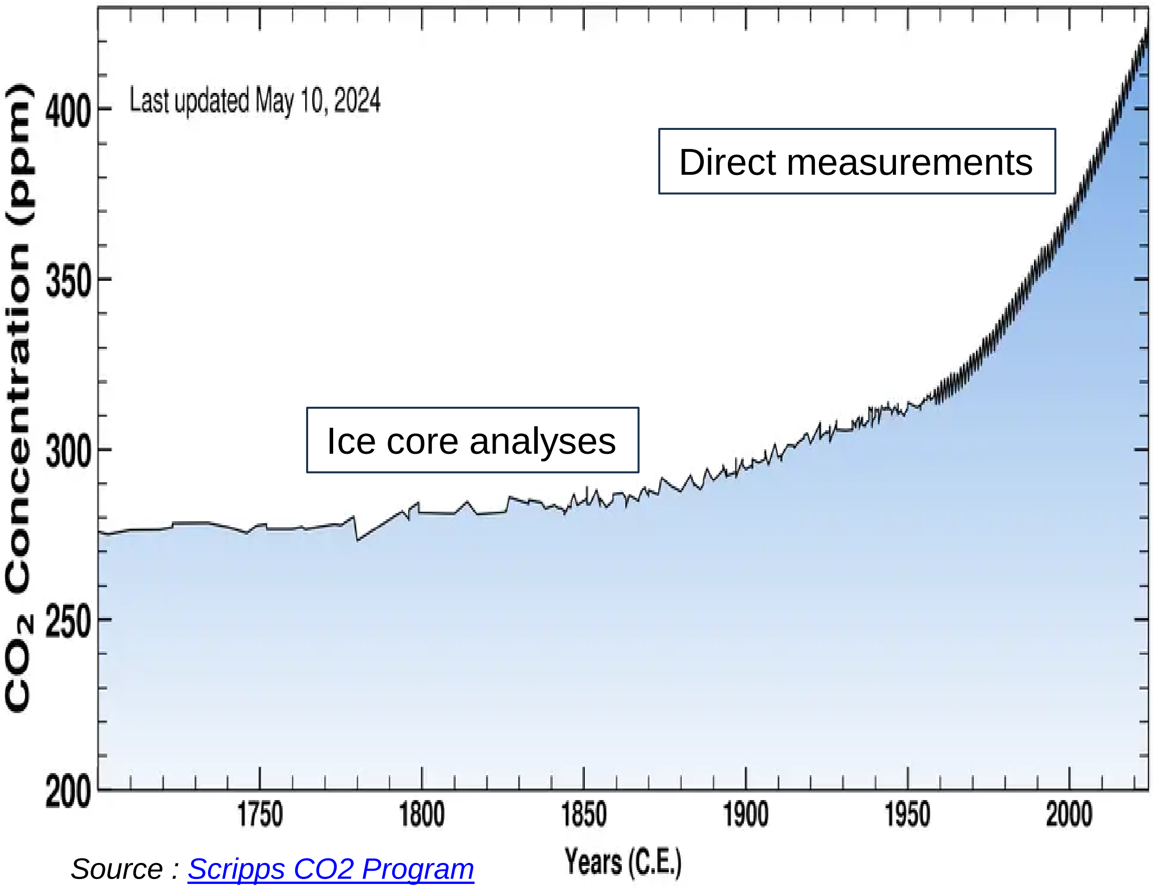
- Monthly global temperature anomalies from January 1880 to August 2024.
- Deviations from the period 1951-1980 (set to 0°C as a reference).
  - ➢ Acceleration of the warming at the turn of the 1980s.
  - ➢ Last two decades: warmest on record.
  - ➢ 2024: warmest year on record ; +1.6°C above the 1850-1900 mean.

Source : NASA scientific visualization studio
https://svs.gsfc.nasa.gov/5190/

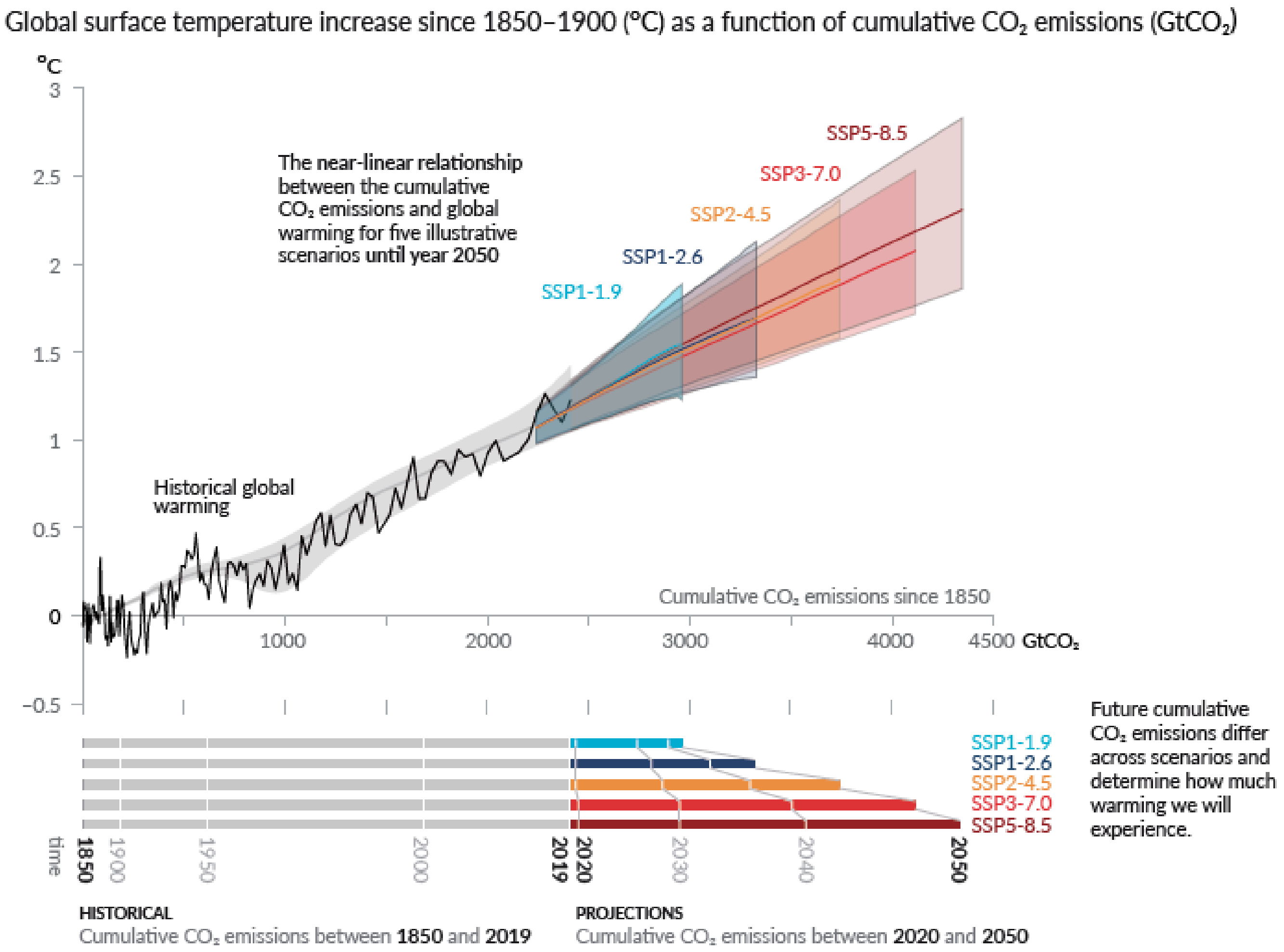
Why should we matter about climate and energy together ?

Atmospheric CO_2 mixing ratio:

- 1800 : ~280 parts per million
- End of 2024: 425 parts per million (+50%)



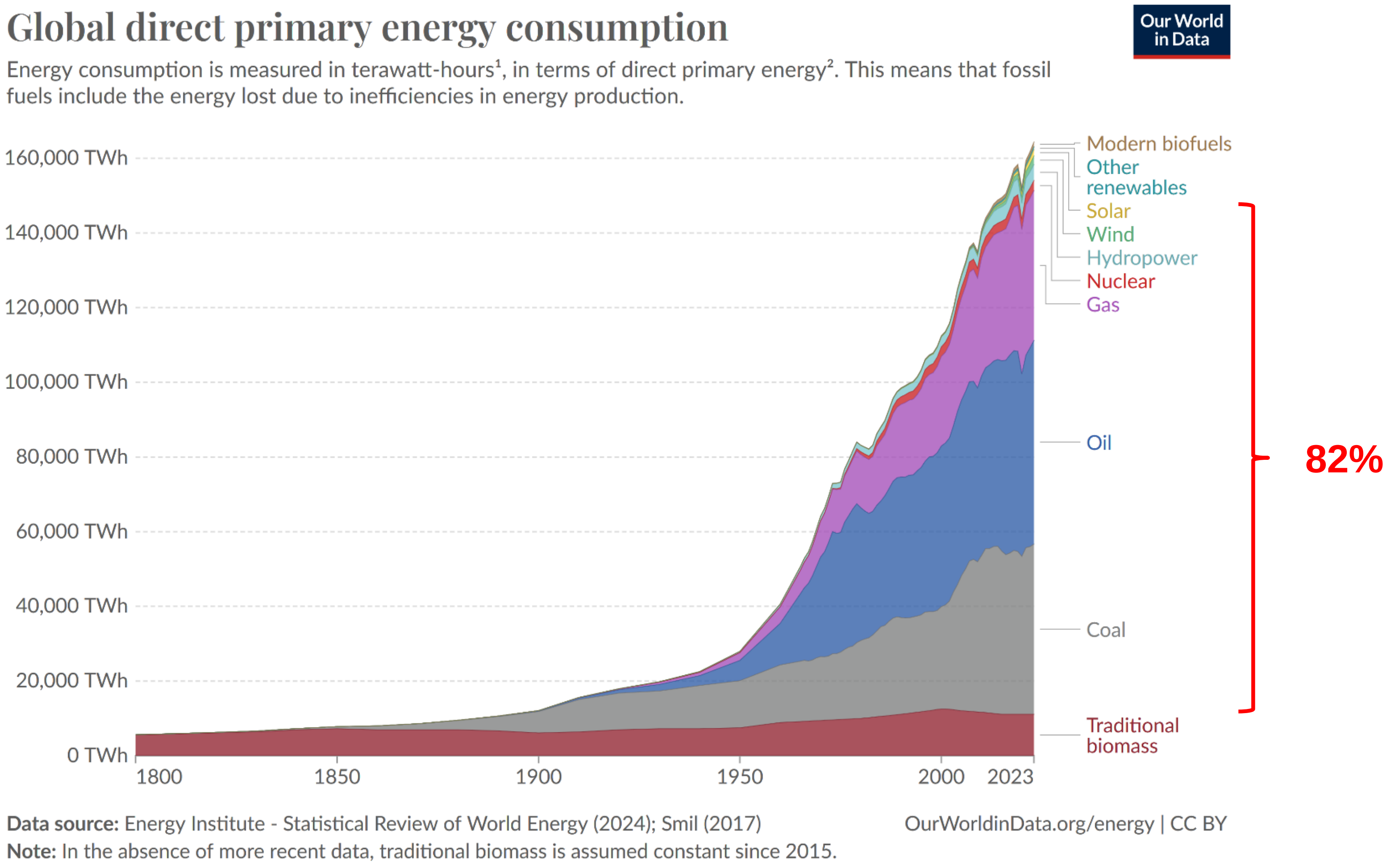
Source : [Scripps CO2 Program]



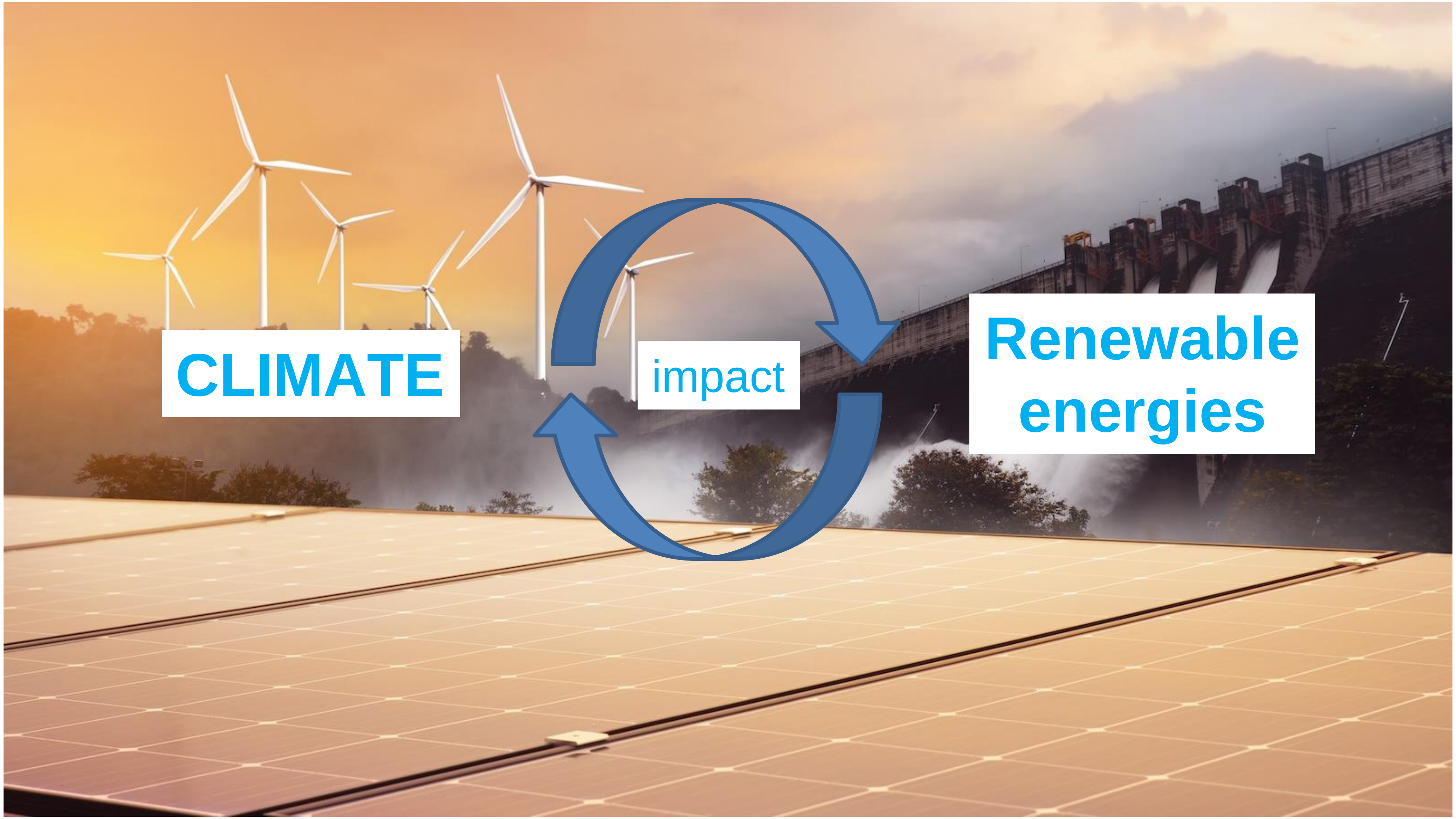
Linear relation between cumulative CO_2 and temperature increase

Why should we matter about climate and energy together ?

Most of the extra CO_2 comes from burning fossil fuels = energy



Why should we matter about climate and energy together ?

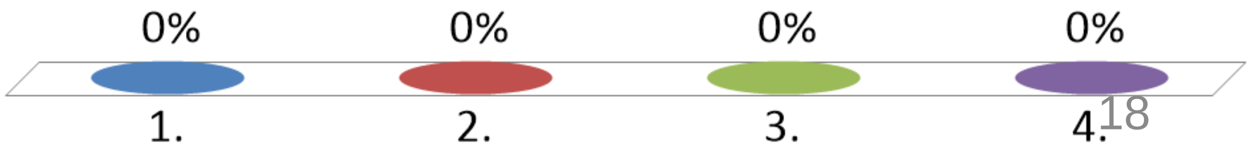


Source : bombermoon / Getty Images

Quiz : what is the average annual carbon footprint of a Swiss citizen ?

In CO_2 equivalent (including all greenhouse gases)

A. 2 tons
B. 8 tons
C. 13 tons
D. 21 tons



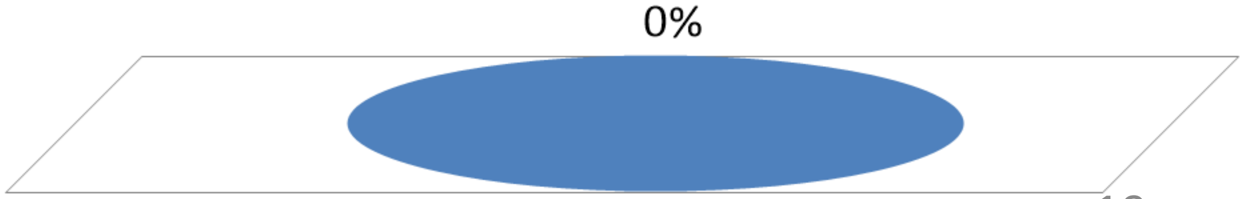
Quiz : how much Swiss glacier mass is lost depending on your travel mean ?

Paris to Geneva <u>by air</u>

- 500 km
- CO_2 emission per km and per individual :
  * 300 g *(short-haul flightt)*
- 1 kg of extra CO_2 melts 15 kg of glacier ice

  (source: [Marzeion et al., Nature, 2018]())

** 120 g by car*
** 2 g by train*



Quizz : how much Swiss glacier mass is lost depending on your travel mean ?

Paris to Geneva by air: ~2 tons of ice melted

«Ice Watch» exhibition in Paris during COP 21 in 2015

Photo : Eric Feferberg / AFP

The climate system

Definition of «climate» and «climate change»

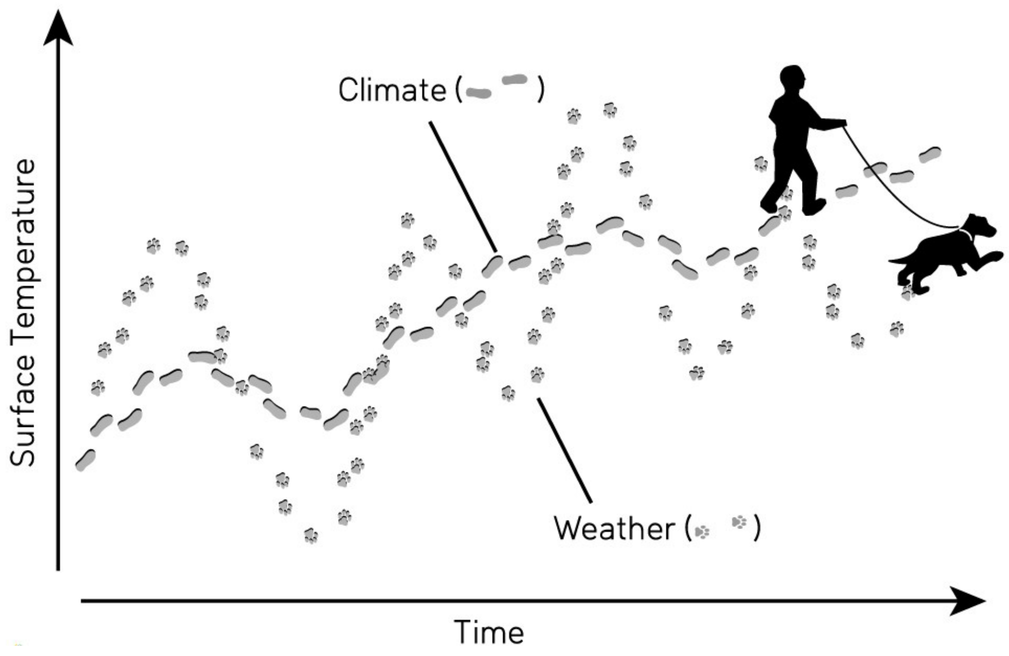
- **Climate** is the **average weather** in a given area over a long period of time.

  Definition by the World Meteorological Organization (WMO) :

  30 years.

- **Climate change** is any **systematic change in the long-term statistics** of climate variables such as temperature and precipitation, sustained over several decades or longer.

- It can be generated by:
  - Natural forcings (changes in solar radiation or changes in the Earth's orbit, plate tectonics,natural internal processes of the climate system).
  - Anthropogenic forcing.



Source: *RealClimate «The dog is the weather», 2012*

- https://www.climateurope.eu/what-is-climate-and-climate-change/

The climate system: five «spheres» ...+1

All marine and terrestrial ecosystems and living organisms, including dead organic matter (litter, soil organic matter, marine detritus).

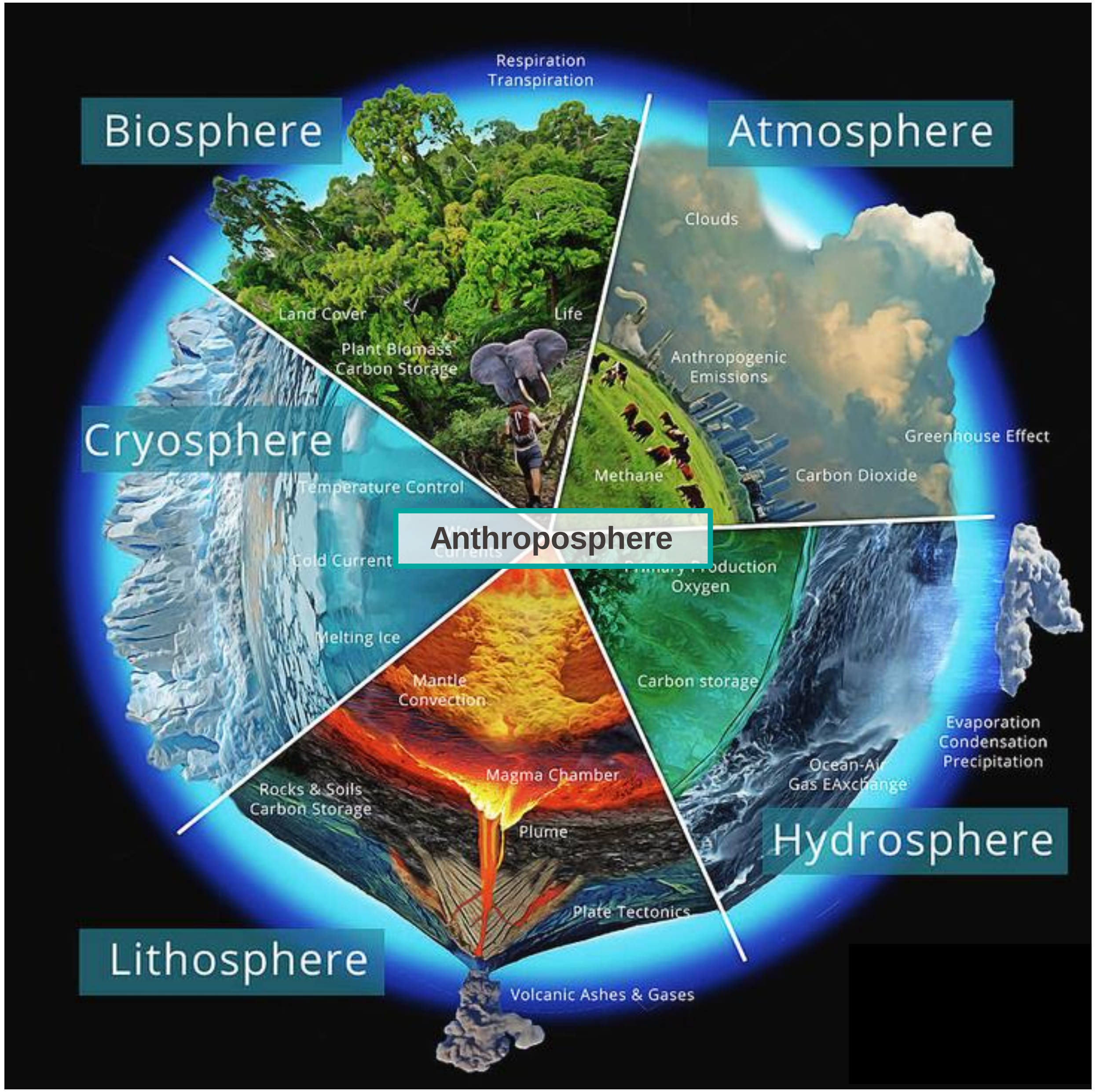
Carbon

Water in solid form: sea ice, lake ice, river ice, snow cover, glaciers, ice sheets, frozen ground (including permafrost).

Albedo

The upper layer of the solid Earth : crustal rocks and the cold and mainly elastic part of the uppermost mantle.

Volcanism



The gaseous envelope surrounding the Earth.

Energy balance

Anthroposphere : human activities having significantly affected Earth's biogeochemistry and climate.

Forcing

Water in liquid form: oceans, seas, rivers, lakes, underground water.

Water cycle

Source: Karsten Scheider / Science Photo Library

Atmosphere

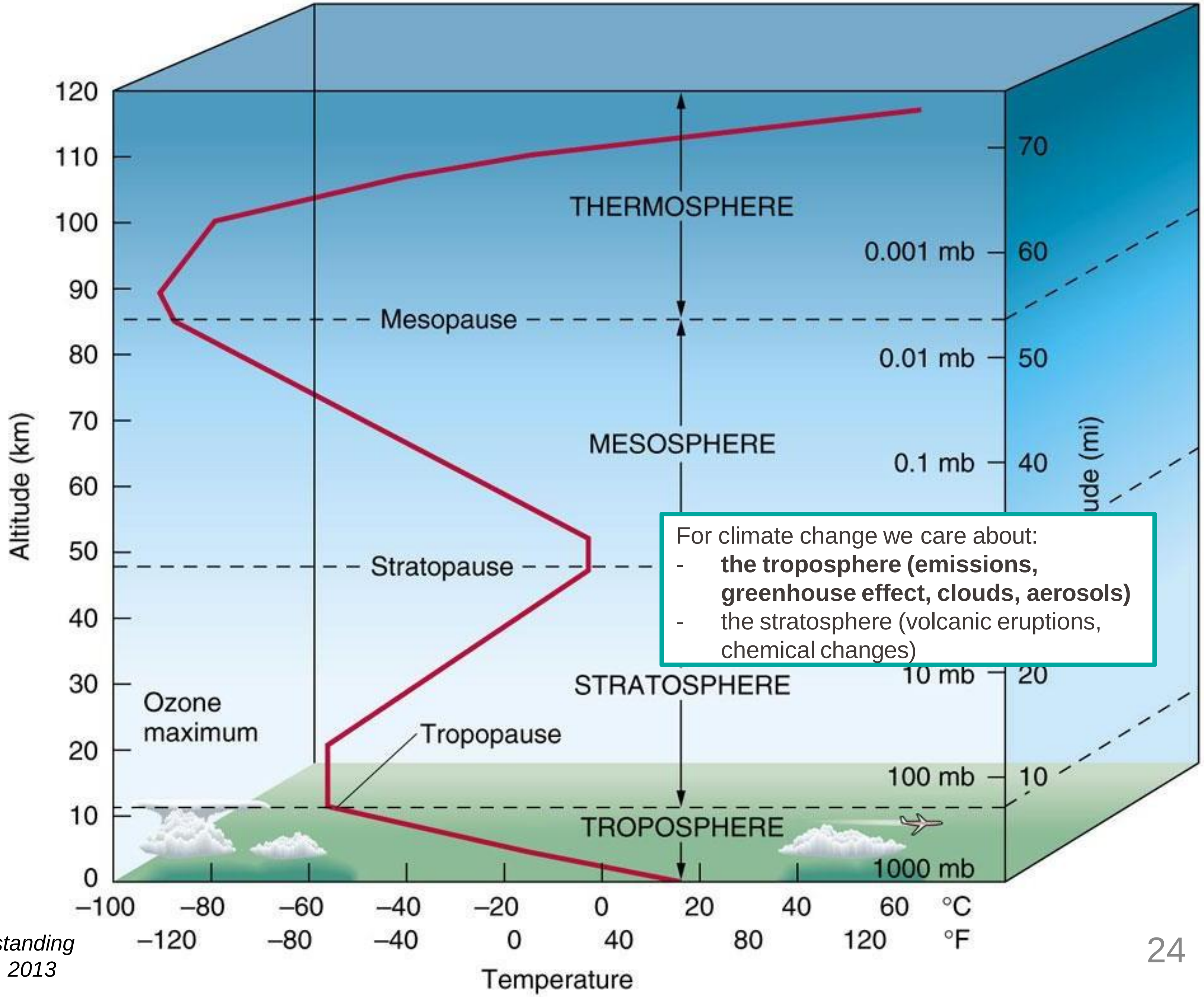
Four layers structuring it based on the vertical temperature profile:

- *Troposphere*: sun warms the surface, because atmosphere is mostly transparent to visible solar radiation, warm and moist air rises, **cools with altitude** and forms clouds, average **lapse rate** of -6.5 °C km^{-1}.

- *Stratosphere*: dry and ozone-rich (critical for life on Earth); ozone absorbs UV radiation; air **warms with altitude** (inversion).

- *Mesosphere*: lack of heat source (high energetic radiation absorbed above); **cools with altitude**.

- *Thermosphere*: **warms with altitude** due to absorption of solar radiation (X-rays, extreme UV) and photodissociation of nitrogen and oxygen molecules.



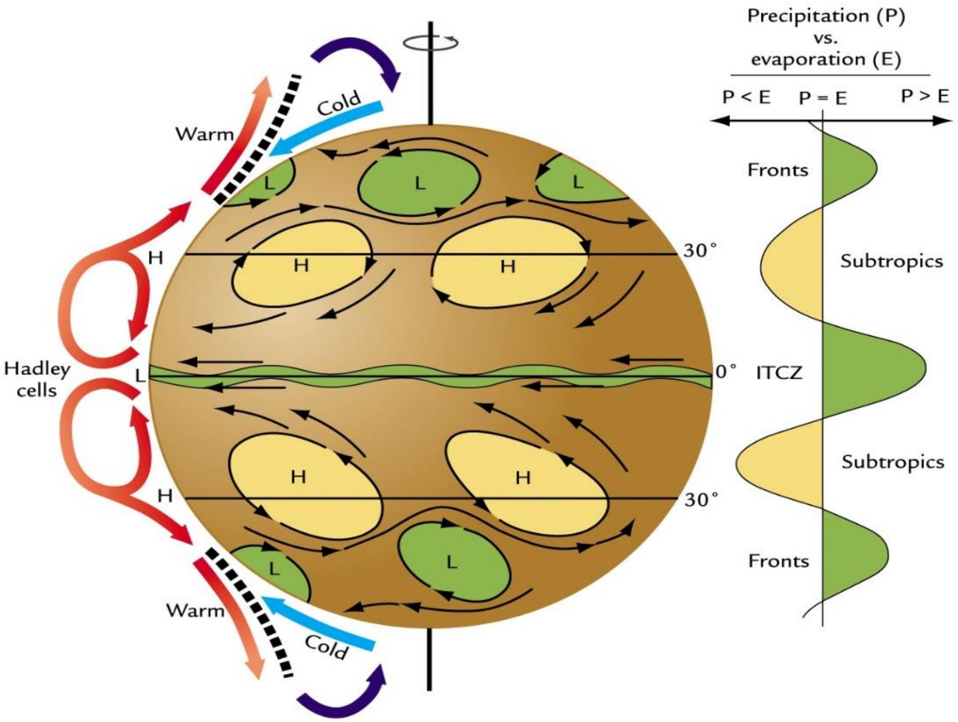
For climate change we care about:
- **the troposphere (emissions, greenhouse effect, clouds, aerosols)**
- the stratosphere (volcanic eruptions, chemical changes)

Source: Aguado and Burt, Understanding Weather and Climate, 6th Edition, 2013

Atmosphere

- The atmosphere is very dynamic at time scales of hours to weeks
- Convection in equatorial regions
- Dry in subtropical regions
- Gyres in mid and high latitudes
- Westerlies in mid-latitudes
- Polar fronts at high latitudes

Thermal infrared image of the Earth
From Meteosat ESA satellite

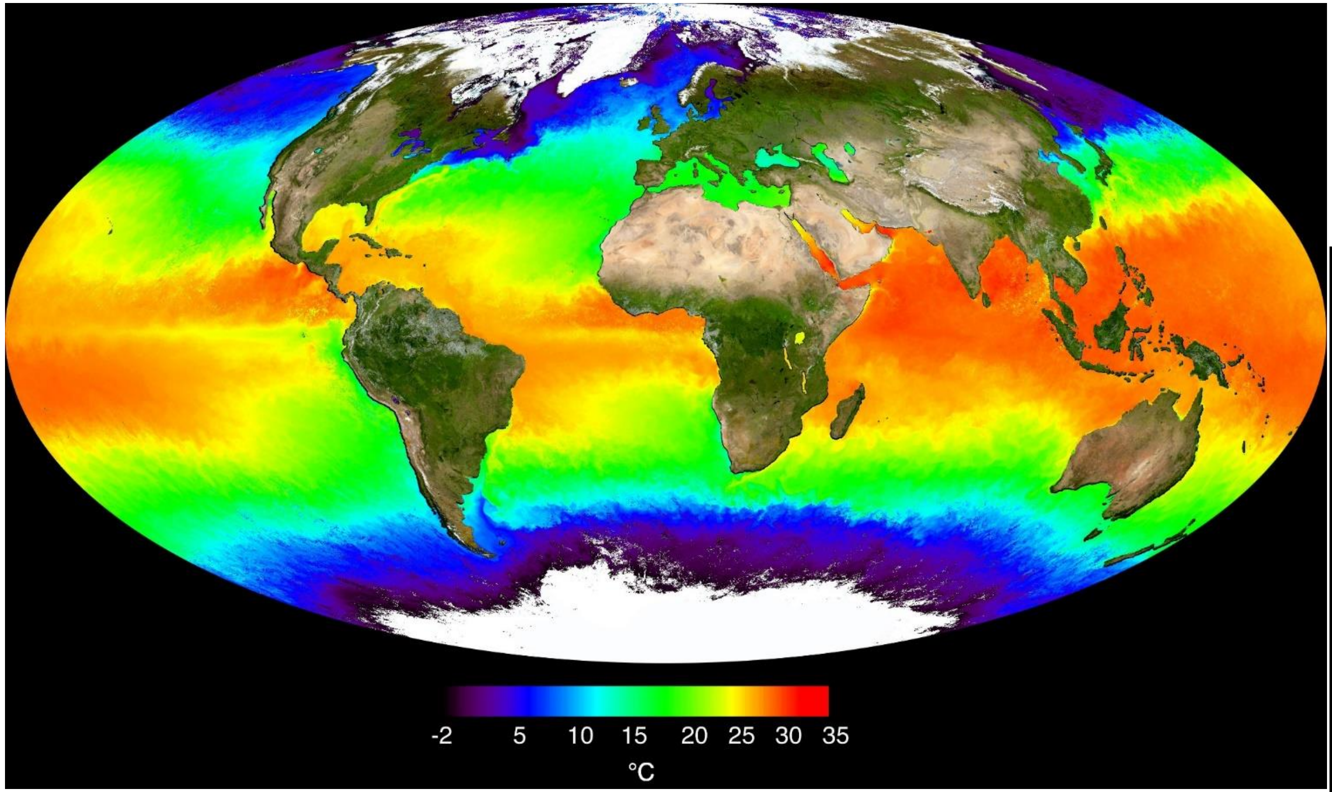


Source: W. Ruddiman, Earth's Climate: Past and Future, 2nd edition, 2007

Oceans (a major part of hydrosphere)

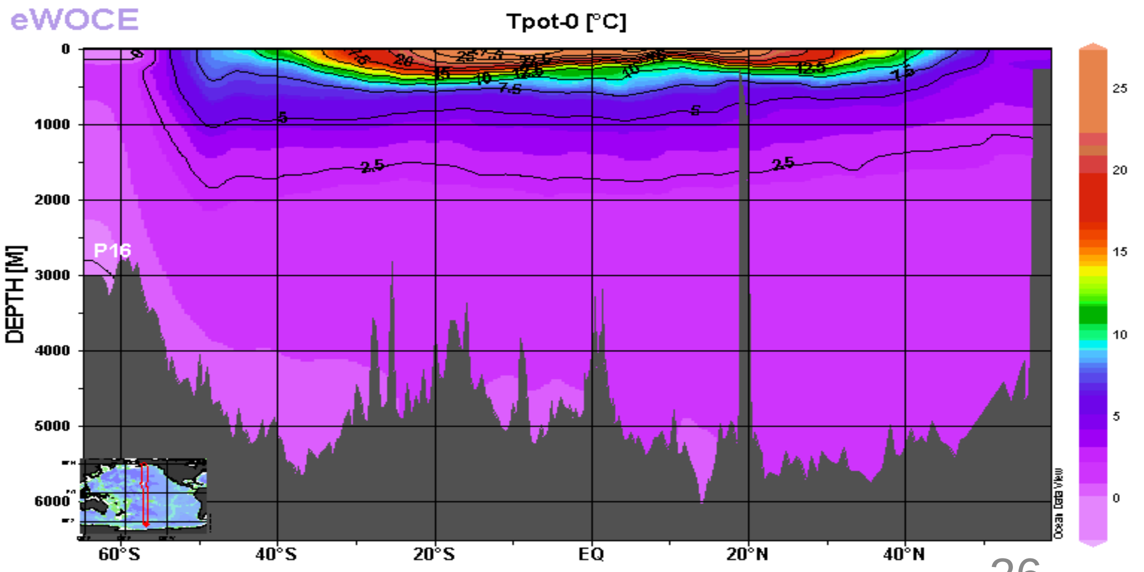
- 70 % of Earth surface. Mean depth of 3800 m
- 50 % of energy transport in tropics and subtropics
- 300 times the mass of the atmosphere ⇒ **Huge reservoir of heat/cold**
- They move because of wind, Earth rotation and density differences
- Heated from top

Ocean mean surface temperature (°C) *(composite for May 2001)*



Source: [MODIS data, NASA / GSFC]()

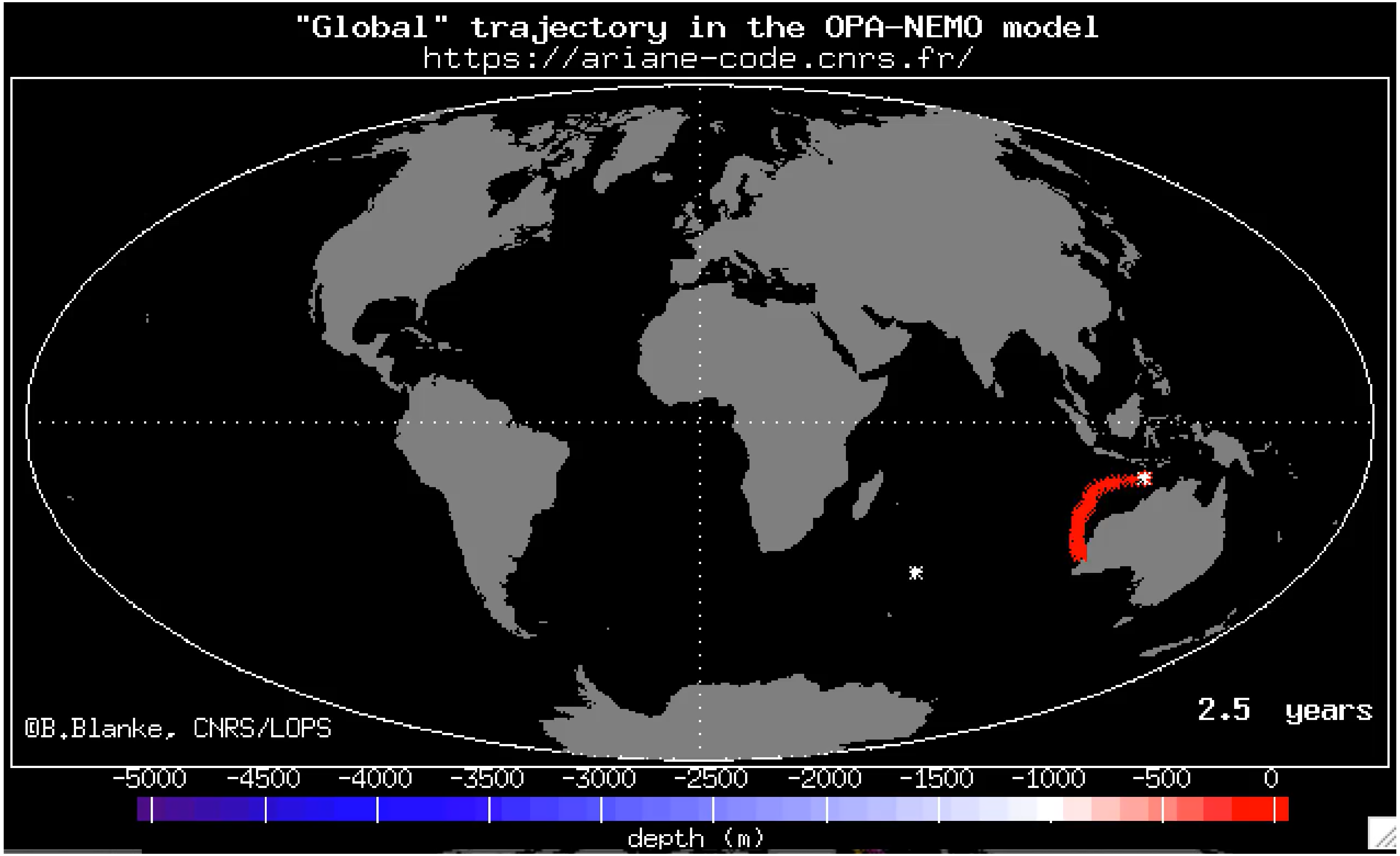
Pacific ocean temperature profile (°C)



Source: [WOCE Atlas, Pacific ocean, P16 section]()

Ocean circulation

Source : https://ariane-code.cnrs.fr/



Ariane OPA-NEMO model simulation of the displacement of a numerical water parcel

What is the main driver of deep ocean circulation ?

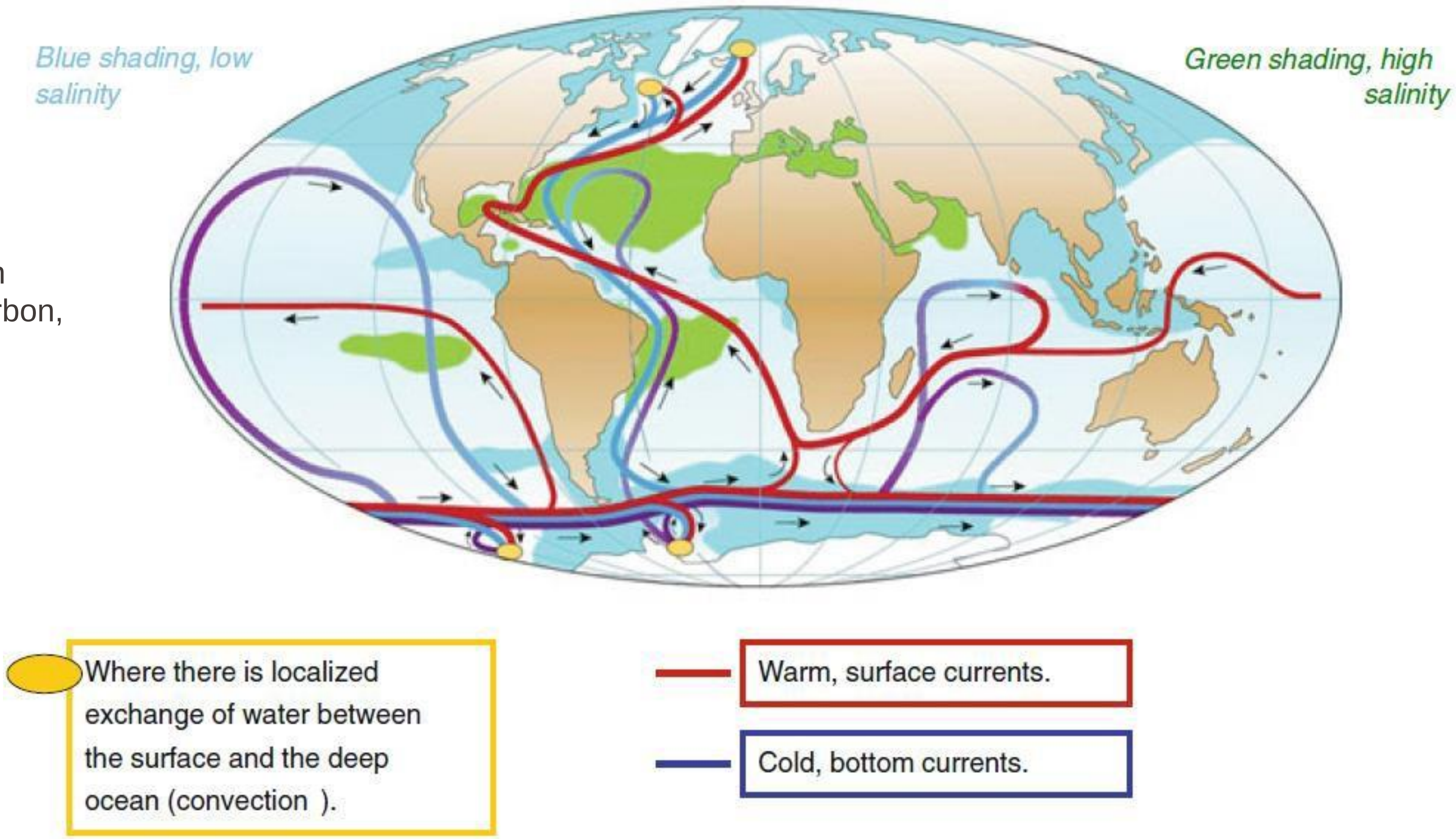
A. Atmospheric winds at surface
B. Gradients of solar radiation
C. Water density differences
D. The Coriolis effect
E. Volcanic activity at mid-ocean ridges
F. I don’t know

Global Ocean Circulation (thermohaline circulation)

The thermohaline circulation (thermo = heat, haline = salt) in oceans **redistributes** heat, carbon, oxygen and salinity

It impacts marine ecosystems, regional climate and weather

Source: IPCC, AR6, Box 2.2

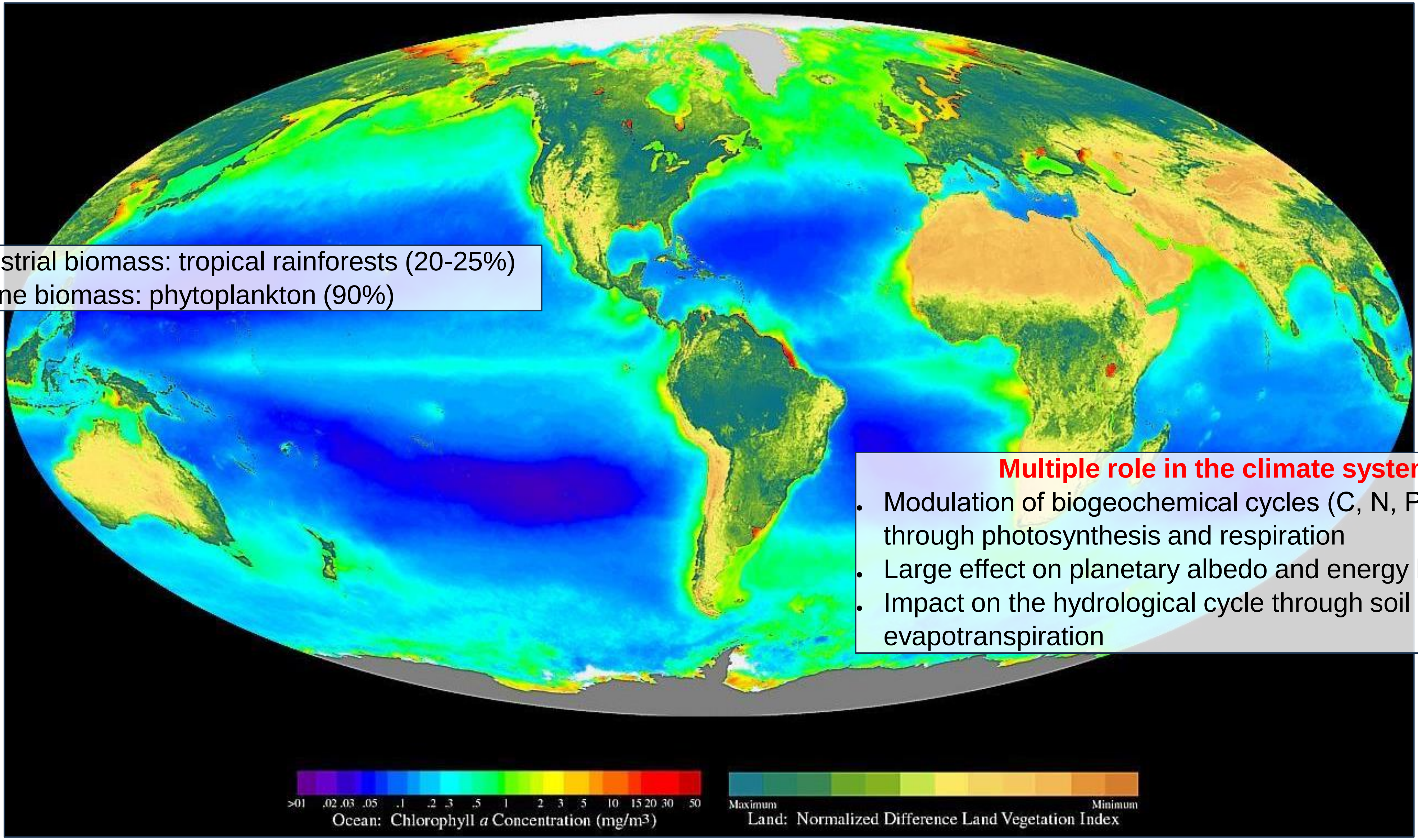


Deep water forms in the North Atlantic and near Antarctica and flows throughout the ocean basins.

Source: Demystifying Climate Models Fig. 6.3

Biosphere (terrestrial and marine)

- Largest terrestrial biomass: tropical rainforests (20-25%)
- Largest marine biomass: phytoplankton (90%)

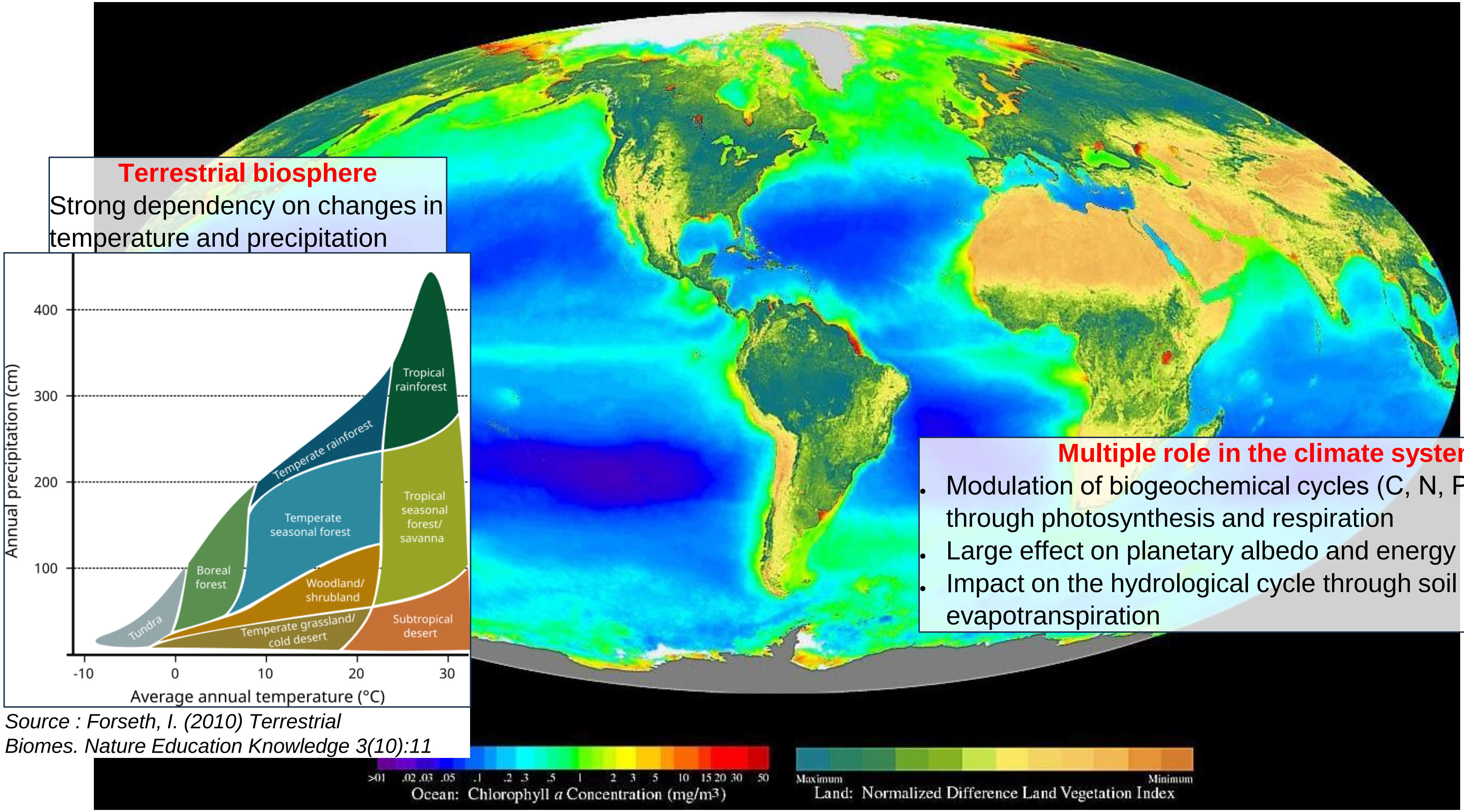


Multiple role in the climate system

- Modulation of biogeochemical cycles (C, N, P, S, O,…) through photosynthesis and respiration
- Large effect on planetary albedo and energy balance
- Impact on the hydrological cycle through soil moisture and evapotranspiration

Source : SeaWiFS Project, Goddard Space Flight Center and ORBIMAGE

Biosphere (terrestrial and marine)



Terrestrial biosphere

Strong dependency on changes in temperature and precipitation

Source : Forseth, I. (2010) Terrestrial Biomes. Nature Education Knowledge 3(10):11

Multiple role in the climate system

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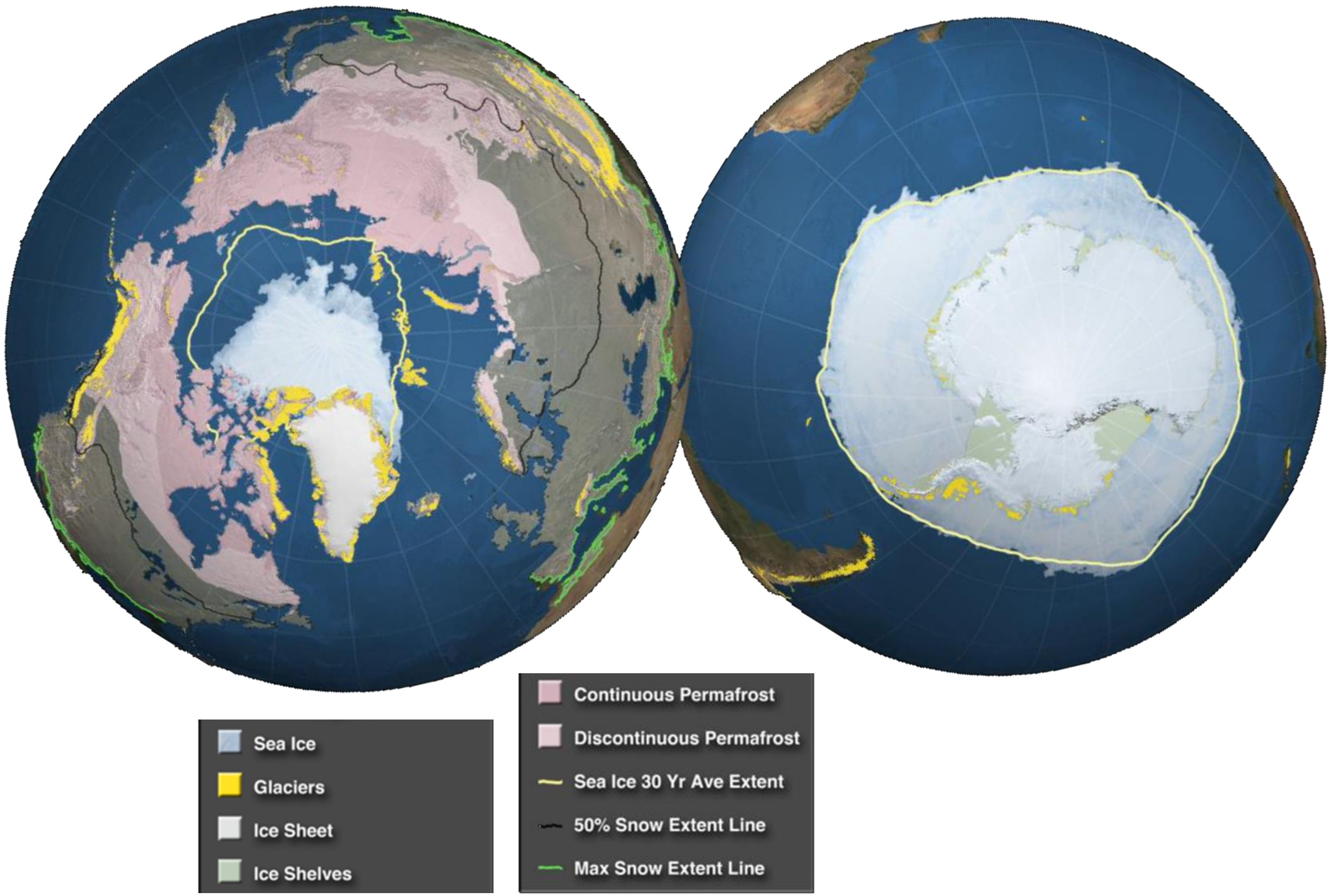
Cryosphere (terrestrial and marine)



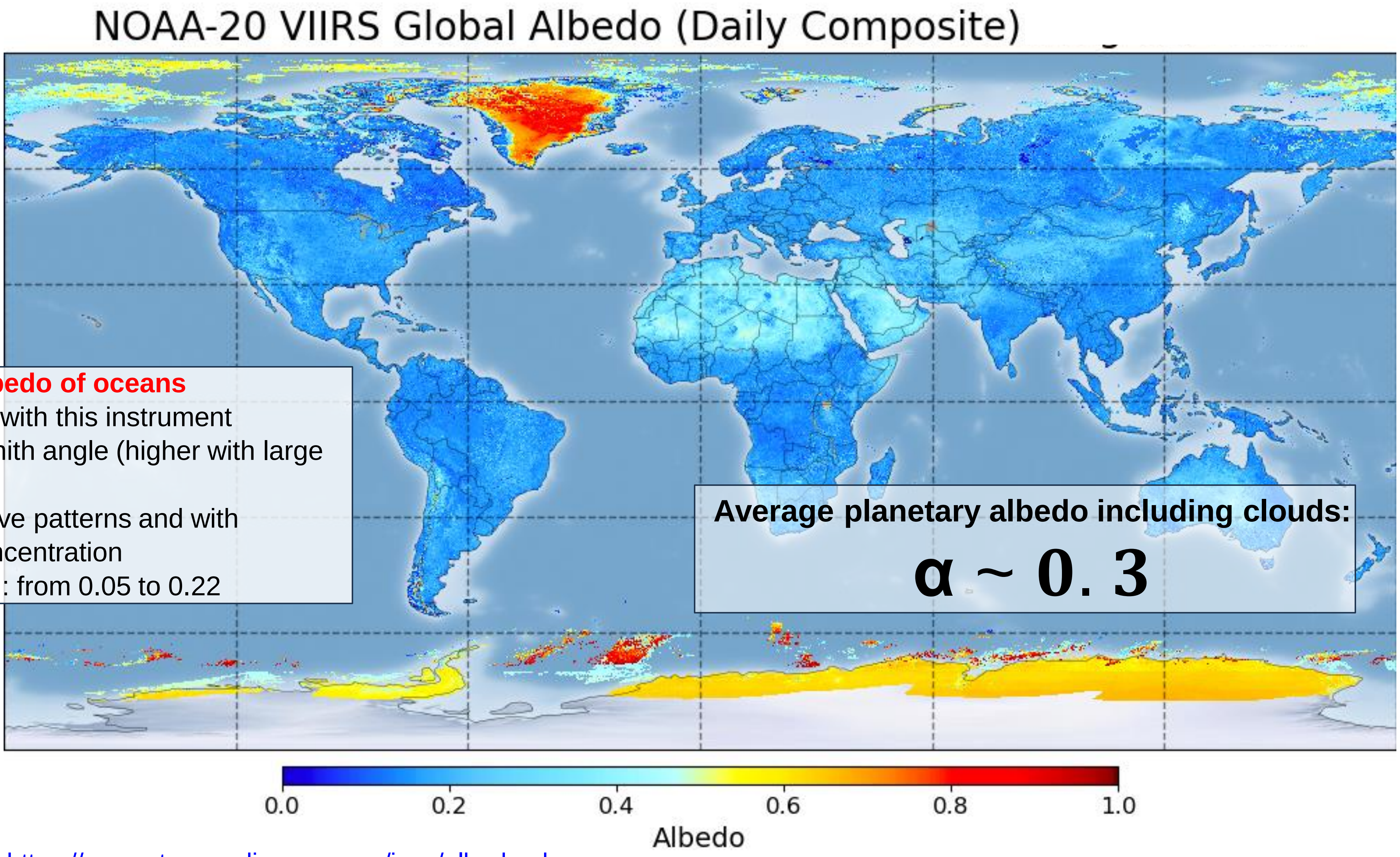
Multiple role in the climate system

- Snow, sea-ice and glaciers : Albedo effect (largest albedo).
- Regulation of global sea level (potential of ~6 m with Greenland, potential of ~60 m with Antarctica).
- Impact on ocean circulation (sea ice and freshwater inputs) but also atmospheric circulation (jet stream).
- Glaciers are important source of freshwater (2 billions inhabitants around the Hindu-Kush Himalayas).
- Permafrost dynamics impacts the carbon cycle and soil stability.

- https://www.wikiwand.com/en/Cryosphere

A major parameter : Albedo

Reflectivity of a surface
1: non-absorbing white surface
0: non-reflective black surface



Albedo of oceans

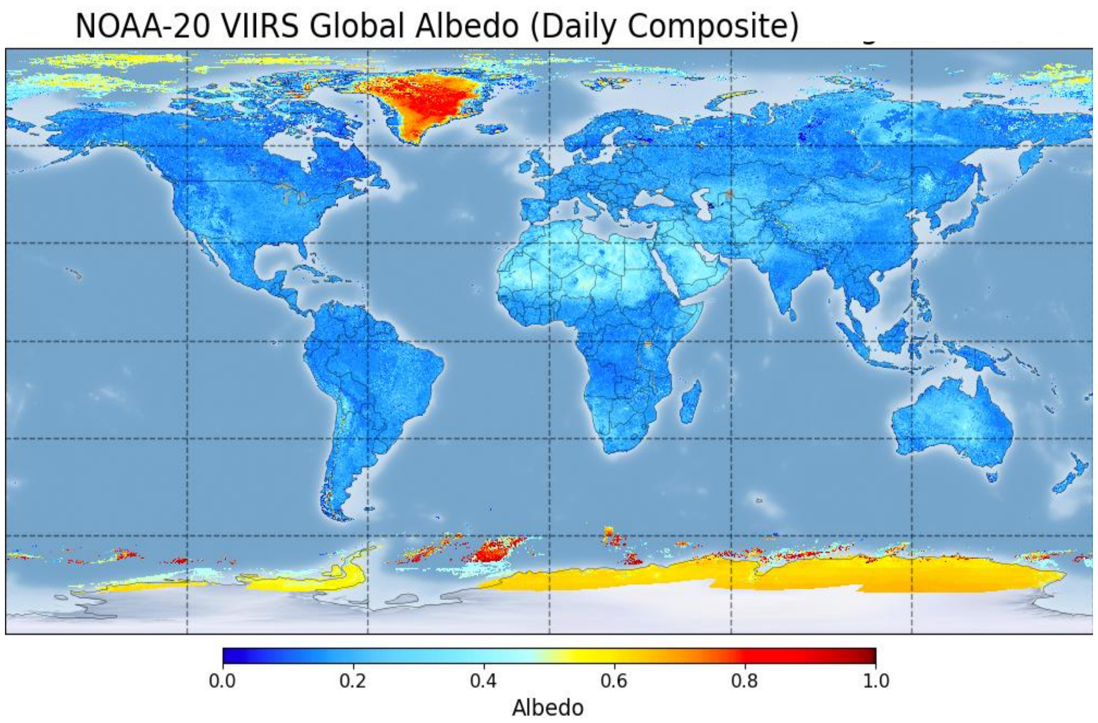
- Not measured with this instrument
- Varies with zenith angle (higher with large angle)
- Varies with wave patterns and with chlorophyll concentration
- Typical values : from 0.05 to 0.22

Average planetary albedo including clouds:

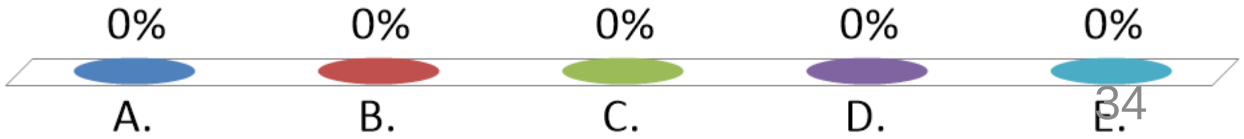
$$\alpha \sim 0.3$$

https://www.star.nesdis.noaa.gov/jpss/albedo.php

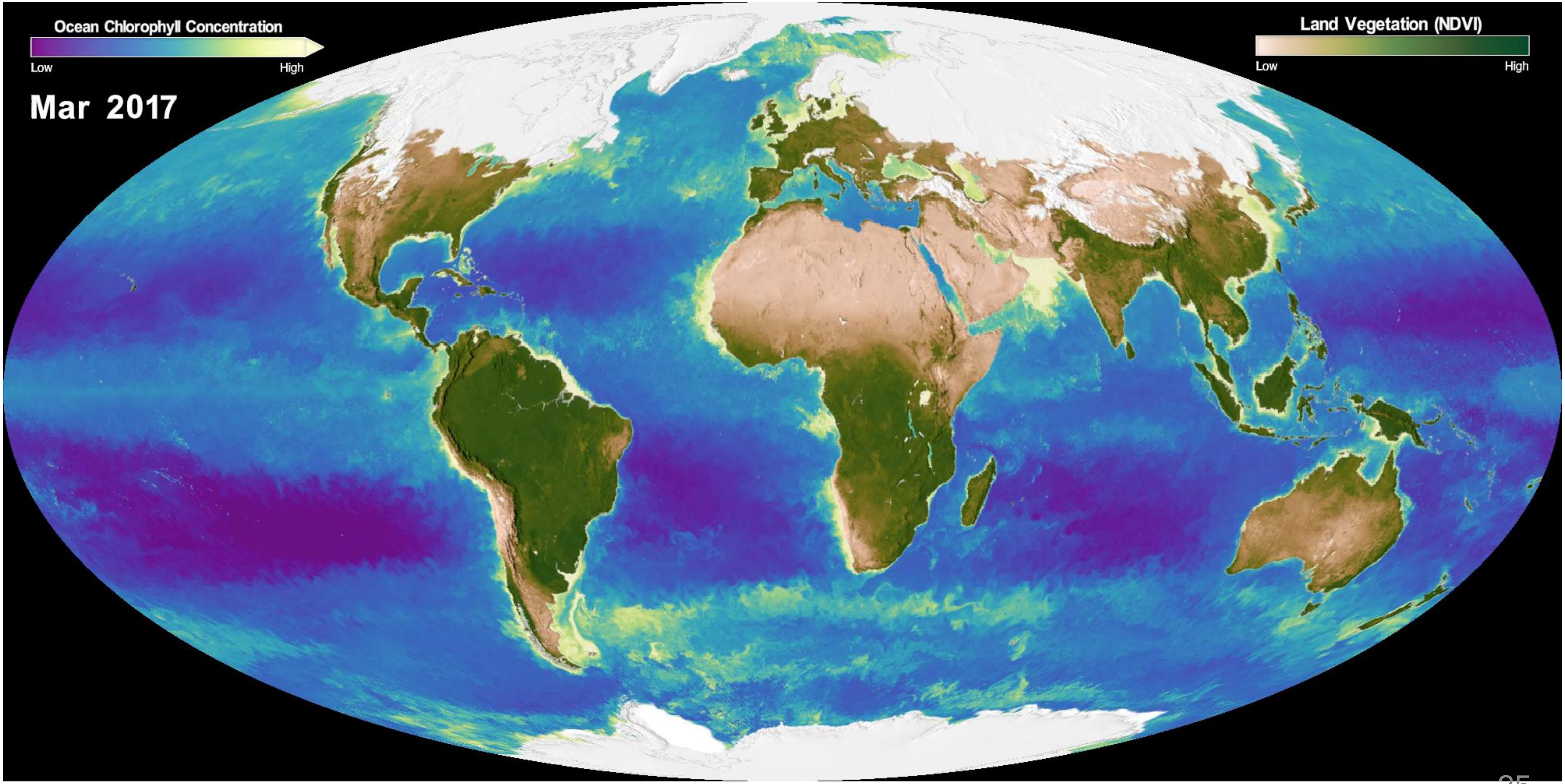
Which month for this global map ?



A. December
B. March
C. August
D. October
E. I don't know

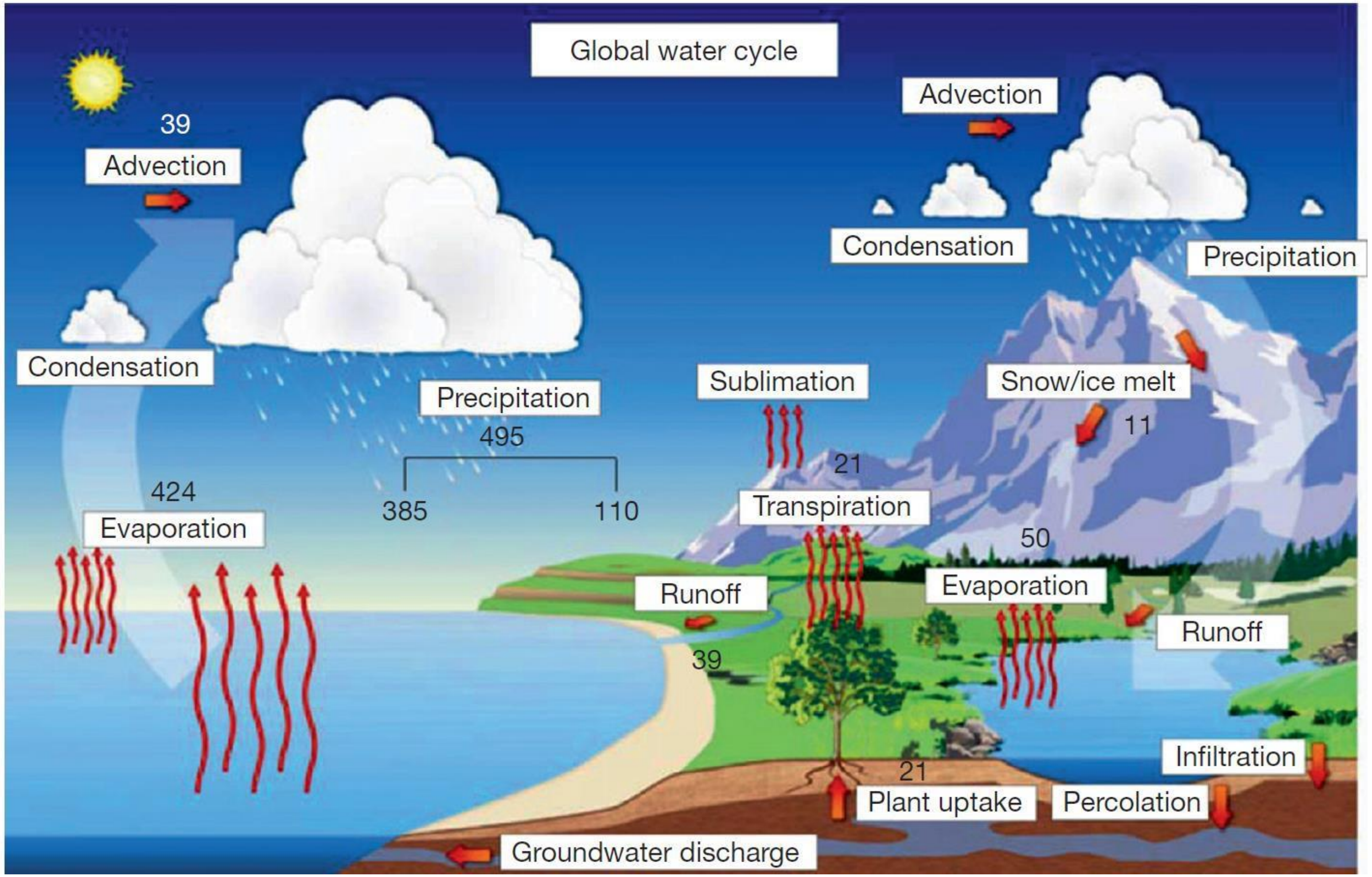


A major parameter : Albedo



https://svs.gsfc.nasa.gov/5006/

Water cycle : connecting climate system components



fluxes in 10^3 km^3 yr^{-1}

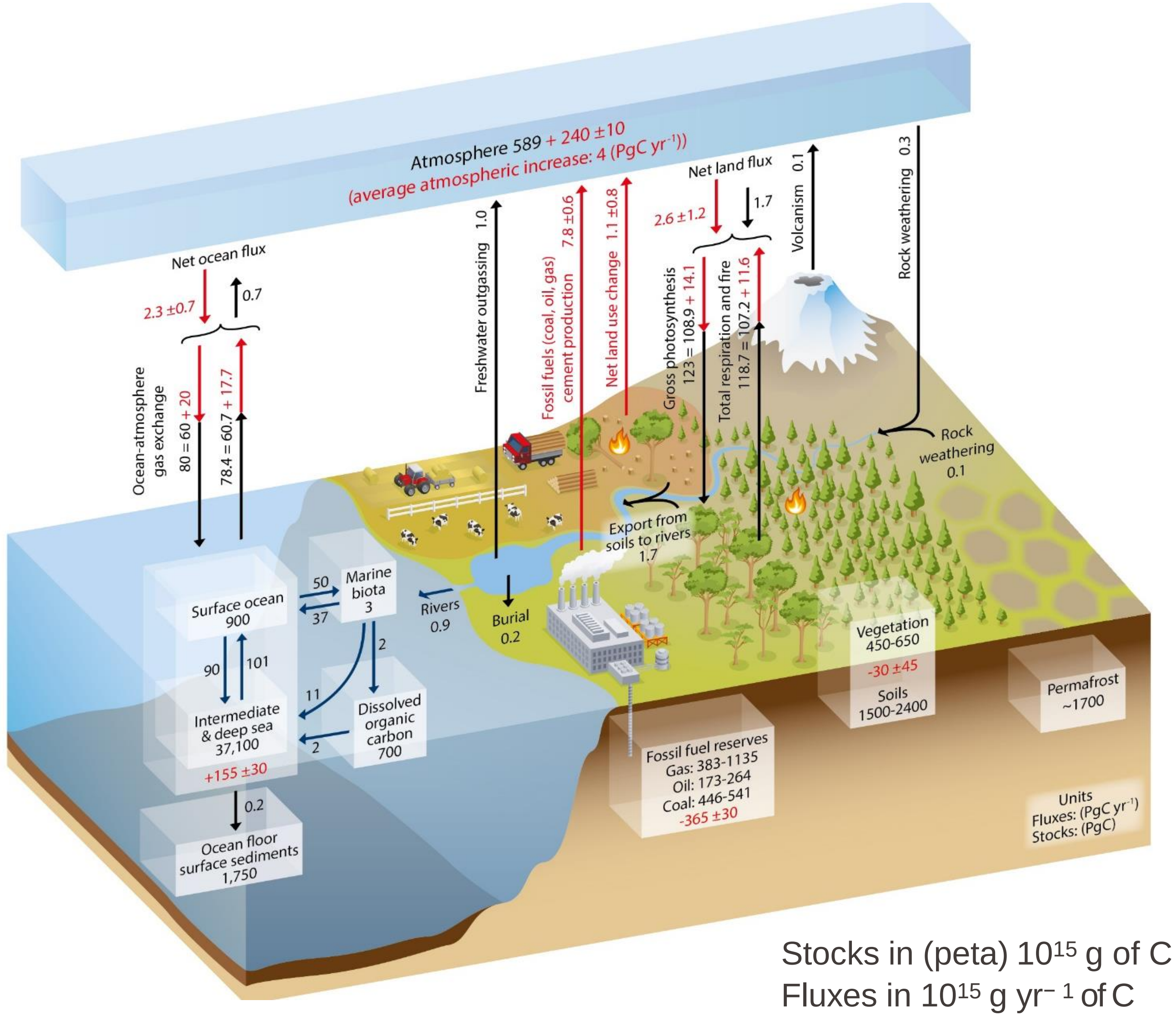
Total: ~500,000 km^3/year
Human-induced emissions: ~1,500 km^3/year (0.3%)

- Source: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/hydrological-cycle

- Evaporation: water changes state from a liquid to vapor.
- Condensation: water vapor changes into water droplets (clouds).
- Advection: movement of solid, liquid, and gaseous water through the atmosphere.
- Precipitation: in solid or liquid phase.
- Runoff: movement through land.
- 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.

Carbon cycle : connecting climate system components



Stocks in (peta) 10^{15} g of C
Fluxes in 10^{15} g yr^{-1} of C

Reservoirs:

- Continental biosphere.
- Oceans.
- Cryosphere (permafrost).
- Atmosphere.
- Lithosphere (tectonics, volcanism).
- Anthroposphere (fossil fuel, land use).

Fluxes and time scales:

- Yearly driven by photosynthesis and respiration.
- Decadal-centennial time scales by anthropogenic impact and climate variability.
- Millenial to millionary time scales by orbital forcing.
- Multi-millionary time scales by tectonics and volcanism.

Carbon dioxide is the second most abundant greenhouse gas on Earth.

- *Source: https://www.pmel.noaa.gov/co2/file/Fig%206.1%20Schematic%20of%20the%20global%20carbon%20cycle*

Anthroposphere

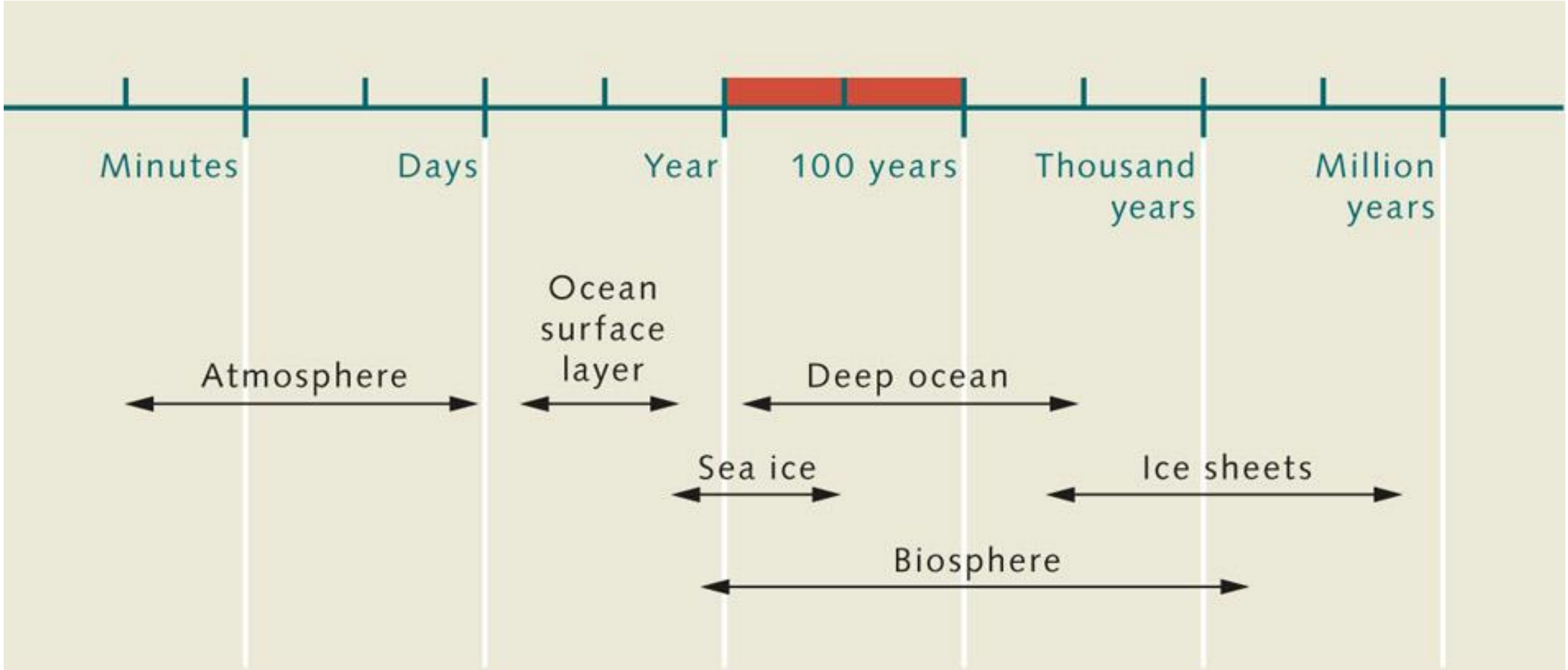
Source : https://globaia.org/anthroposphere

8 billion humans:
A sphere of ~1 km diameter

One could add:

- Land use / agriculture / forestry
- Contrails from aircrafts
- Coastal eutrophisation
- …

Timescales

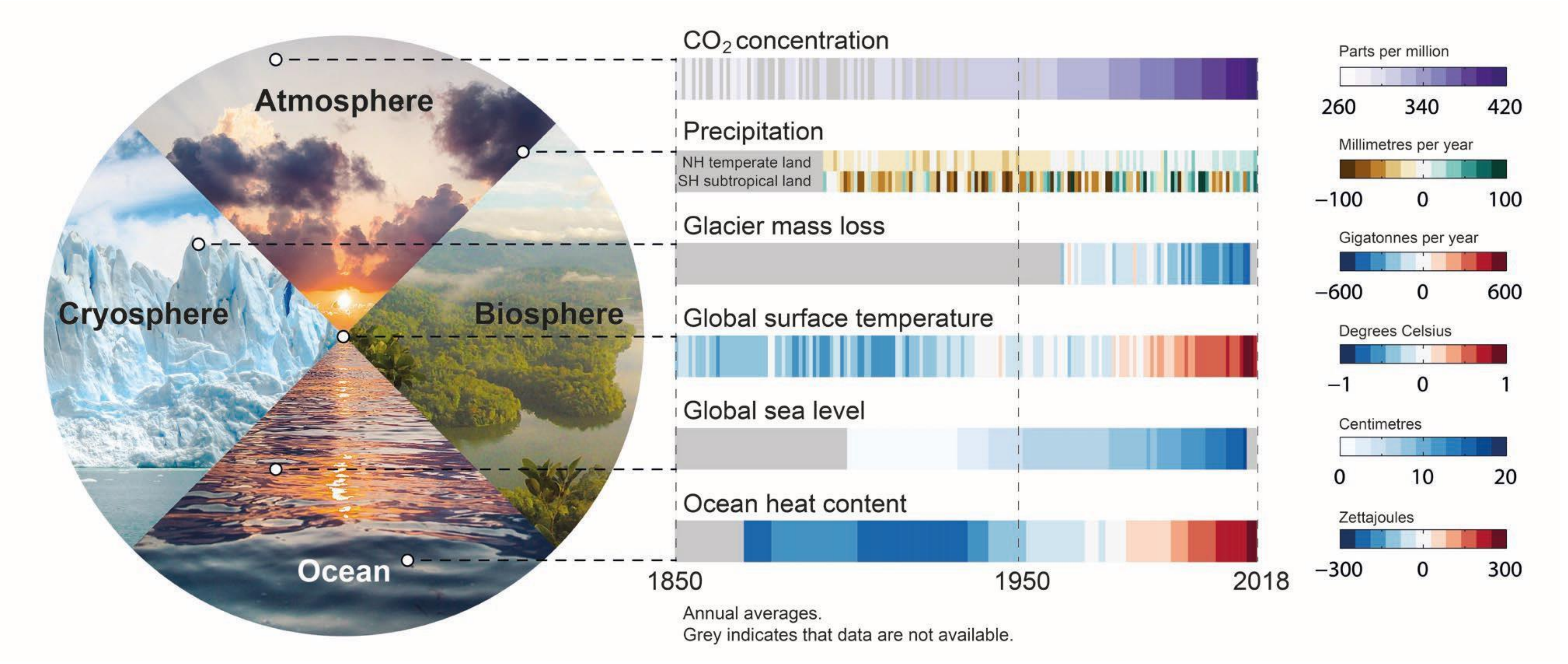


Note : The lithosphere works on even longer time scales (tectonics)

Source : Meincke, J.; Latif, M., Geographische Rundschau 47(2): 90-96, 1995

Important observed changes in the climate system

Six key indicators of ongoing changes: Essential climate variables



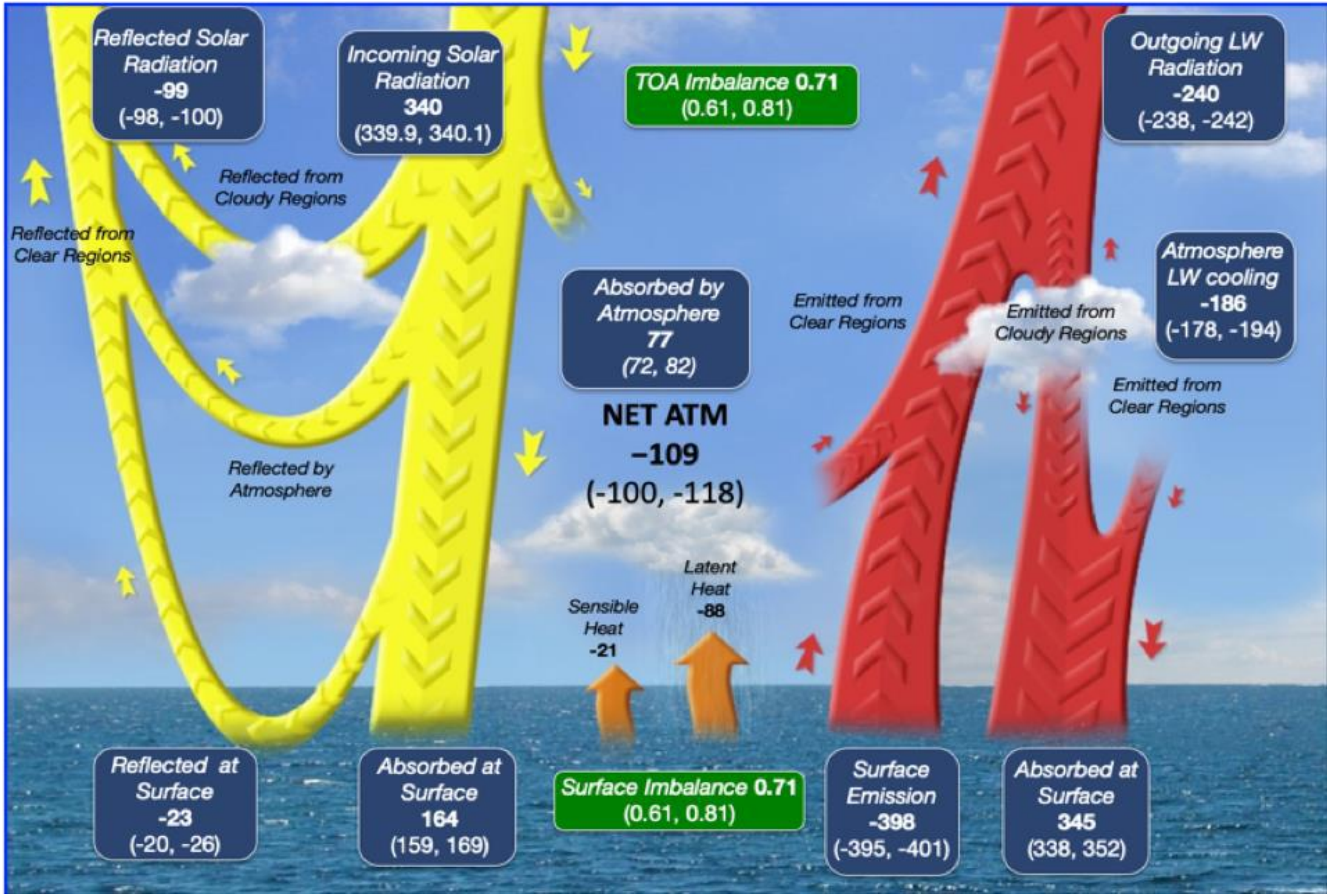
Source: IPCC AR6, Ch1, Fig. 1.4

Earth energy balance

Earth's Energy Balance

Unit: W.m^{-2}

Albedo



Source: *https://ceres.larc.nasa.gov/science/*

Shortwave:
- Incoming solar radiation: +340
- Reflected: -99 (Earth's albedo)
- Absorbed by atmosphere: +77
- Absorbed at surface: +164

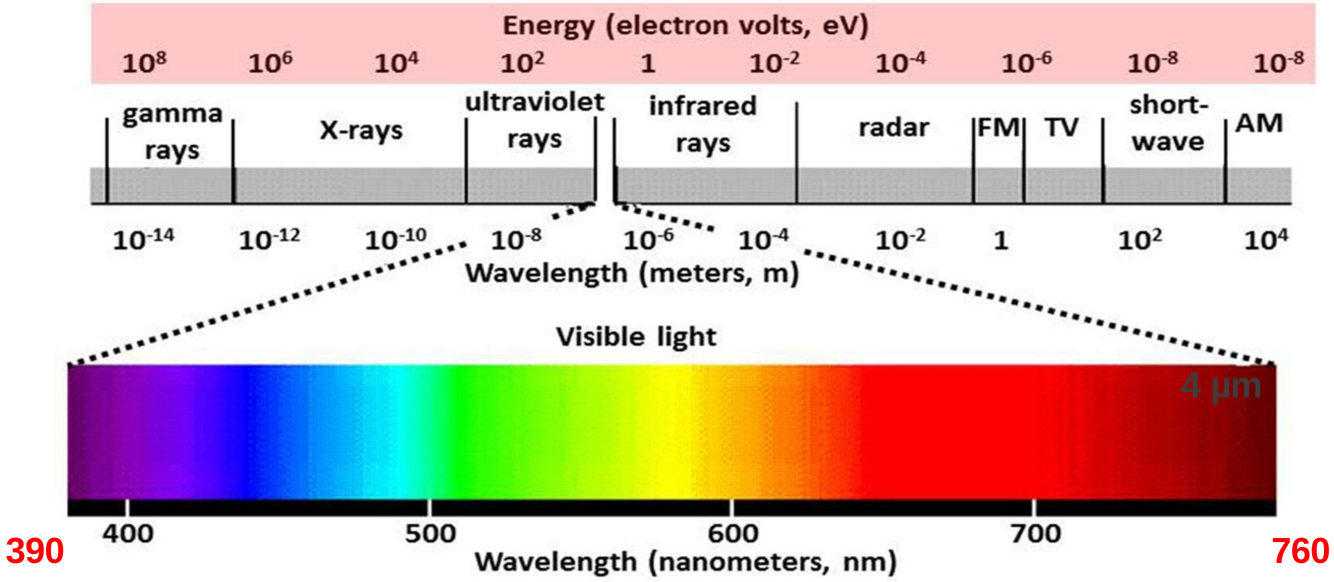
Longwave:
- Emitted by surface: -398
- Atmospheric loss (in all directions): -186
- Outgoing to space: -240

Greenhouse gases absorb surface infrared radiation and re-emit in all directions, including back to the surface.

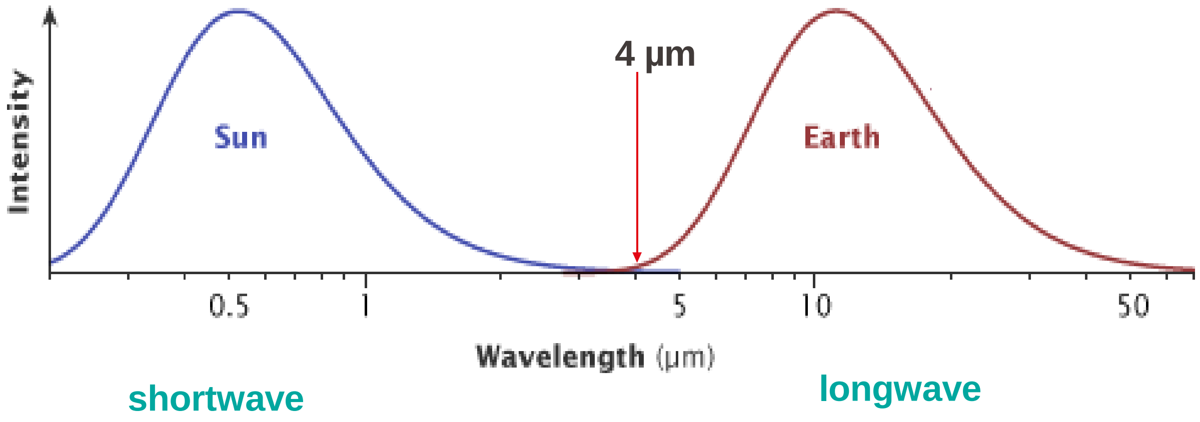
On average:
- The surface has a net surplus of radiant energy
- The atmosphere has a net loss.

Imbalance compensated by **sensible** (conduction & convection) and **latent heat** (evaporation) transfer from the surface to the atmosphere.

It's a lot about electromagenetic radiation...



Source: https://ozonedepletiontheory.info/what-is-radiation.html



Visible: 0.39 – 0.76 µm, define each color with single wavelength (monochromatic)

Solar radiation: < 4 µm, shortwave

Terrestrial radiation: > 4 µm, longwave (thermal infrared)

- *Figure 4.7, Wallace and Hobbs, 2006*

Blackbody radiation: Stefan-Boltzmann law

Objects emit radiation. In case of a blackbody, it absorbs all radiations and it emits radiation independently of direction, or composition of the body. Its radiation only depends on the ***temperature of the body***.

The blackbody is losing energy by emission of radiation, so heat must be supplied to keep its temperature constant.

Most objects can be approximated by using blackbody radiation laws.

Stefan-Boltzmann law : **the total flux density (irradiance) F_B is given as:** $F_B = \sigma T^4$

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} (Stefan-Boltzmann constant)

Effective emission temperature of a blackbody can be calculated from its irradiance F_B.

F_B corresponds to the integration of the radiation of the blackbody over all wavelengths.

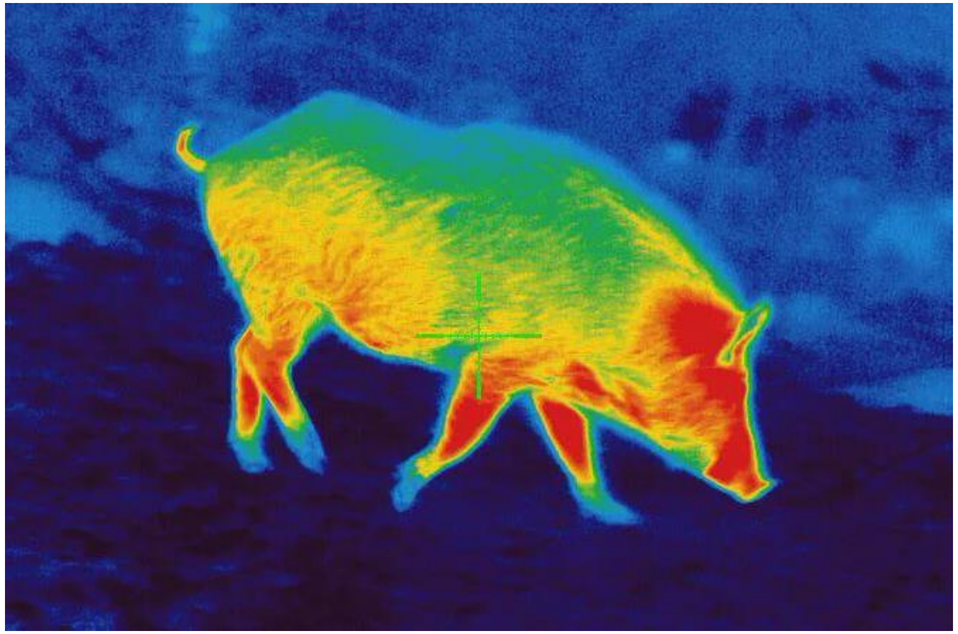


Photo : a wild boar seen by thermal camera, Pulsar company

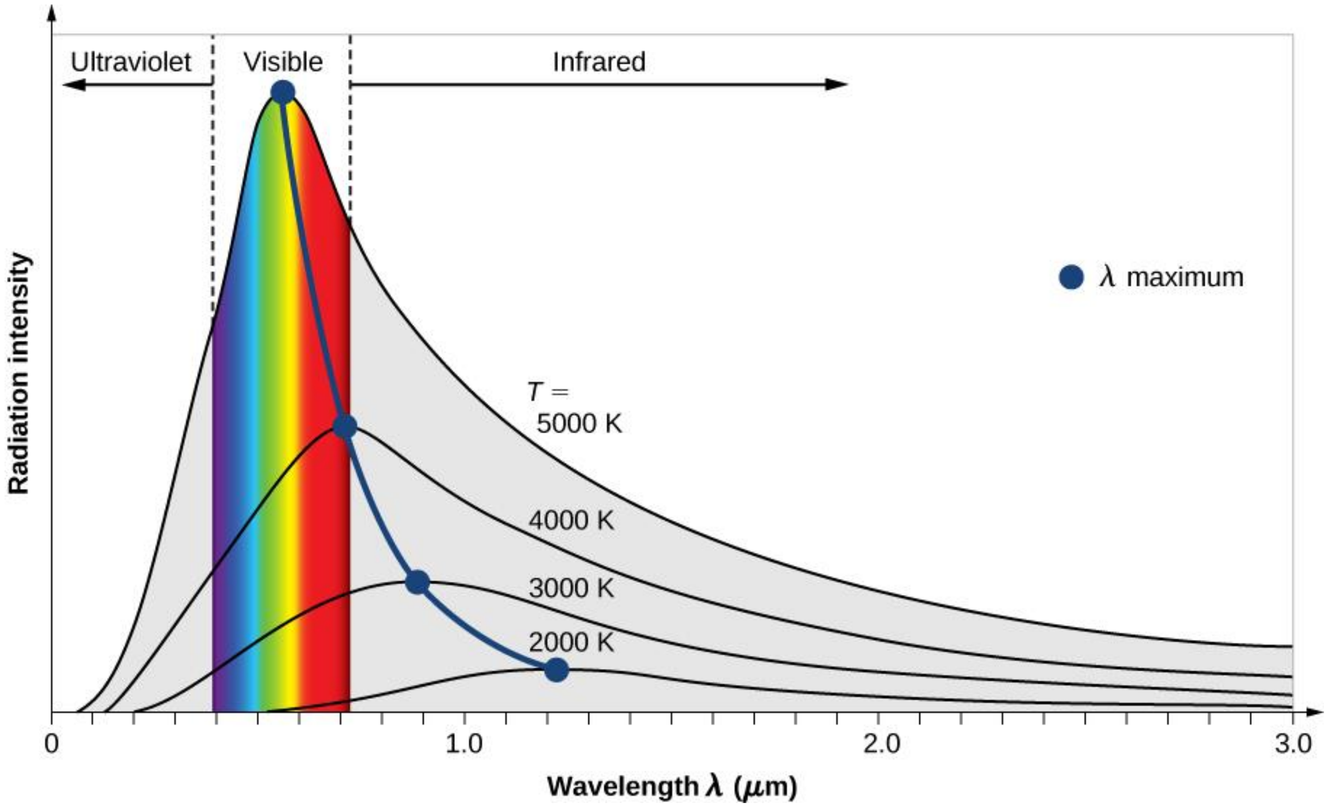
Source: Wallace and Hobbs, 2006

Blackbody radiation

When the temperature of the blackbody increases:

- The intensity of radiation increases
- The maximum radiation is observed at shorter wavelength.

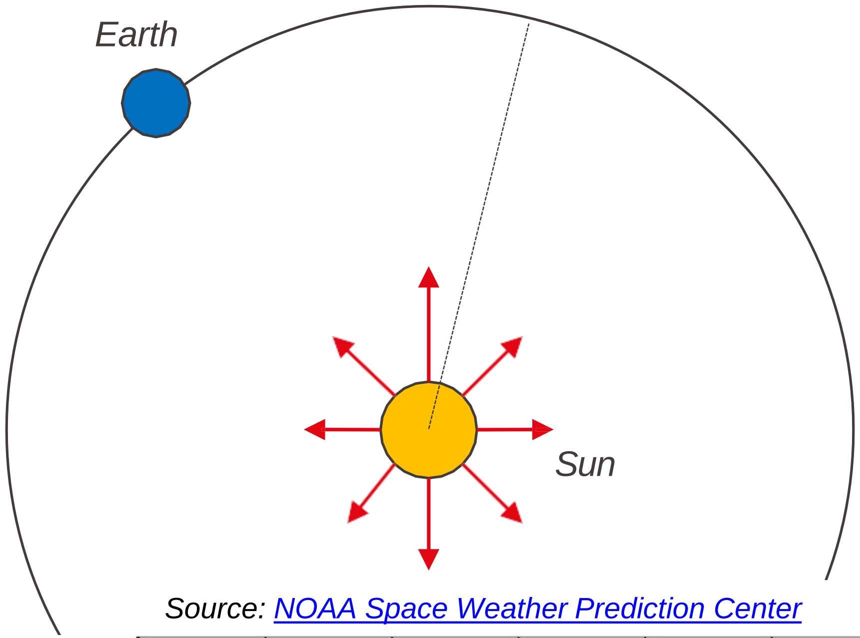
Maximum radiation of the sun: 0.5 µm
Radiation temperature: ~5780 K



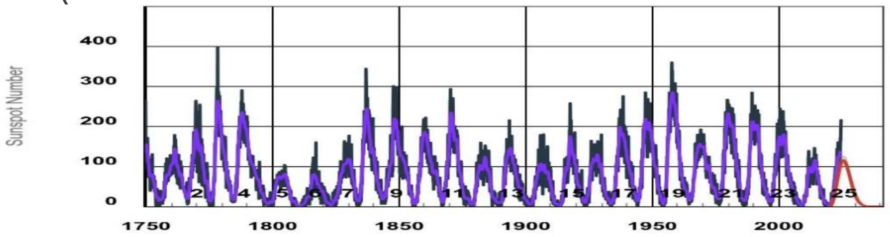
Emission spectra of a blackbody at four different temperatures

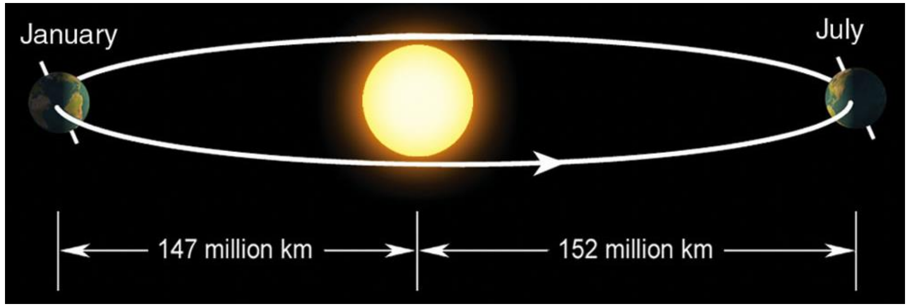
Source : [MIT]

Solar constant and radiative balance



Source: [NOAA Space Weather Prediction Center]





Source: https://atmos.uw.edu/~hakim/101/seasons/

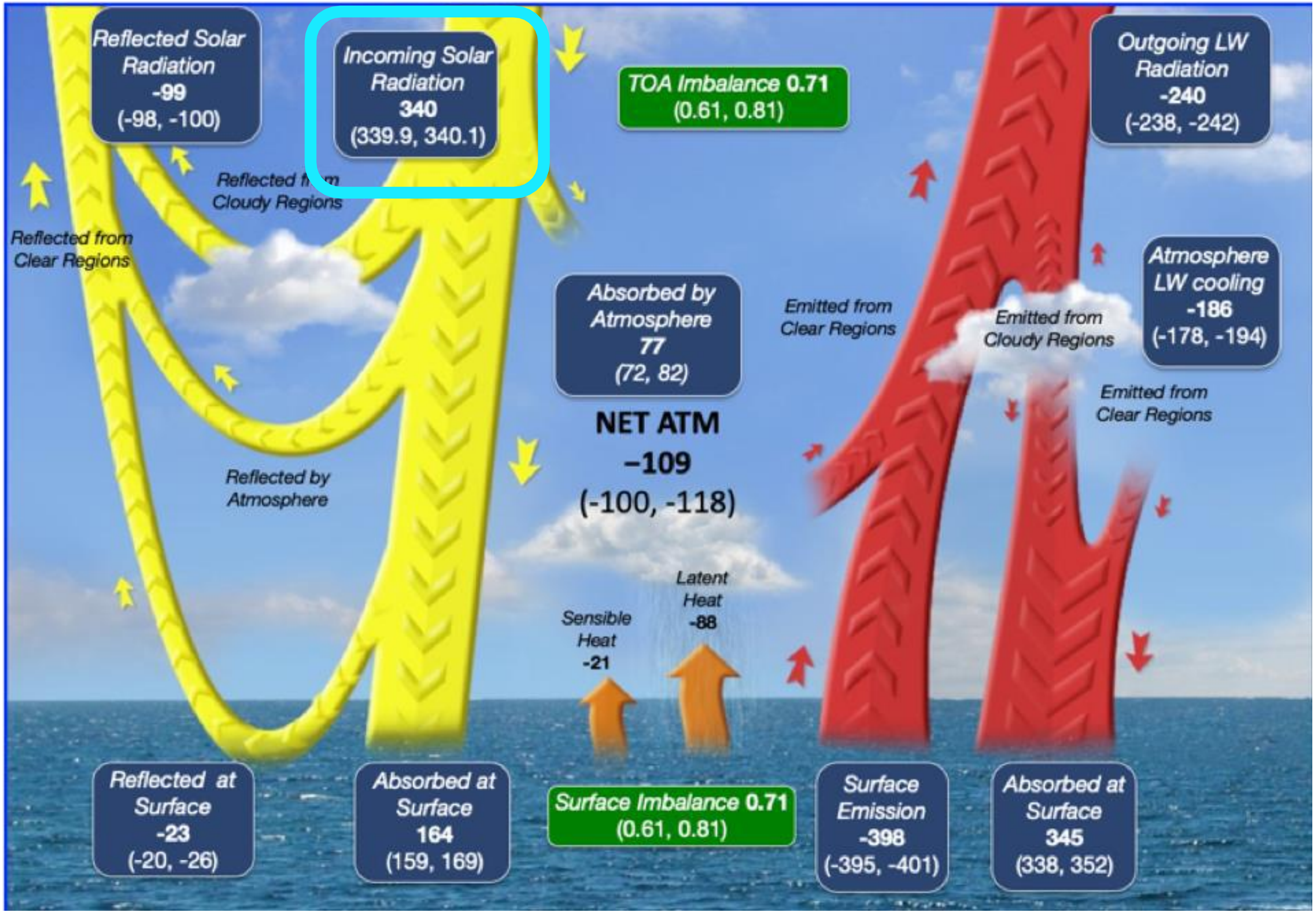
- The solar luminosity (irradiance x surface) is 3.8×10^{26} W
- Due to the conservation of energy, the same amount of energy is distributed in any sphere centered on the sun ; with a radius r the surface area is $4\pi r^2$. For the Earth, **$r = 150 \times 10^6$ km**
- So the energy received by each m^2 on Earth is: $3.8 \times 10^{26} / 4\pi r^2$

$$= 1370\ W\ m^{-2}$$ **Solar constant**

<u>It can vary because of</u>:

- Eccentricity of the Earth's orbit (r varies by $\pm$1.75 %). Currently **larger** solar constant **in January** as the Earth is closer to the sun. Lower in July.
- It varies by 0.01 to 0.02% as the sun rotates (29-day cycle). Different groups of sunspots facing the Earth.
- It varies by **0.1 % over the 11-year solar cycle**, together with sunspot maxima *(2025: current maximum, running from 2019 to 2030).*
- It increases as the Sun ages (1 % every 100 million years).

Earth's Energy Balance



Source: https://ceres.larc.nasa.gov/science/

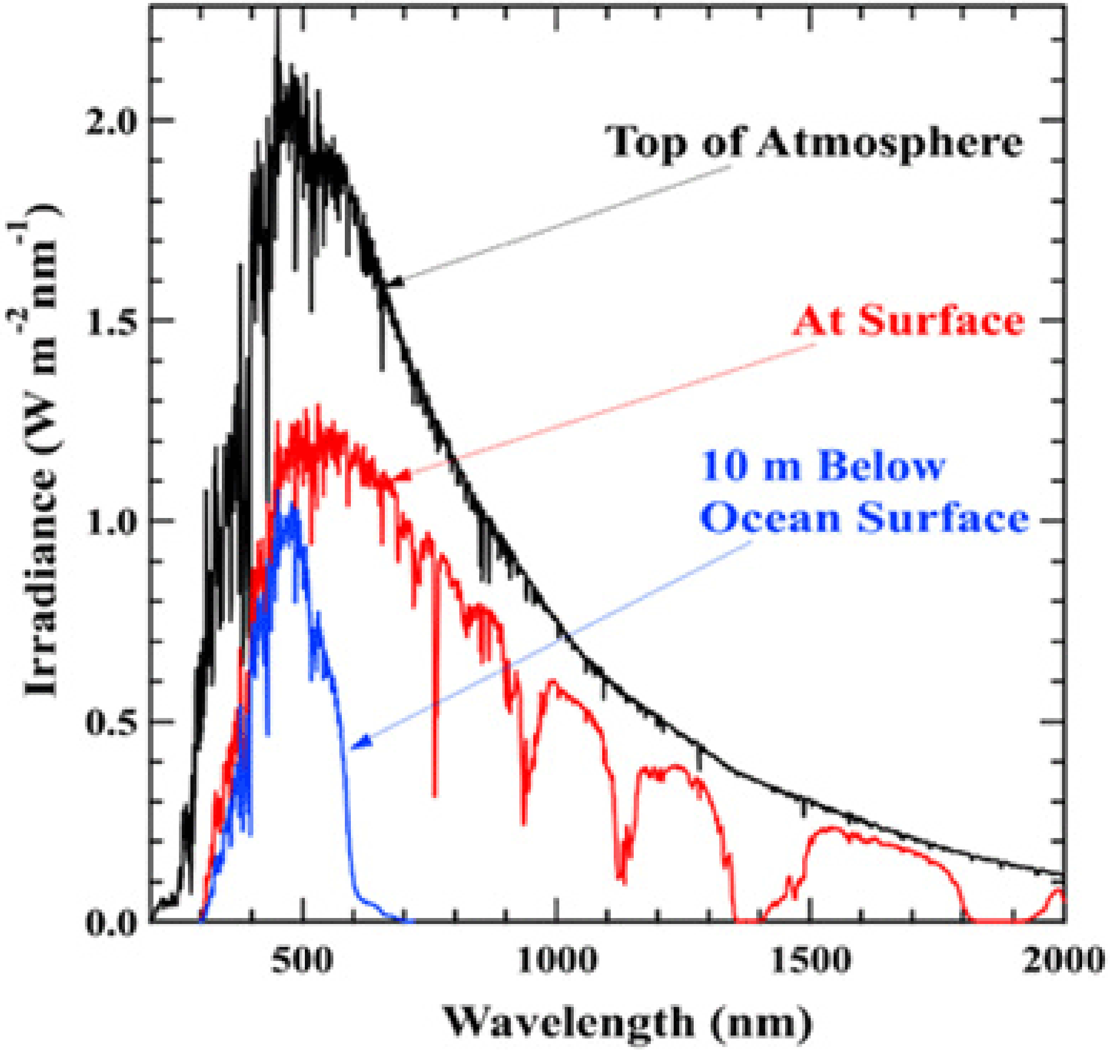
Solar constant is 1370 W m^{-2}

Earth receives on average 340 W m^{-2}

Why such a difference ?

➔ See exercise this afternoon

What gets through the atmosphere ?



Black : irradiance reaching the top of the atmosphere.

Red : irradiance reaching the Earth' surface. Less radiation at all wavelengths, with specific windows of much lower irradiance. This implies that the Earth's atmosphere interacts with solar radiation.

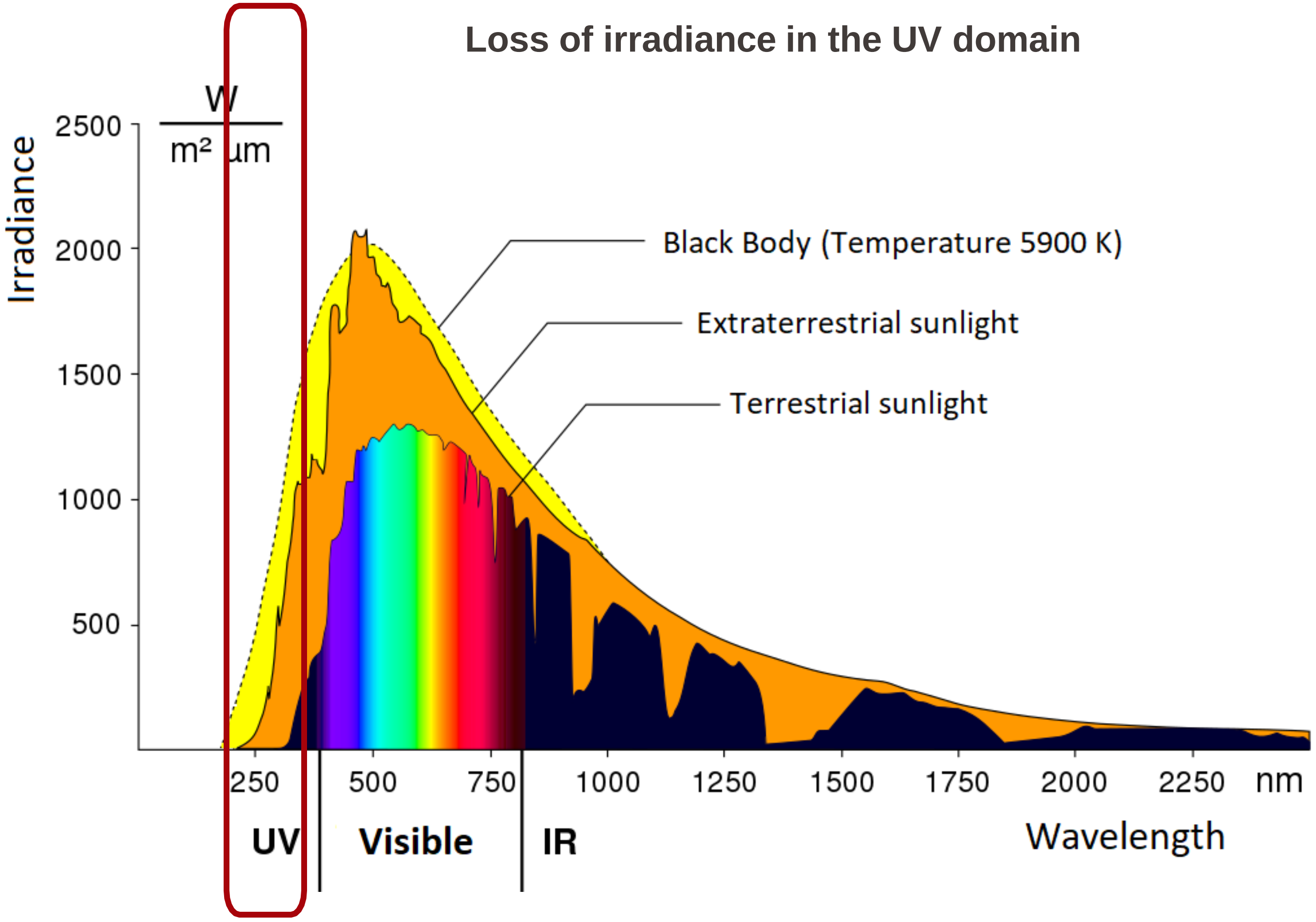
Blue : irradiance at 10 m below the ocean surface.

Blue : Water suppresses a large part of solar irradiance (only ~16% remaining at 10 m) and all of it at long wavelengths (absorption, scattering). Explains why blue dominates when diving in water.

Source: SORCE, University of Colorado

What gets through the atmosphere ?

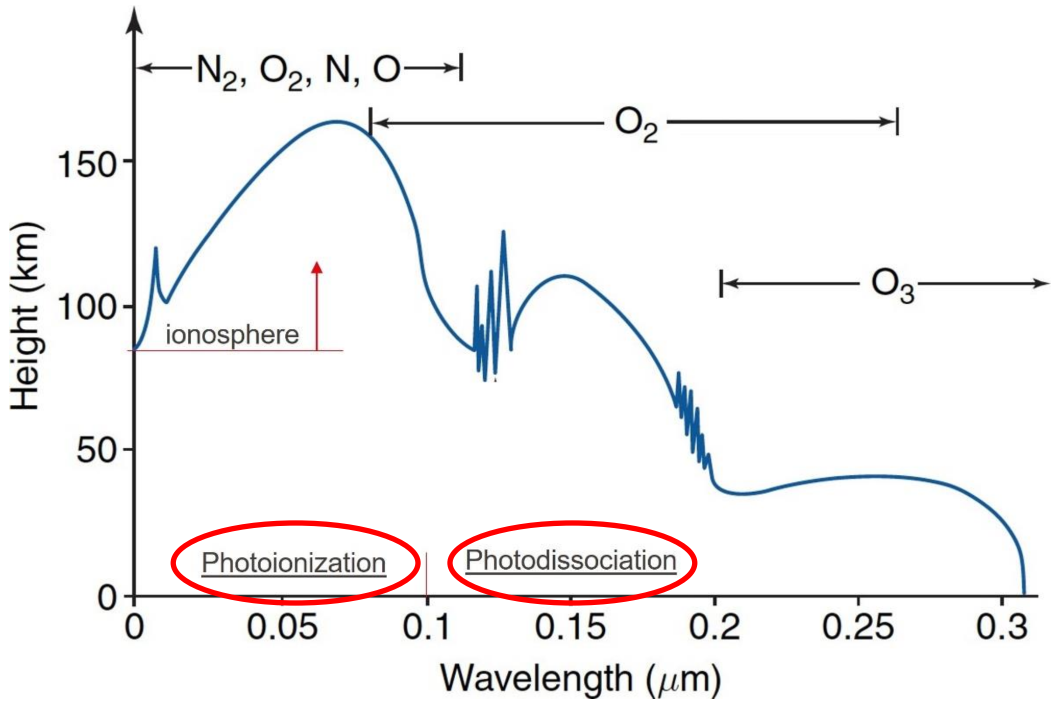
Loss of irradiance in the UV domain



Source: www.sciencedirect.com/topics/physics-and-astronomy/solar-spectra

Depth of penetration of solar UV radiation

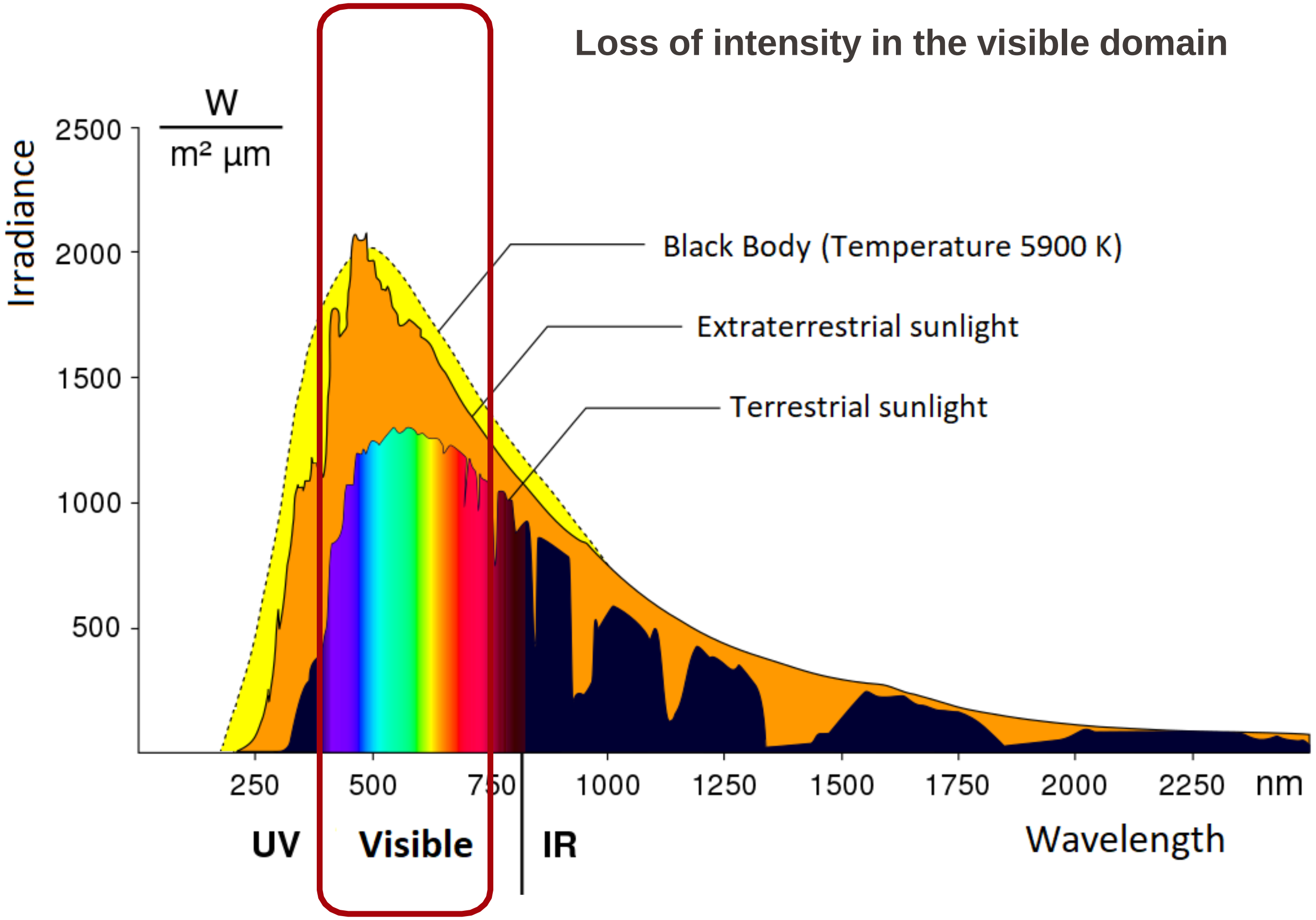
Source: Wallace and Hobbs,2006



Remove electrons from atoms, extreme ultraviolet $\lambda \leq 0.1\ \mu m$, in ionosphere (upper part of thermosphere)

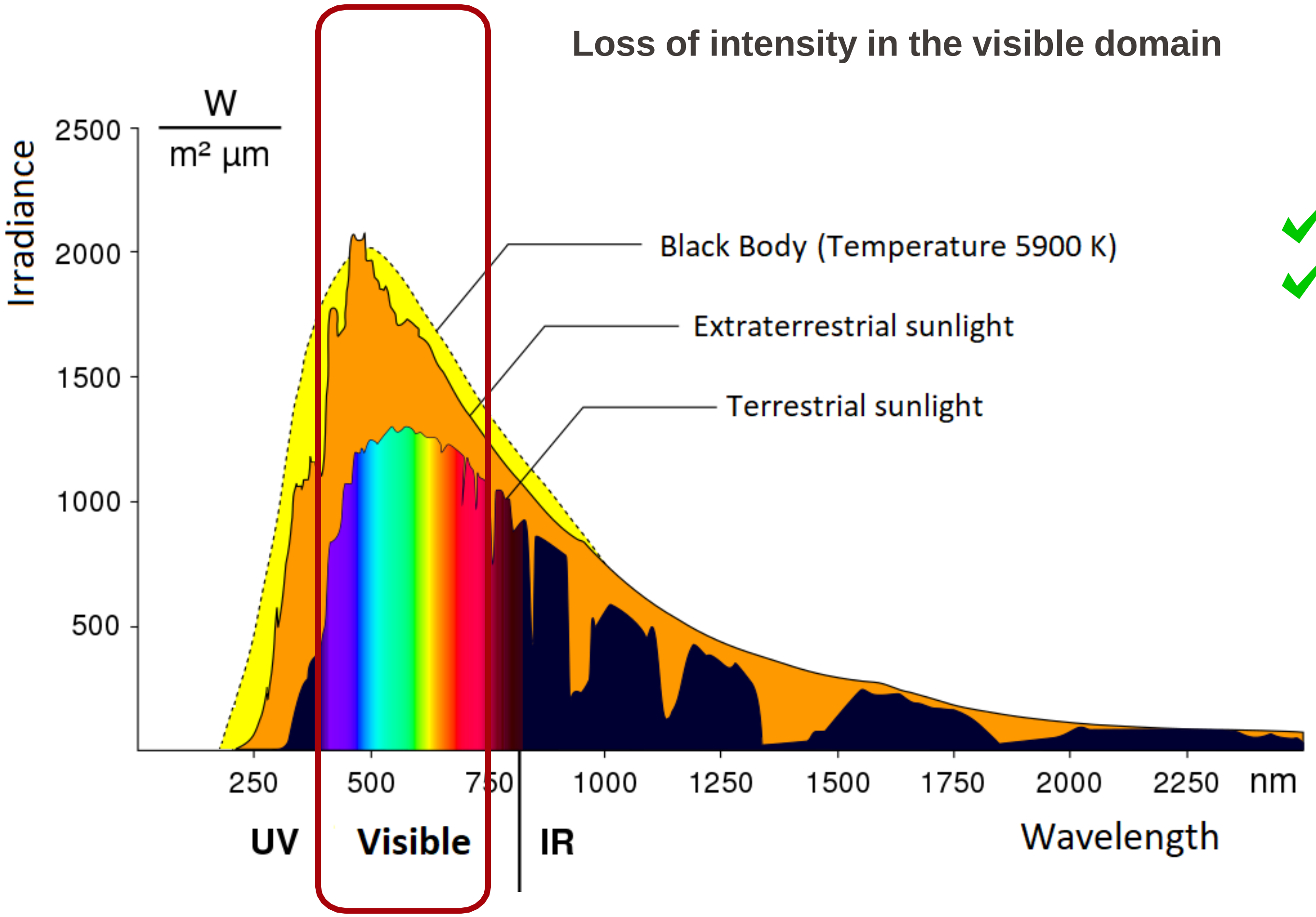
Break molecules, ultraviolet $\lambda \leq 0.31\ \mu m$, down to stratosphere, O_2 breakup produces O_3 **(reduces UV at surface)**

What gets through the atmosphere ?



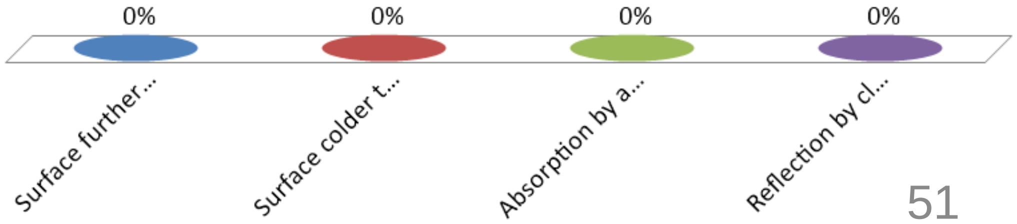
Source: www.sciencedirect.com/topics/physics-and-astronomy/solar-spectra

Why does the radiation intensity at Earth' surface is lower than at the top of the atmosphere <u>in the visible domain</u> ?

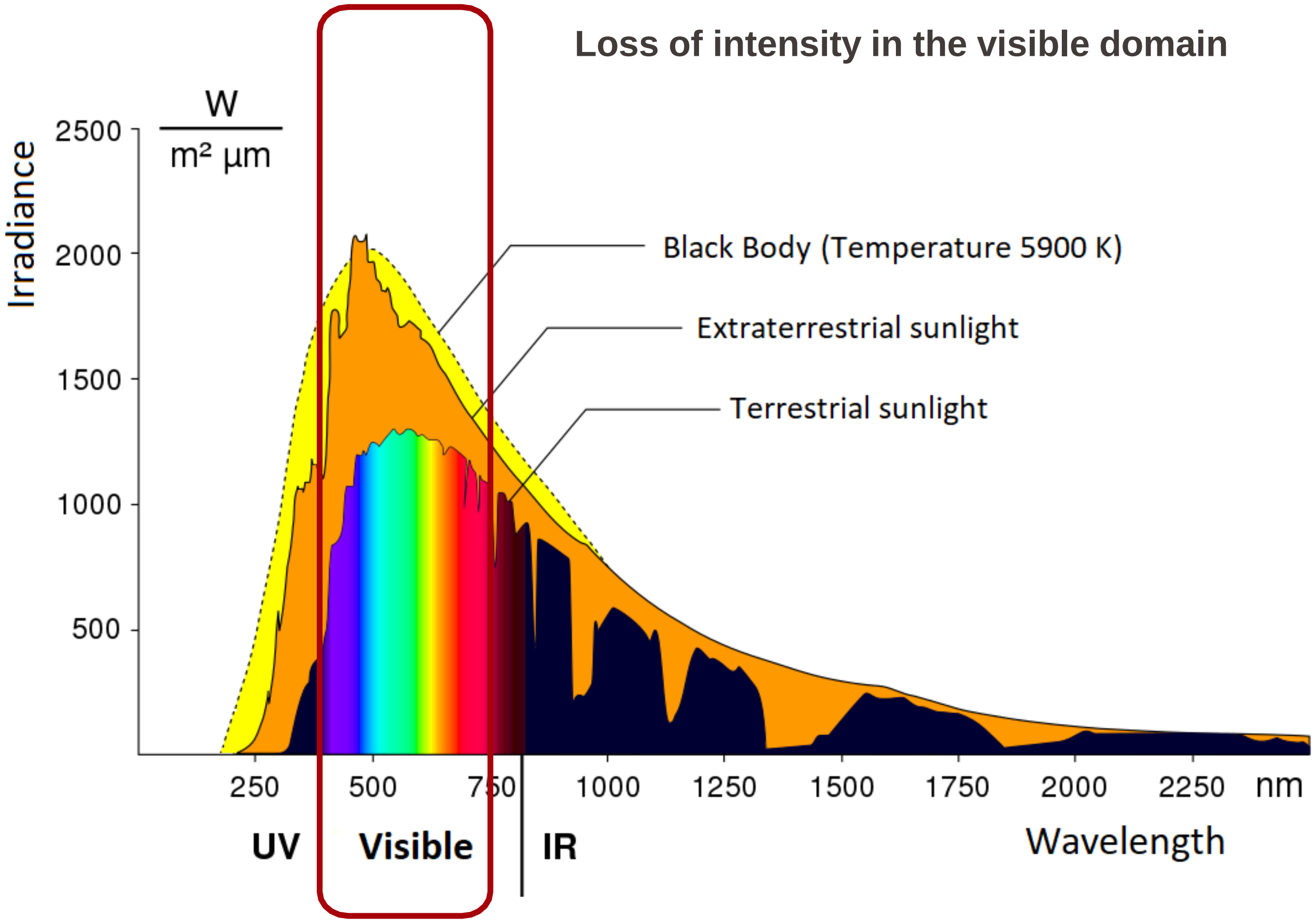


A. Surface further from sun
B. Surface colder than top of atmosphere
✔C. Absorption by atmosphere
✔D. Reflection by clouds

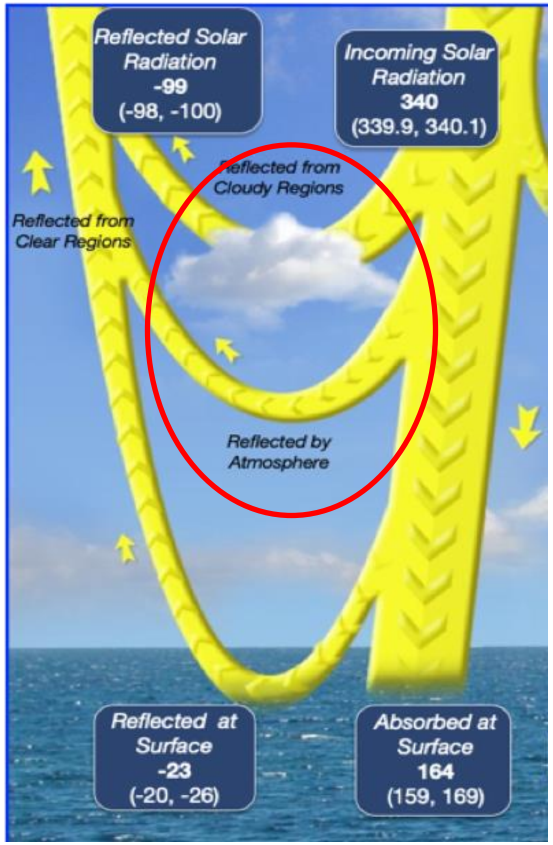
Source: *www.sciencedirect.com/topics/physics-and-astronomy/solar-spectra*



What gets through the atmosphere ?



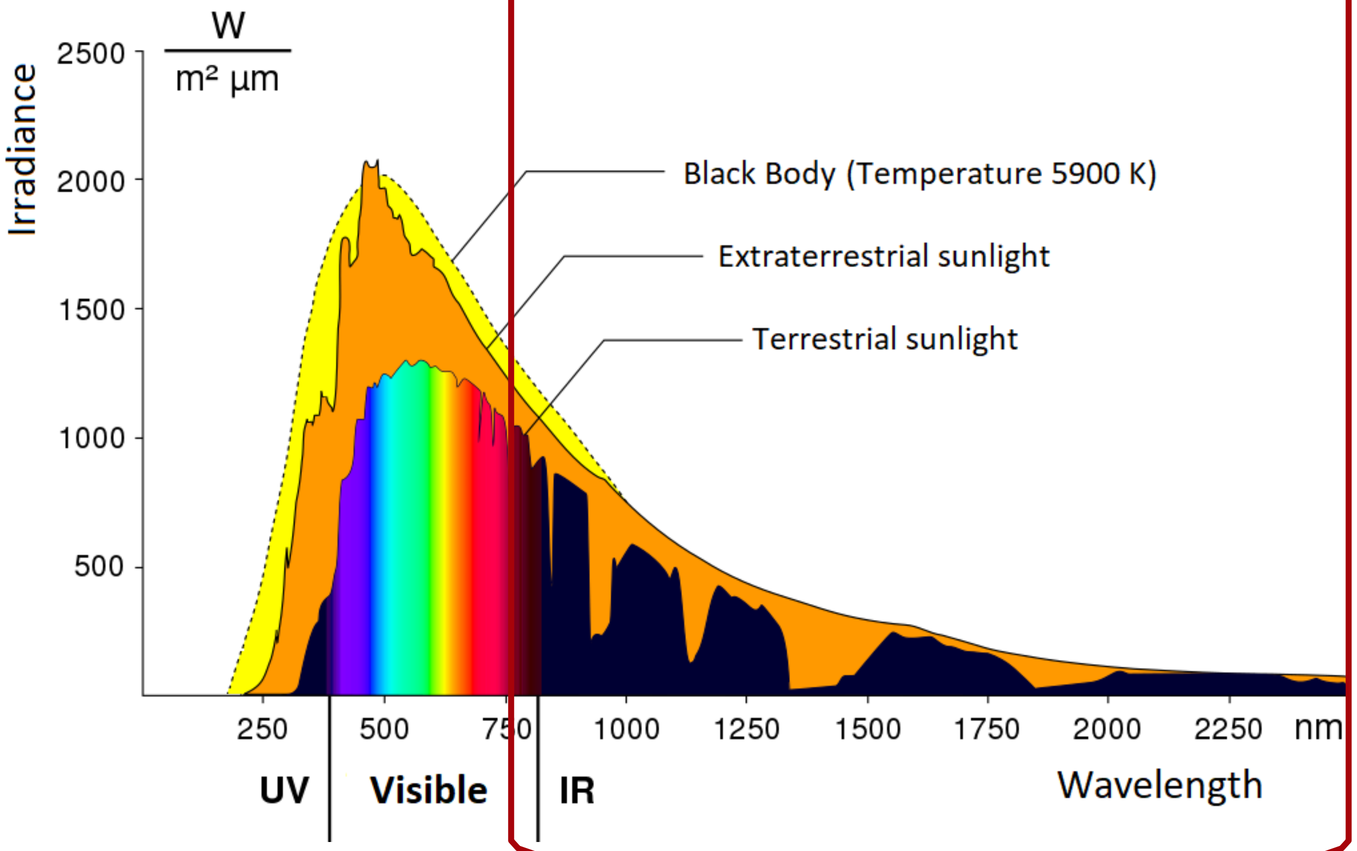
Source: *www.sciencedirect.com/topics/physics-and-astronomy/solar-spectra*



Visible wavelength: attenuation by clouds and by scattering in clear sky regions (aerosols)

What gets through the atmosphere ?

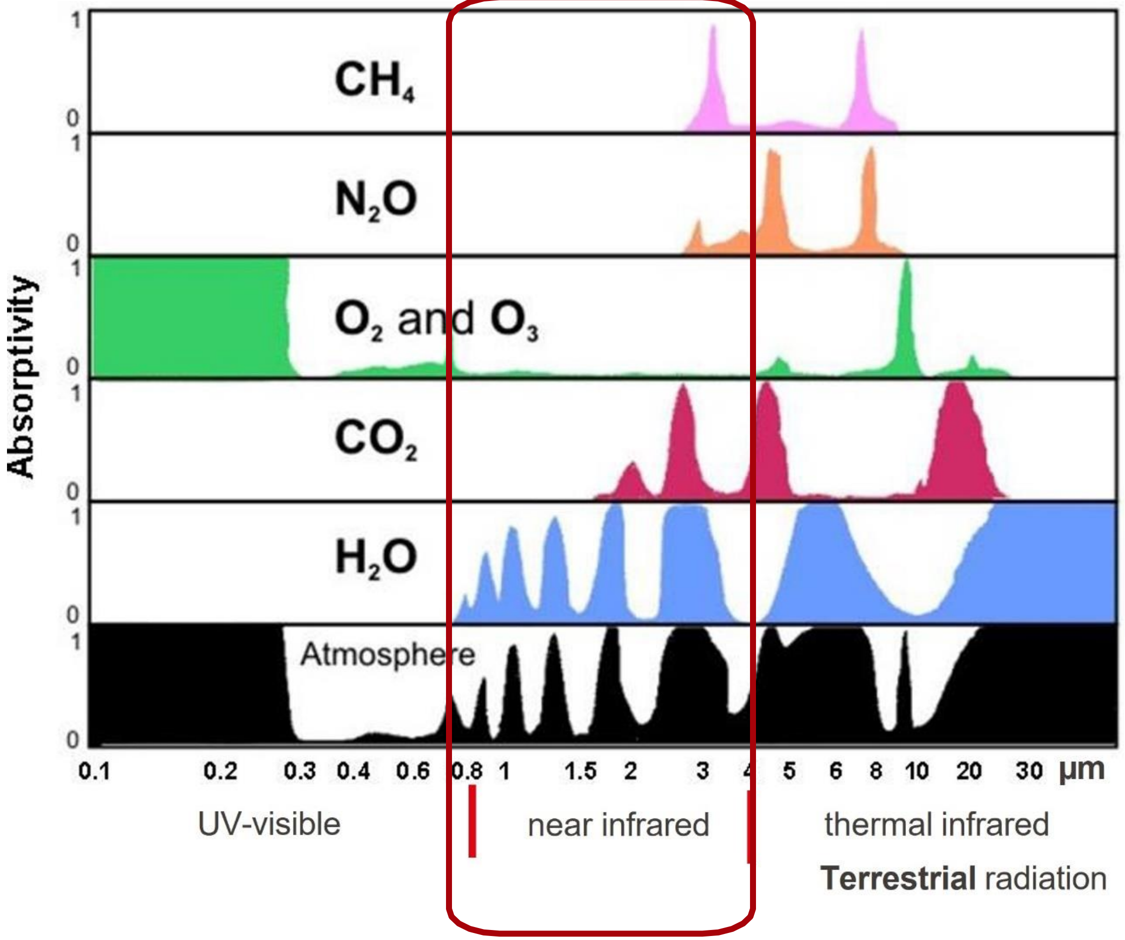
Specific wavelengths with strong absorption



Source: www.sciencedirect.com/topics/physics-and-astronomy/solar-spectra

Absorptivity: 1=fully opaque, 0=fully transparent

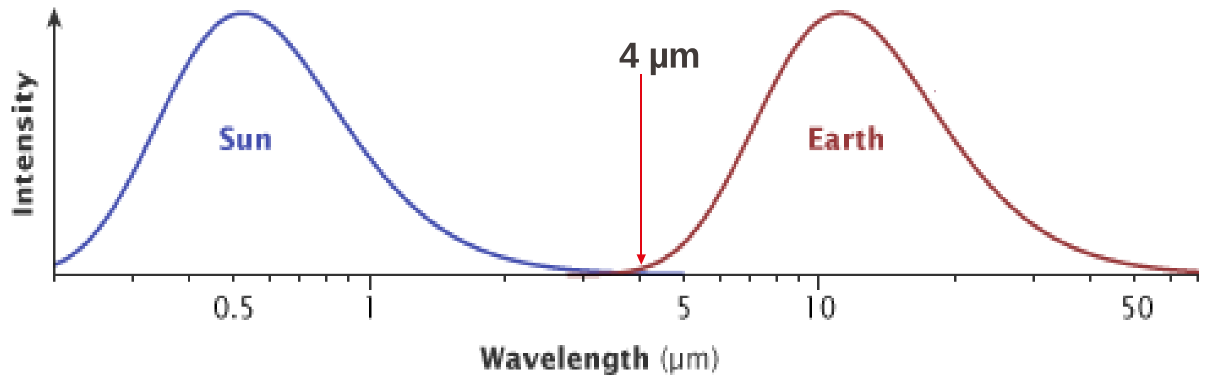
Source: https://www.e-education.psu.edu/meteo3/l2_p7.html



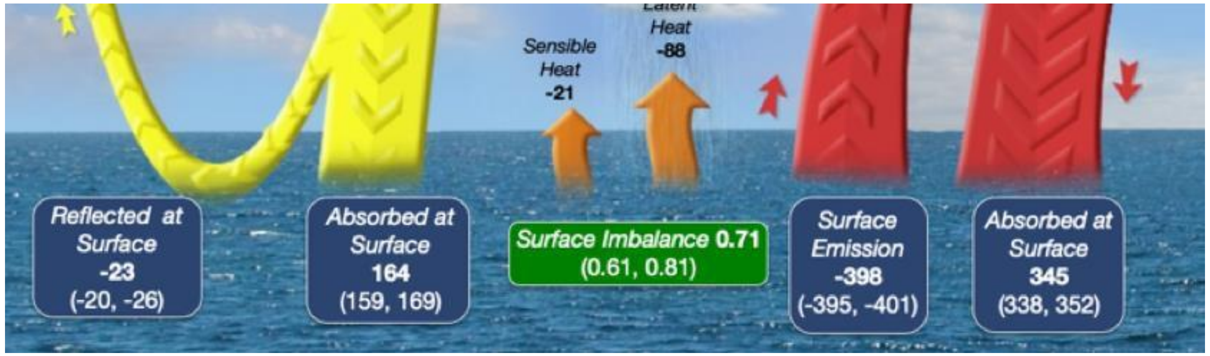
Near infrared: trace gases absorbing over specific wavelength ranges

What gets back to space ?

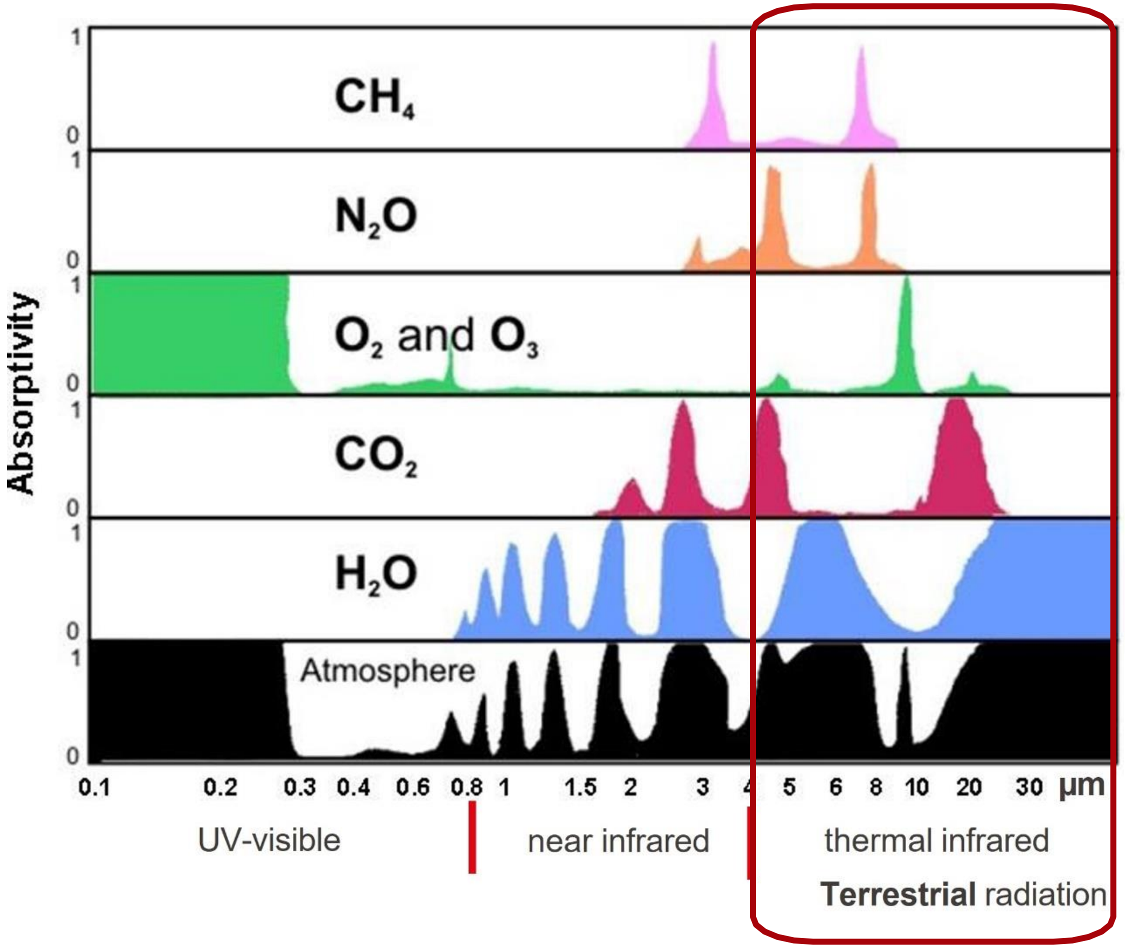
Thermal infrared:
domain of Earth radiation



Source: Figure 4.7, Wallace and Hobbs, 2006



Absorptivity: 1=fully opaque, 0=fully transparent

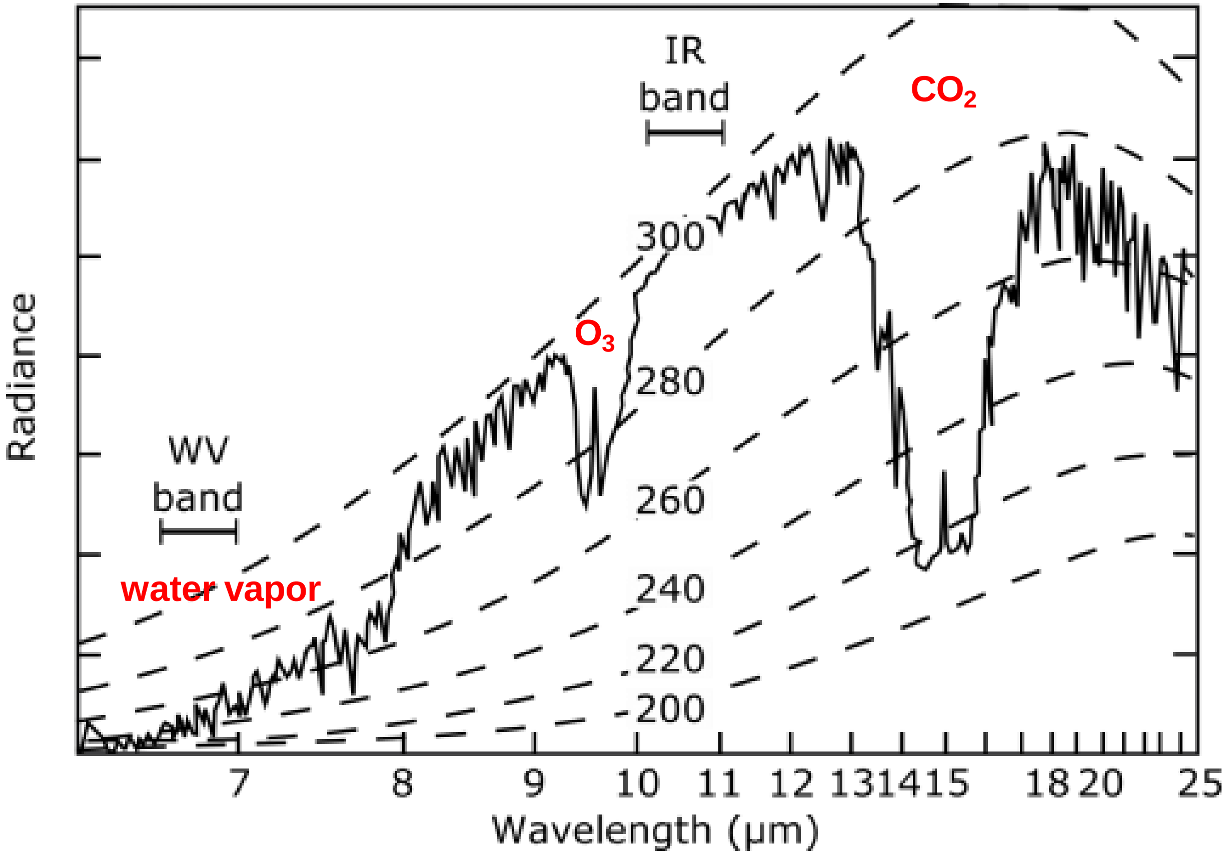


Thermal infrared: trace gases absorbing over specific wavelength ranges

What gets back to space ?

Nimbus 4 satellite measurement of the Earth's infrared spectrum.
Observations over the tropical Pacific ocean in April 1970.

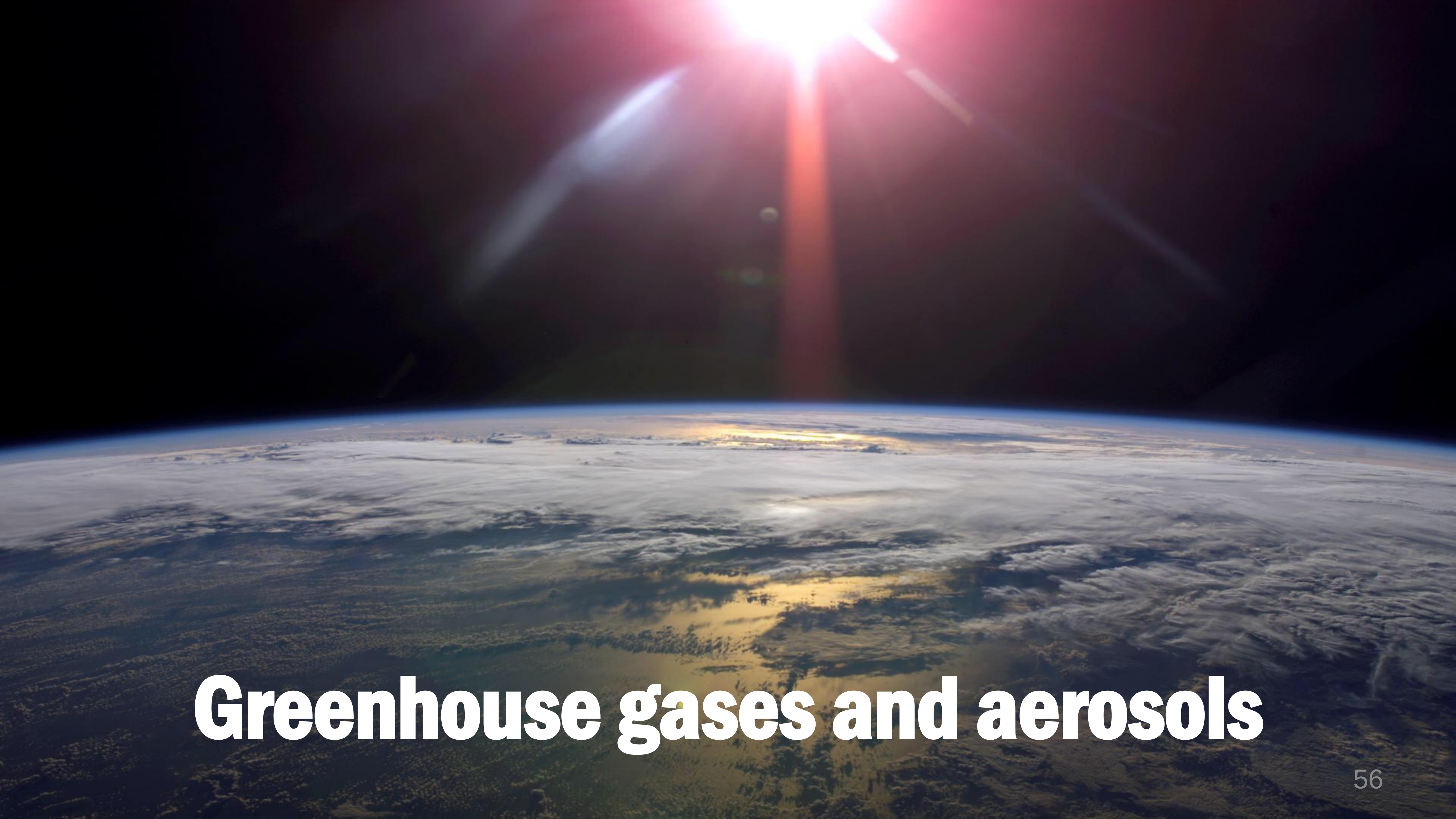
Dashed lines: emission spectra of blackbodies at different temperatures



Source: Hanel and Conrath, Nature, 1970

It shows that:

- Part of the spectrum fits the emission of a blackbody close to 25°C (surface of tropical Pacific) → atmospheric window without absorption.
- A large part of the spectrum sees a much reduced radiation in two specific windows (~9.5 and 15 µm) and below 8 µm.
- Overall, about 40% of a blackbody emission at ~25°C is lost → absorption by the atmosphere (greenhouse effect).
- The corresponding blackbody temperature gives indications of the source of emission.



Greenhouse gases and aerosols

Greenhouse gases

Some fundamentals:

1. **Temperature** measures the average energy of molecular motion in matter: translation, intramolecular vibration, and rotation.

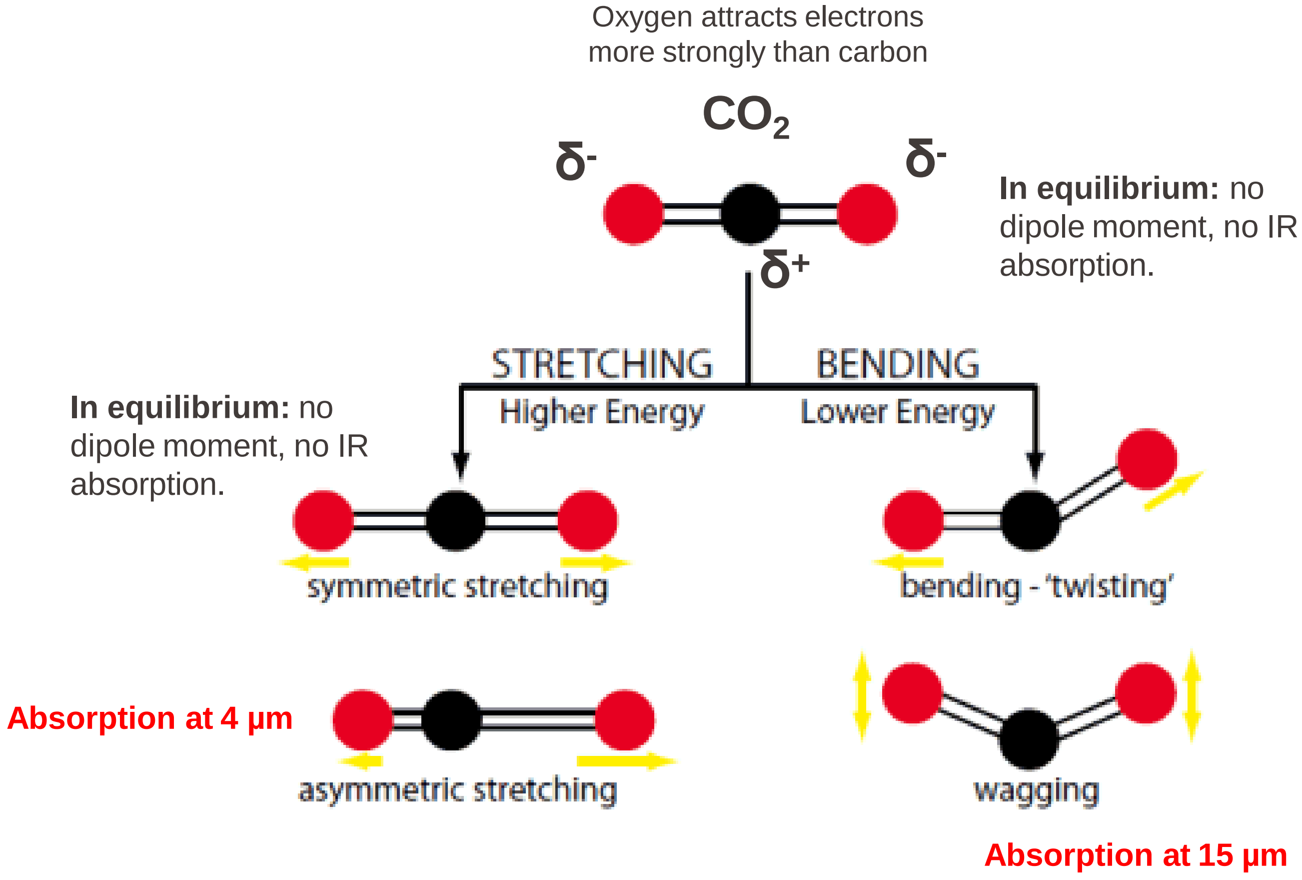
2. **Molecular vibrations** *(and some rotations)* have energy level spacings that correspond to IR energies in the electromagnetic spectrum. Thus IR radiation absorbed by molecules causes increased vibration.

3. **Collisions** between energized molecules and other molecules in the atmosphere transfer energy to the whole medium, increasing the average thermal energy and thus raising temperature.

Greenhouse gases

4. Some molecules have a dipole: the average center of their charges do not always coïncide. In equilibrium for CO_2, no dipole moment.

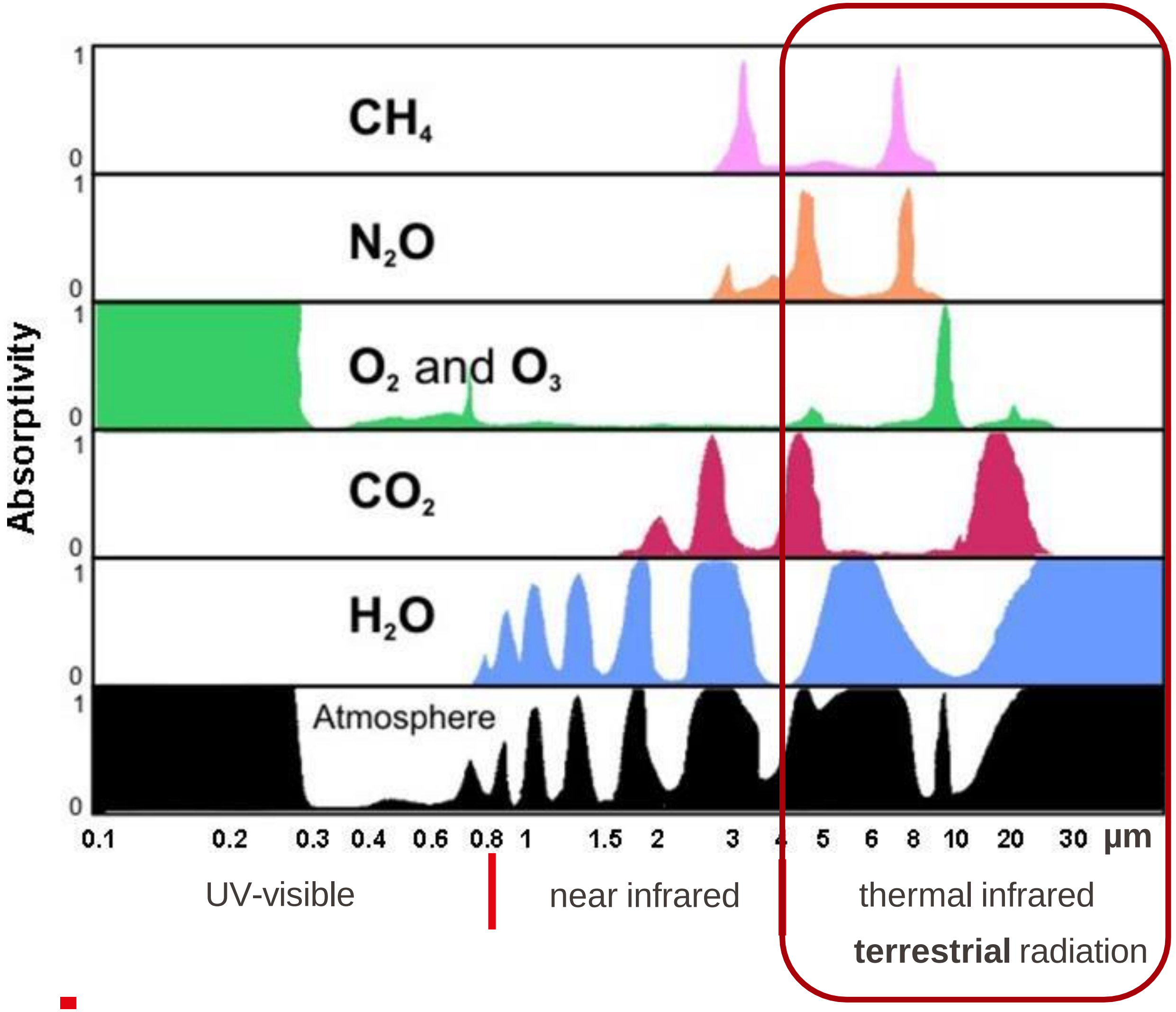
4. Molecular vibrations absorb IR energy if the molecule changes its dipole moment. All molecules with three or more atoms meet this criterion and are IR absorbers.
5. The Earth's atmosphere is composed at ~99% of N_2 (78%), O_2 (21%), and Ar (~0.9%), which are not IR absorbers. The remaining 0.1% includes so-called «trace gases», several of them absorbing IR.
6. This is the case for water vapor, which is the main greenhouse gas.
7. Water vapor and other greenhouse gases are naturally present in the atmosphere. The greenhouse effect is a natural phenomenon.



Source: http://www.chm.bris.ac.uk/motm/CO2/?C=S;O=A

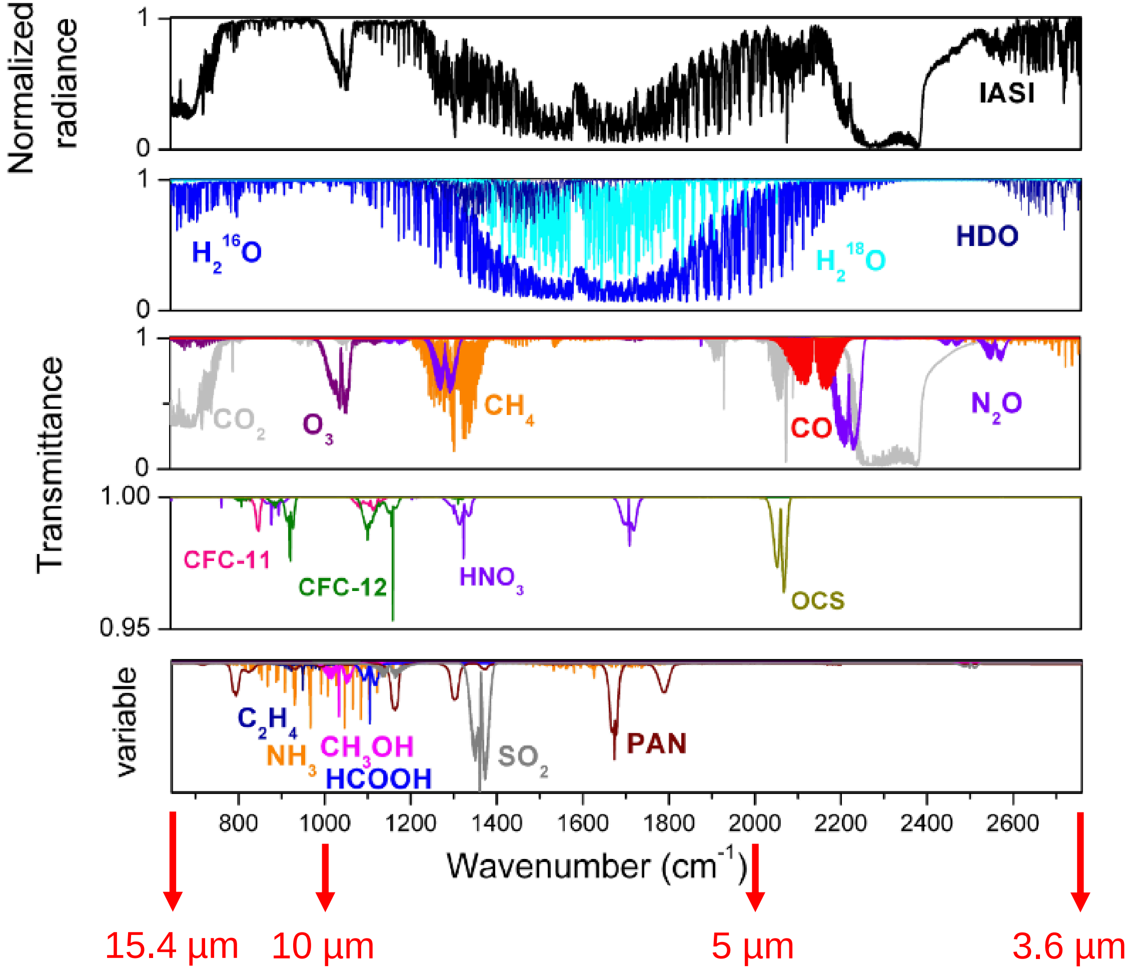
Greenhouse gases

Strong absorption by greenhouse gases in the thermal infrared range.



Many more greenhouse gases than H_2O, CO_2, CH_4, N_2O, O_3

IASI interferometer on Eumetsat satellite

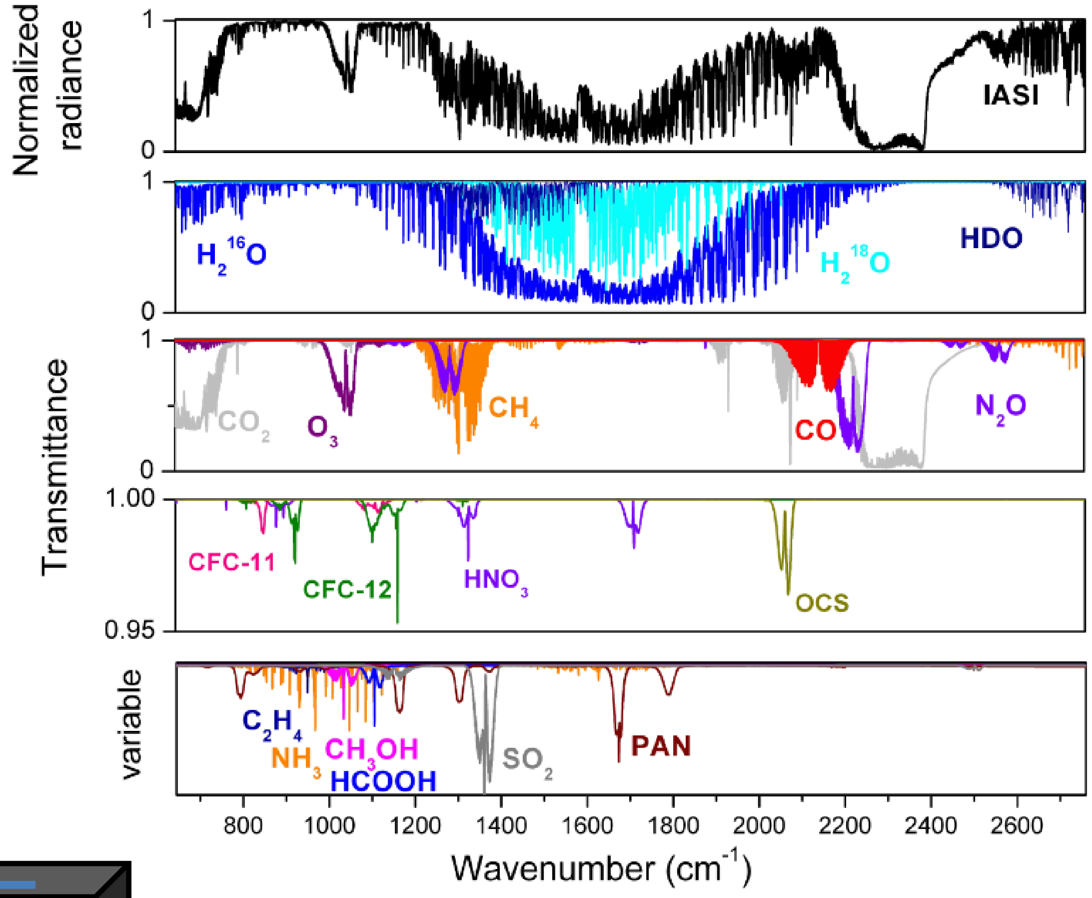


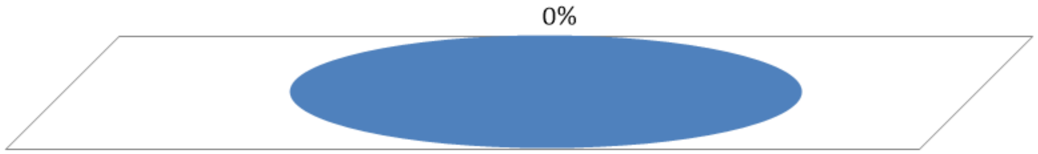
Source: *[Clerbaux et al., Atm. Chem. Phys. 2009](#)*

Greenhouse gases: an inconsistency ?

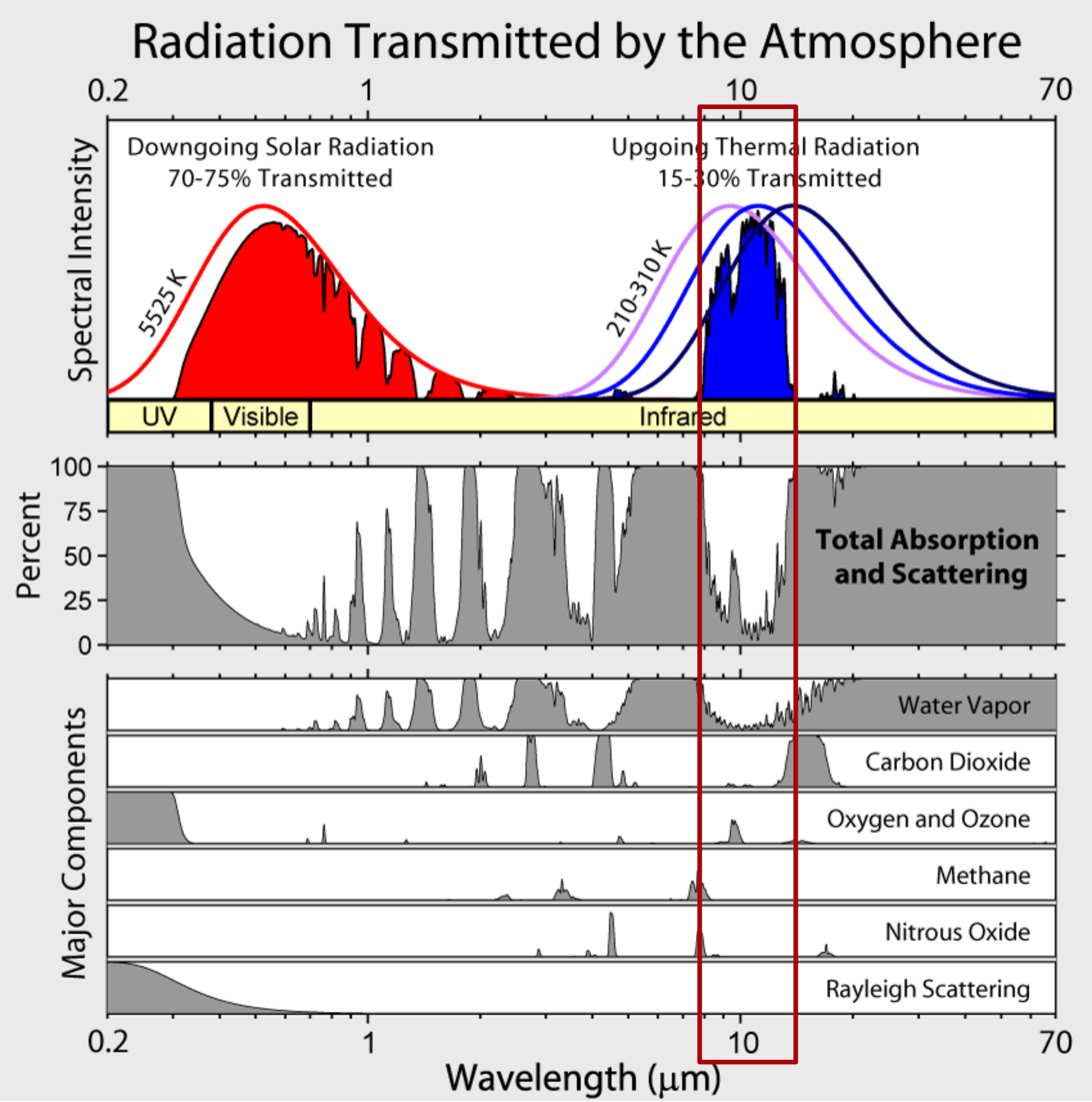
Do you see an anomaly among the molecular constituants ?
Which one ? *(only one response)*

Rank	Responses
1	CO (two atoms but strong dipole)
2	
3	
4	
5	
6	



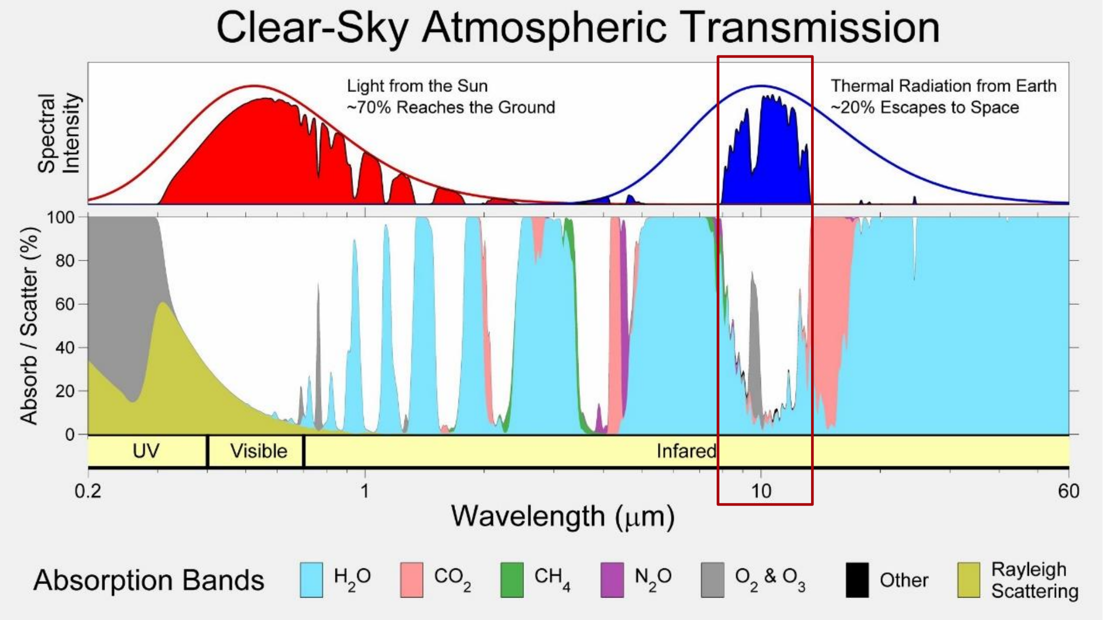


Atmospheric windows



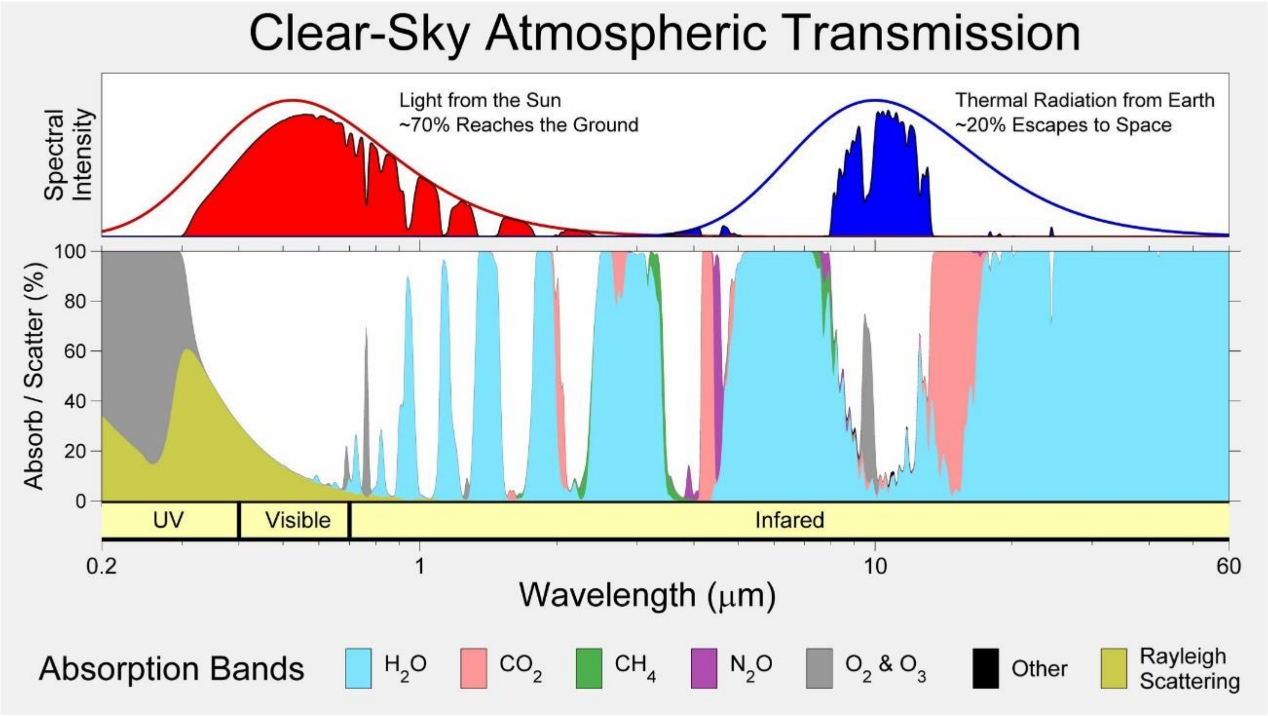
Source: [Wikipedia]

- The atmosphere is largely transparent (window) for shortwave radiation
- There is a window in the longwave spectrum where the absorption or scattering is reduced.
- The window is between ~8–9 μm and ~10–12 μm *(O_3 absorption in-between, at 9.6 μm).*
- Increased amount of greenhouse gases tends to reduce the window.



Source: [Introduction to Climate Data Science, Durham University]

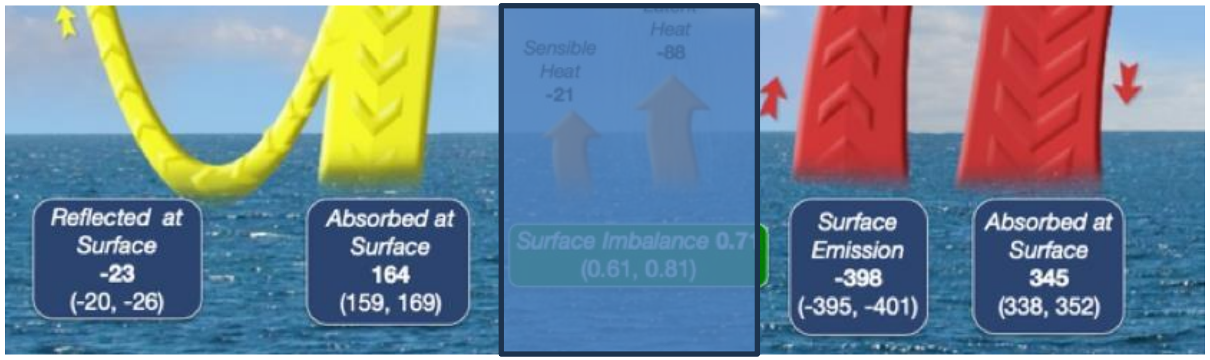
Greenhouse effect in a nutshell



1. Solar radiation *(shortwave)* largely transmitted through Earth's atmosphere *(when no clouds)*.
2. Earth's surface absorbs the solar radiation and warms.
3. The Earth emits thermal infrared IR *(longwave)* radiation *(~blackbody).*
4. The atmosphere is much less transparent to thermal infrared radiation and absorbs it *(except for a window)*.
5. The absorbed radiation warms the atmosphere.
6. The atmosphere emits thermal IR radiation in all directions, including towards the surface.
7. The net thermal IR flux from the Earth (~blackbody) to space is reduced.
8. The radiative cooling of the Earth's surface is reduced and leads to surface warming.

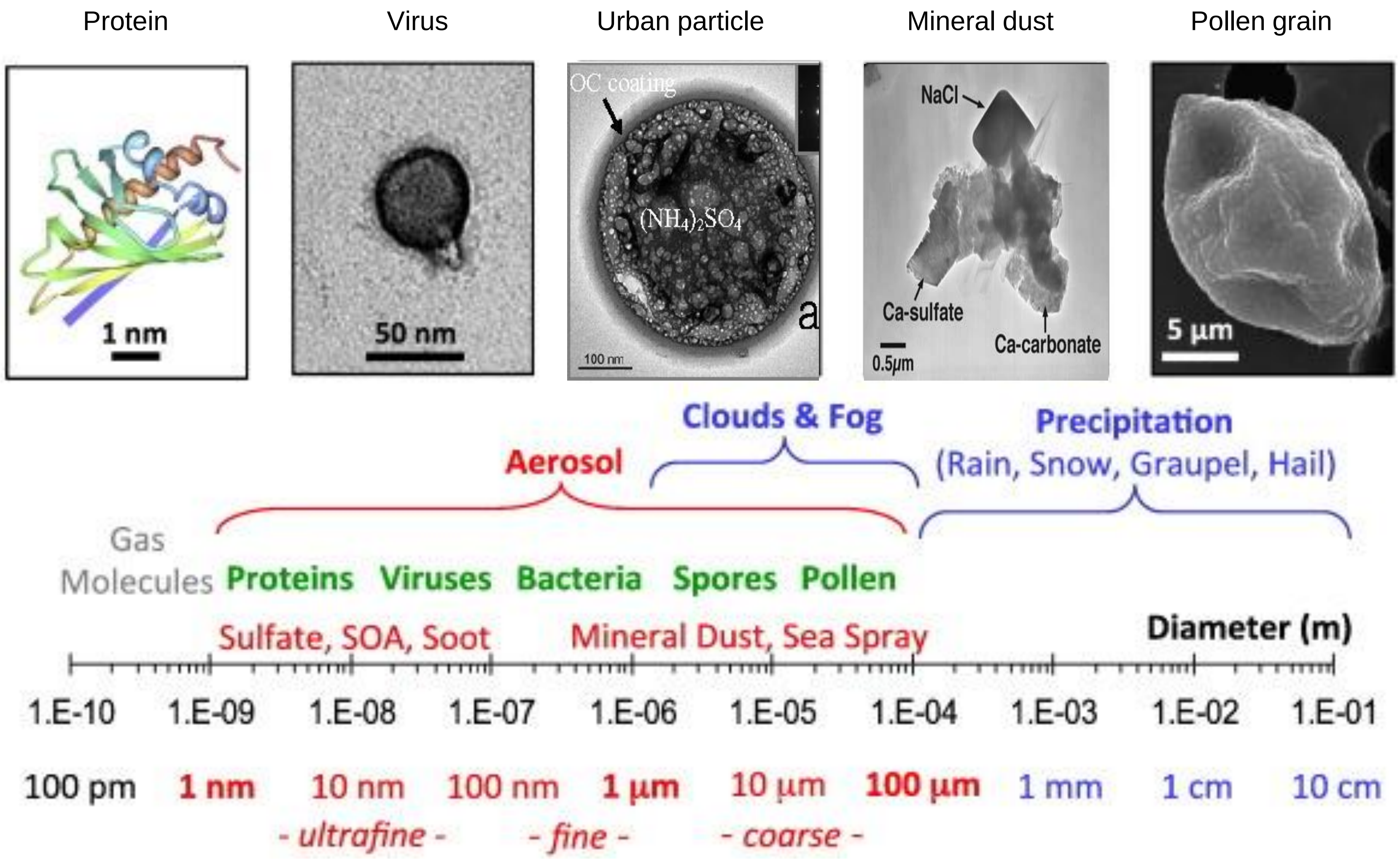
On top of that:

- Convective transport of sensible heat and latent heat (phase change of water vapor) cools the surface and warms the troposphere.
- This leads to an observed lapse rate of -6.5 K / km.



Aerosols

Aerosols are suspensions of liquid, solid or mixed particles of variable chemical composition and size distribution.



Source: Fröhlich-Nowoisky et al. (2016), https://doi.org/10.1016/j.atmosres.2016.07.018

Aerosols and their sources

- **Primary aerosols**: directly emitted into the atmosphere from natural or anthropogenic sources.
- **Secondary aerosols**: formed in the atmosphere by chemical reactions (nucleation) ; they can then coalesce to form bigger aerosols.

Mixed

Forest fires

Natural

Sea spray

Dust

Volcanic eruptions

Traffic / Transport

Domestic activities

Industry

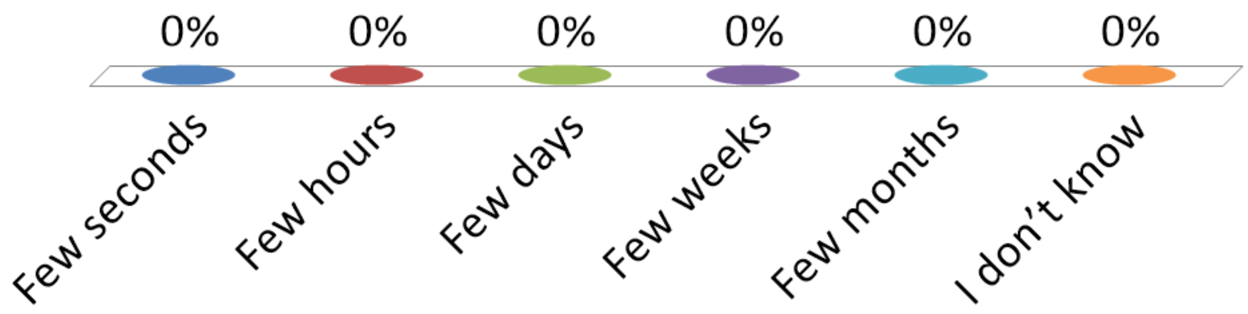
Agriculture

Anthropogenic

What is the typical residence time of a 10 µm aerosol in the atmosphere ?

Residence time: average time for an aerosol to remain in the atmosphere after emission and before it is removed by gravitation, dry or wet deposition or chemical transformation.

A. Few seconds
B. Few hours
✓ C. Few days
D. Few weeks
E. Few months
F. I don't know

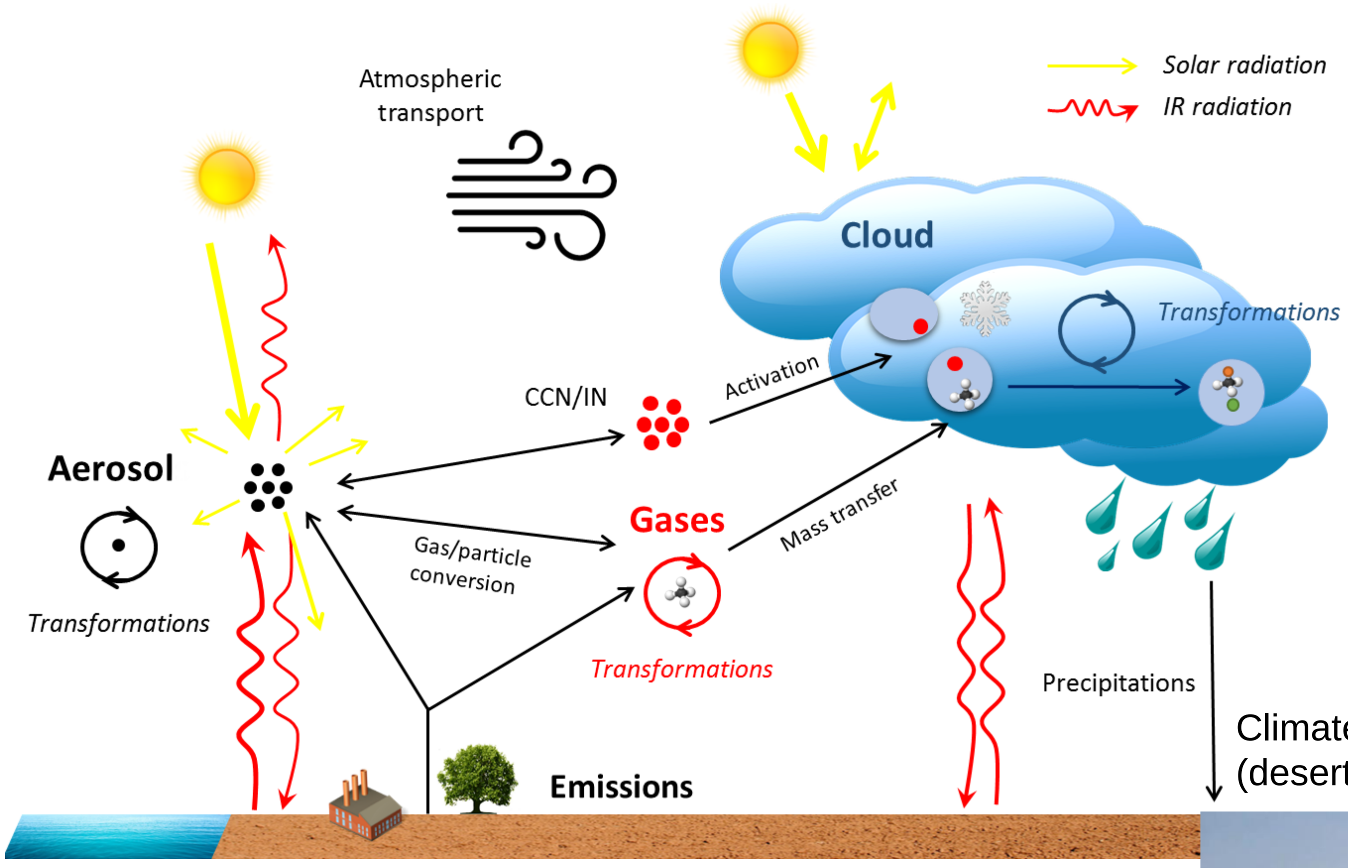


Lifetime of seconds to weeks !
(greenhouse gases = years)
→ Large spatial heterogeneity

Aerosol climate effects

Direct interaction with solar radiation

- Absorption (warming)
  - *mostly black carbon, mineral dust*
- Scattering (cooling)
  - *mostly sulfate and nitrate aerosols, sea spray, secondary aerosols*



Source: Baray et al., Atm. Measurement Tech., 2020

Indirect interaction with solar radiation through clouds

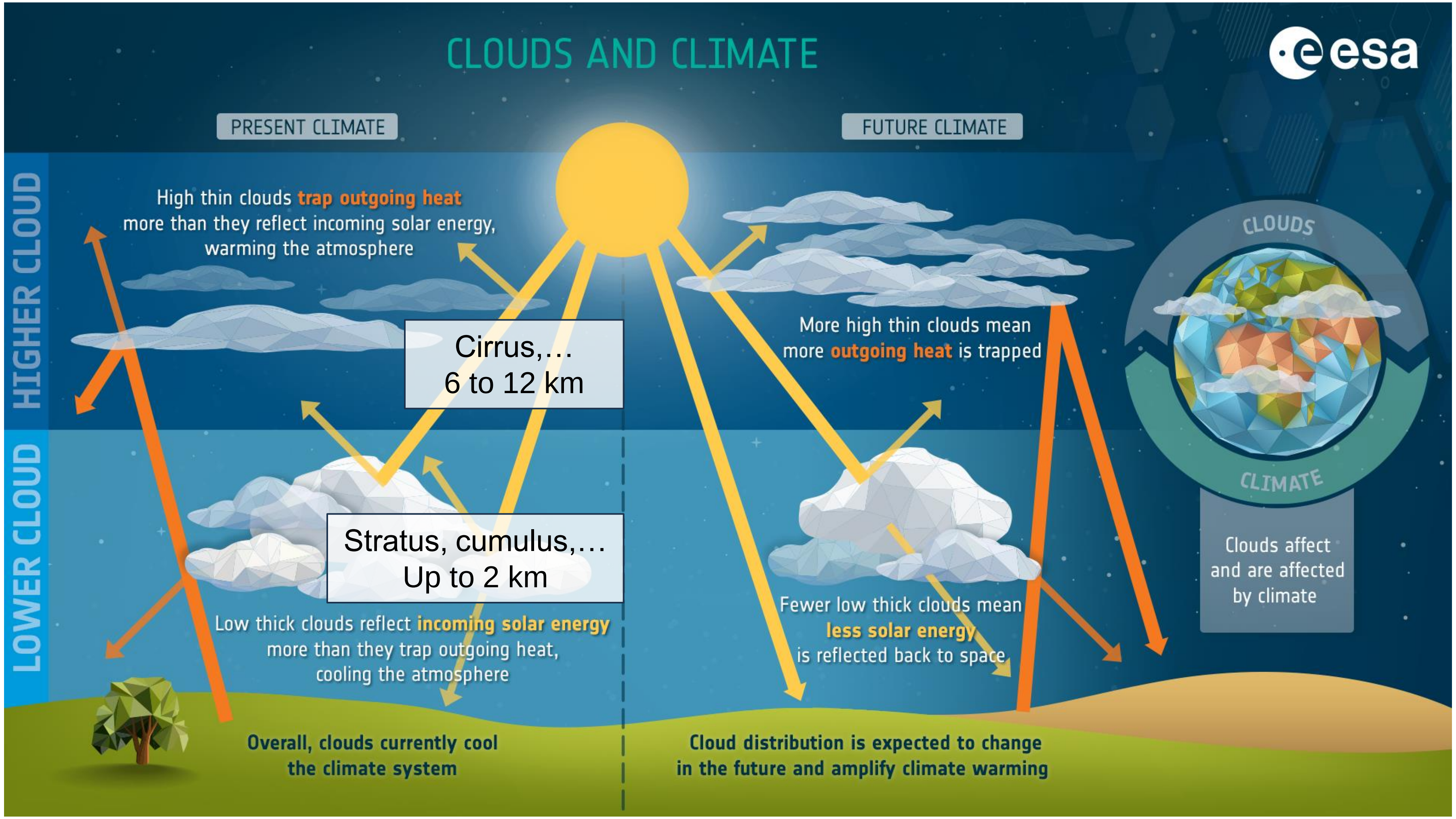
- Cloud condensation nuclei (CCN)
- Ice nucleating particles (INP)
- Generate clouds (warming or cooling depending on altitude)
- Enhance cloud reflectivity (more droplets, higher albedo) and cloud lifetime (thus cooling)

Climate impact through surface albedo (desert dust, black carbon) → warming

Source: Getty Images

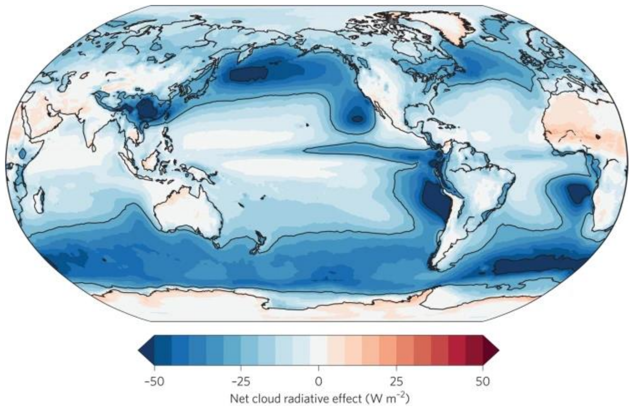
Cooling or heating by clouds

Cloud effect on the Earth's radiative balance depends on cloud amount, cloud altitude and cloud opacity



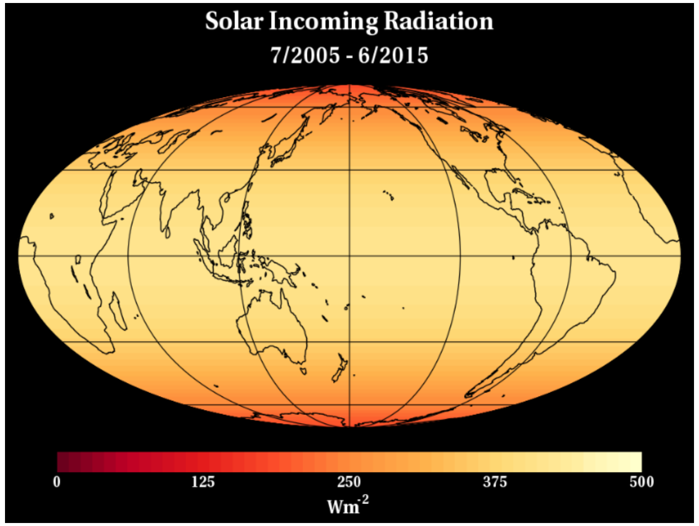
Source: [European Space Agency]

Source: *[Zelinka et al., Nature 2017]*

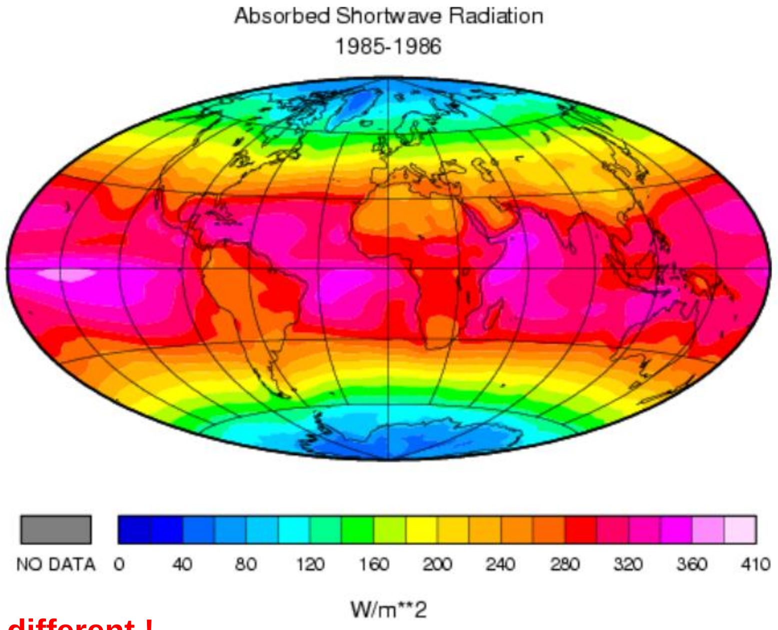


- All-sky versus clear-sky net radiative flux 2001-2016, based on satellite observations and modelling.
- Annual global mean: reduce the radiative input by 18 W.m^{-2}.
- Future scenarios could change the sign of the cloud impact.

Earth's energy balance



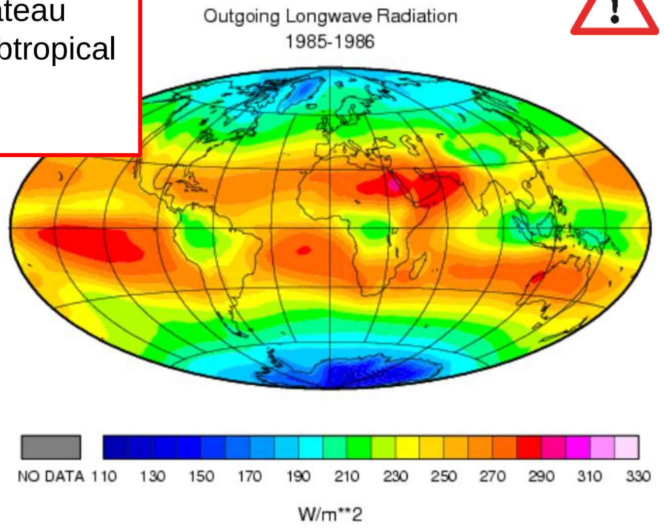
Incoming solar shortwave radiation at top of the atmosphere. CERES-EOS satellite data.



Annual mean net downward shortwave radiation. NASA/ERBS satellite data

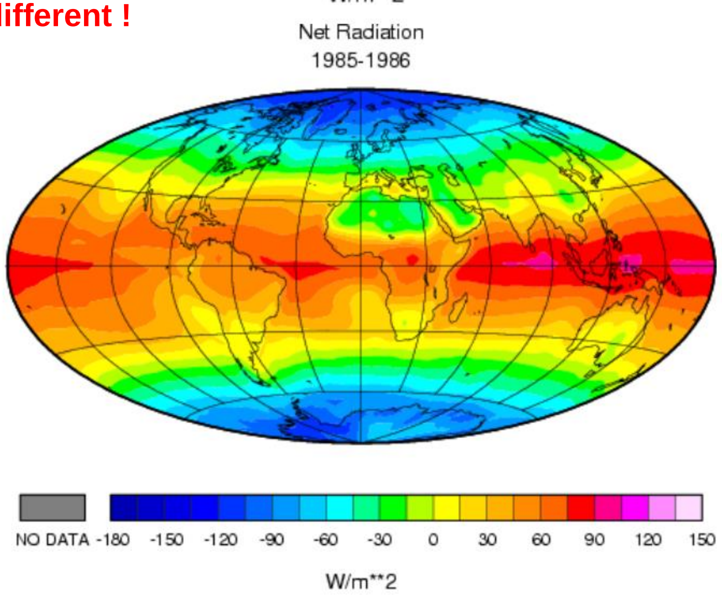
- High albedo of deserts and high latitudes
- Cloud cover
- Low solar radiation at high latitudes

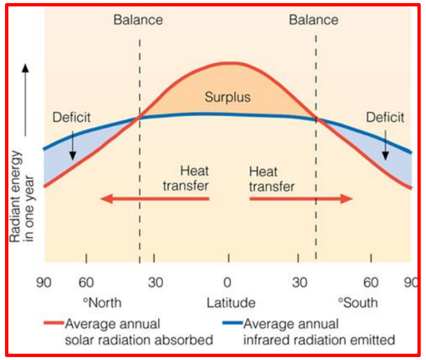
- High clouds along the equator
- Altitude of Tibetan Plateau
- Warm deserts and subtropical oceans
- Cold polar regions



Annual mean net outgoing longwave radiation. NASA/ERBS satellite data

Scales are different !





Net radiation: outgoing longwave minus net downward shortwave

The motor of latitudinal transport of energy by the atmosphere and the oceans from the equator to the pôles !

Sources: [NASA CERES Project](#) and [NASA/ERBE Project](#)

Summary: Climate system, Earth energy balance, greenhouse gases and aerosols

- The climate system can be described as **“spheres”**, having their own dynamics and interacting between each other. The anthropogenic impacts add another sphere.
- The Earth’s climate system is driven by the **sun**.
- The atmosphere mediates the flow of energy from the sun to the Earth and back to space (**effects of greenhouse gases, aerosols and clouds**).
- **Convection and latent heat transfer** are important physical phenomena transferring heat from the surface to higher altitudes.
- In addition to energy transfer, **water and carbon** are important molecules flowing between the spheres.
- The greenhouse effect is a **natural phenomenon**. Human activities increase it, in particular by affecting the **atmospheric window** of longwave radiation centered at 10 µm.
- Aerosols impact the radiative balance both on **shortwave and longwave radiations**. Major control on **clouds**.
- The spatial and temporal patterns of **energy distribution between latitudes** (and altitudes) drive atmospheric and oceanic circulations.