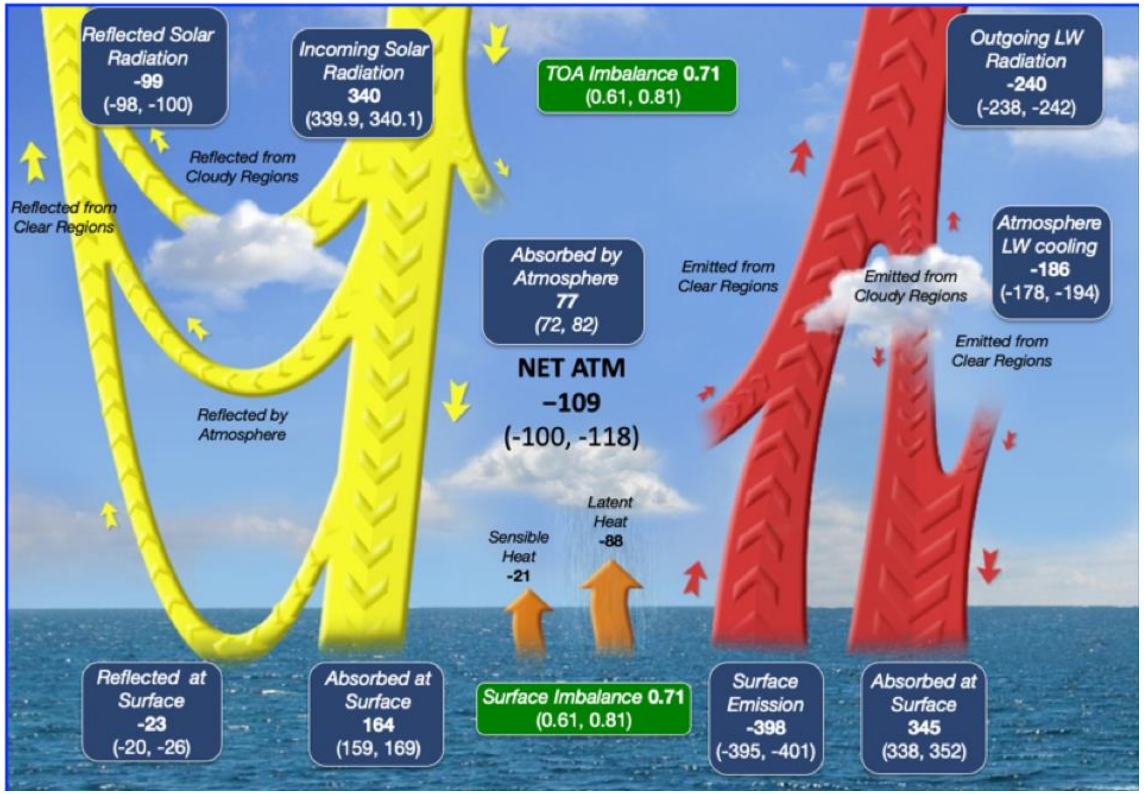
Recap from last lecture

- Know the concepts of latent and sensible heat, adiabatic processes, albedo
- Understand the carbon and water cycles and their roles in the climate system
- Climate relevant processes can happen on the order of hours to centuries
- Distinguish between shortwave and longwave radiation

Earth's Energy Balance (W/m2)



Planck function (T, λ)

$$(B_\lambda(\mathrm{T})) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

Wien's displacement law

$$\lambda_{max}\ (\mu m) = \frac{2897}{T}$$

Stefan-Boltzmann law

$$F_B\ (\mathrm{T}) = \sigma\, T^4$$

General outline

Basics

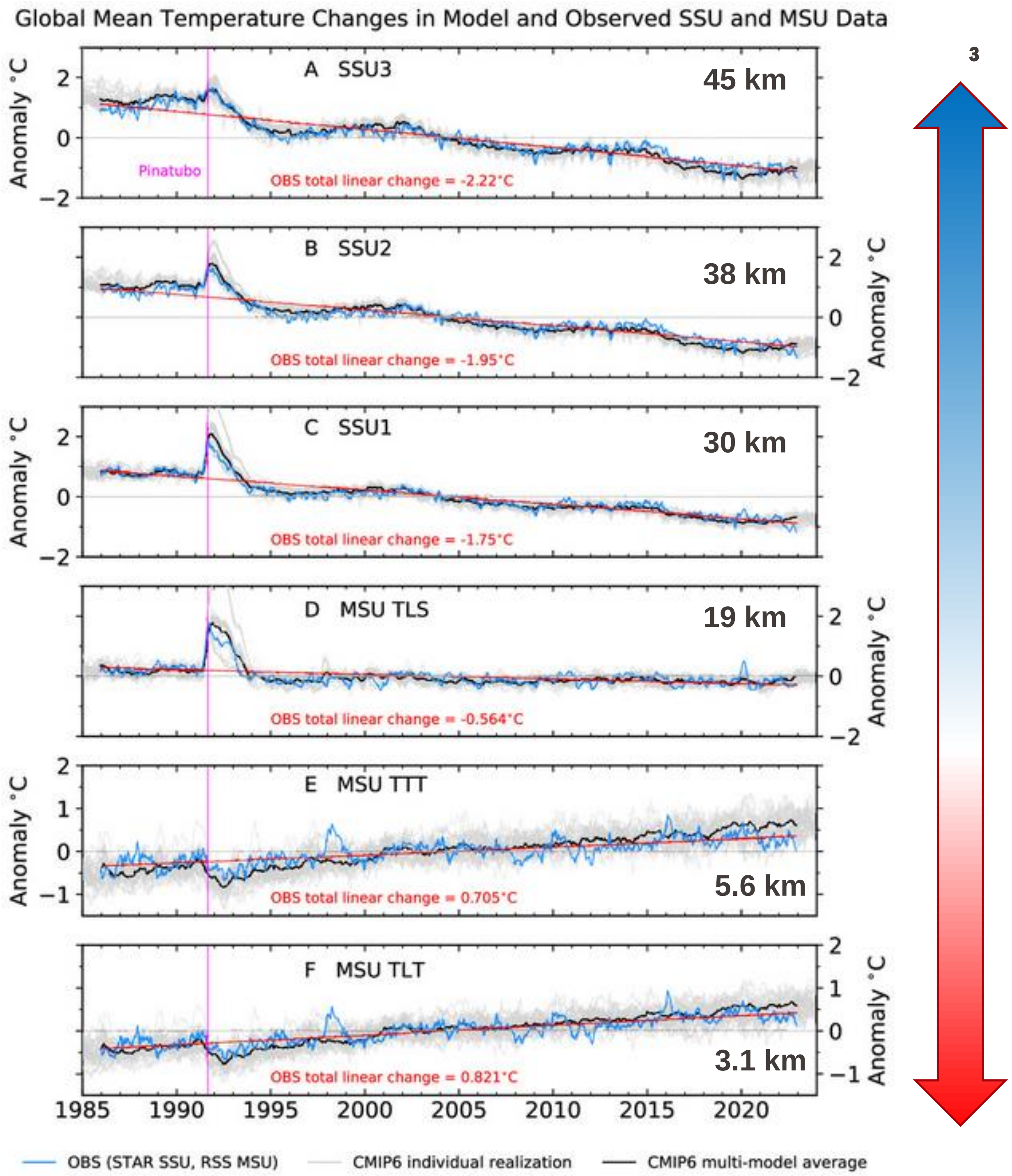
Present and future Climate change

Actions

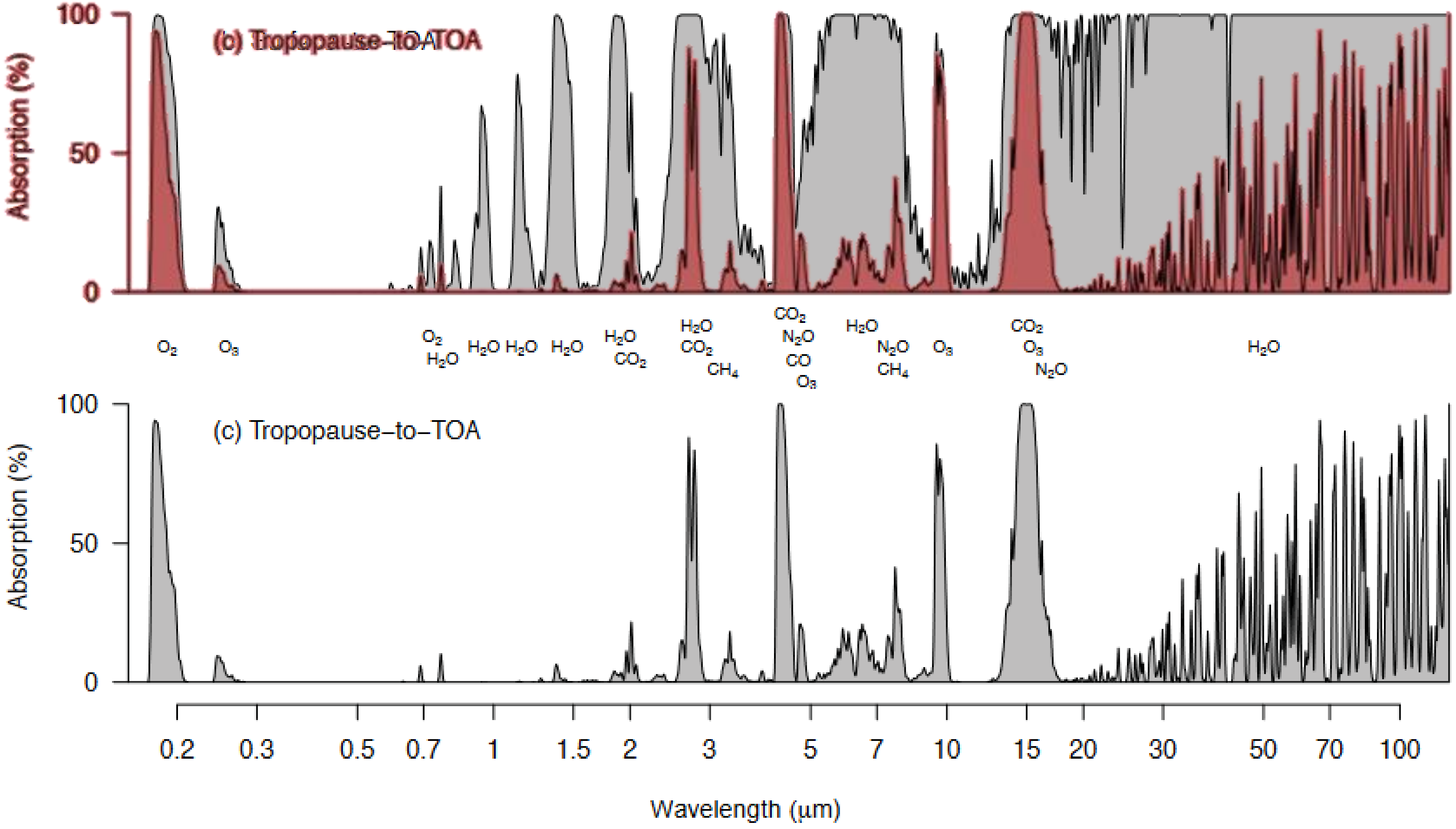
No.	Date	Topics	Deadlines
1.	12.09.2024	Introduction	fill in Questionnaire in exercises (not graded)
2.	19.09.2024	Climate System, Radiation, Greenhouse effect	
3.	26.09.2024	Earth's energy balance, Radiative transfer, aerosols & clouds	
4.	03.10.2024	Radiative Forcing, Feedback mechanisms	Launch of poster assignment
5.	10.10.2024	Climate Sensitivity	
6.	17.10.2024	Paleoclimate	submission of Poster proposal (01.11.2024)
7.	31.10.2024	Climate variability	
8.	07.11.2024	Paris Agreement, Emission Gap, IPCC – present day climate change	
9.	14.11.2024	Extreme Events	
10.	21.11.2024	Climate scenarios (RCPs, SSPs), Tipping elements, 1.5 vs 2.0°C	submission of Poster draft
11.	28.11.2024	Carbon budget, carbon offsets, metrics	submission of assignment (graded)
12.	05.12.2024	Regional climate change	
13.	12.12.2024	Mitigation and adaptation, Climate Engineering	**Poster Conference** (graded)
14.	19.12.2024	Recapitulation of key points, questions and answers session	fill in Questionnaire in exercises (not graded)

Stratospheric cooling

- The stratosphere has been cooling as the troposphere is warming.
- Contributing effects are:
  - Depletion of the ozone layer. Ozone is a greenhouse gas. Less ozone means less IR absorption.
  - More CO_2 in the troposphere means that the flux of 15 µm IR to the stratosphere is diminished. So stratospheric CO_2 absorbs less IR while emitting the same amount.



Atmospheric absorption spectra



Entire atmosphere

Without troposphere

doi:10.5194/esd-7-697-2016

- https://www.pnas.org/doi/10.1073/pnas.2300758120

Summary of greenhouse effect processes

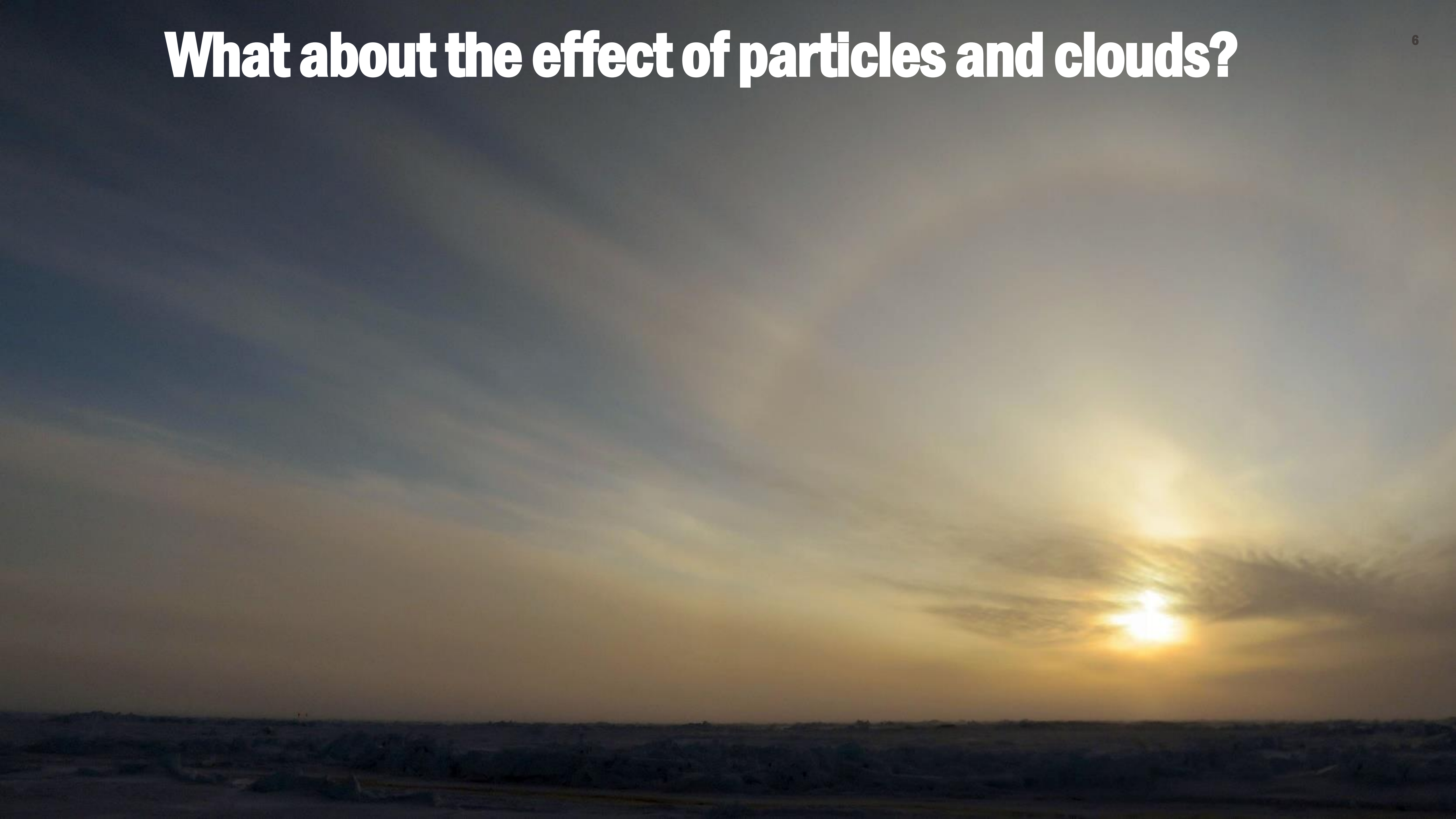
- In summary the greenhouse effect induced by infrared-active gases consists of three elements:

1. Downwelling irradiance from the atmosphere to the surface, heating the surface and elevating the surface temperature;
2. A decrease in upwelling irradiance at the top of the atmosphere; and
3. Radiative cooling (and heating) of the atmosphere, affecting the vertical temperature structure of the atmosphere.

Which type of radiation is referred to in points 1-3?

A. 1 – shortwave,
   2 – shortwave,
   3 – longwave
B. All longwave
C. 1 – longwave,
   2 – longwave,
   3 – shorwave
D. 1 – short- and longwave,
   2 – longwave,
   3 – longwave
E. All shortwave

What about the effect of particles and clouds?



What are aerosols?

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

Paris smog is caused by aerosols.

Sources of aerosols

Forest fires

Sea spray

Dust

Volcanic eruptions

Traffic / Transport

Domestic activities

Industry

Agriculture

Sources of aerosols

Mixed

Natural

Forest fires

Sea spray

Dust

Volcanic eruptions

Traffic / Transport

Domestic activities

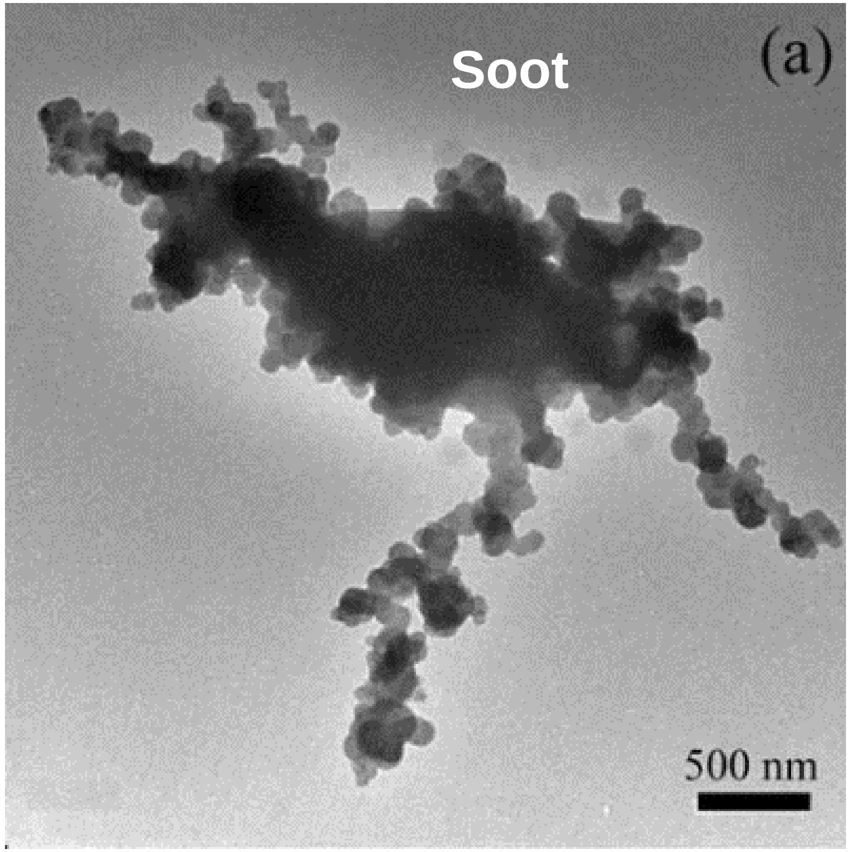
Industry

Agriculture

Anthropogenic

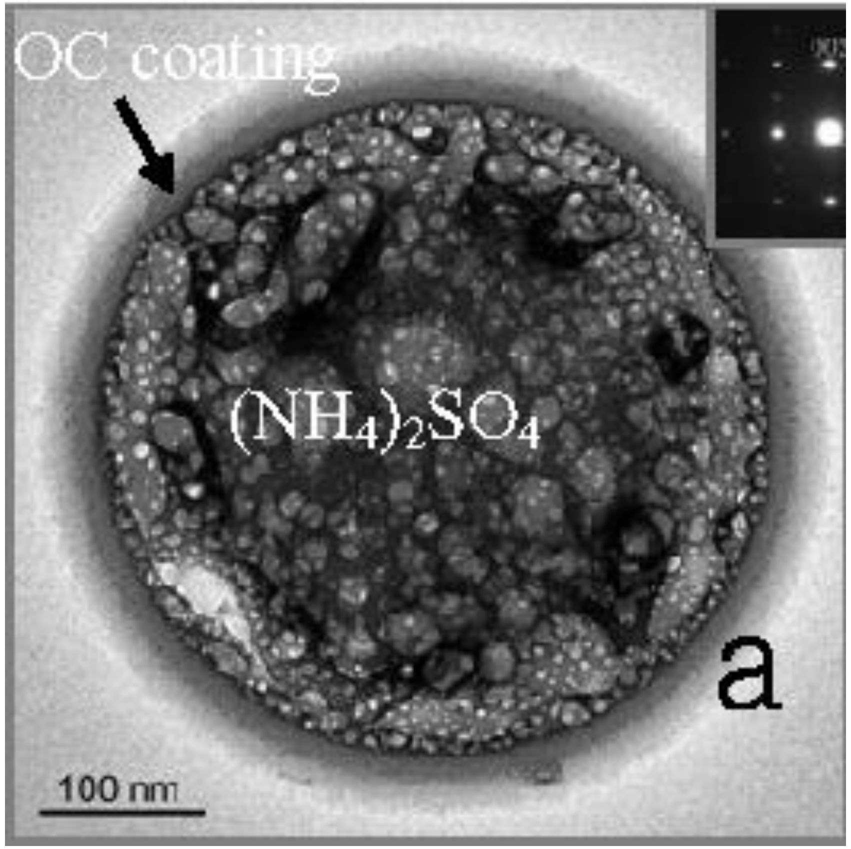
Types of aerosols

Primary



Primary particles are emitted from their source as particles. Examples: soot for combustion, mineral dust from soil.

Secondary

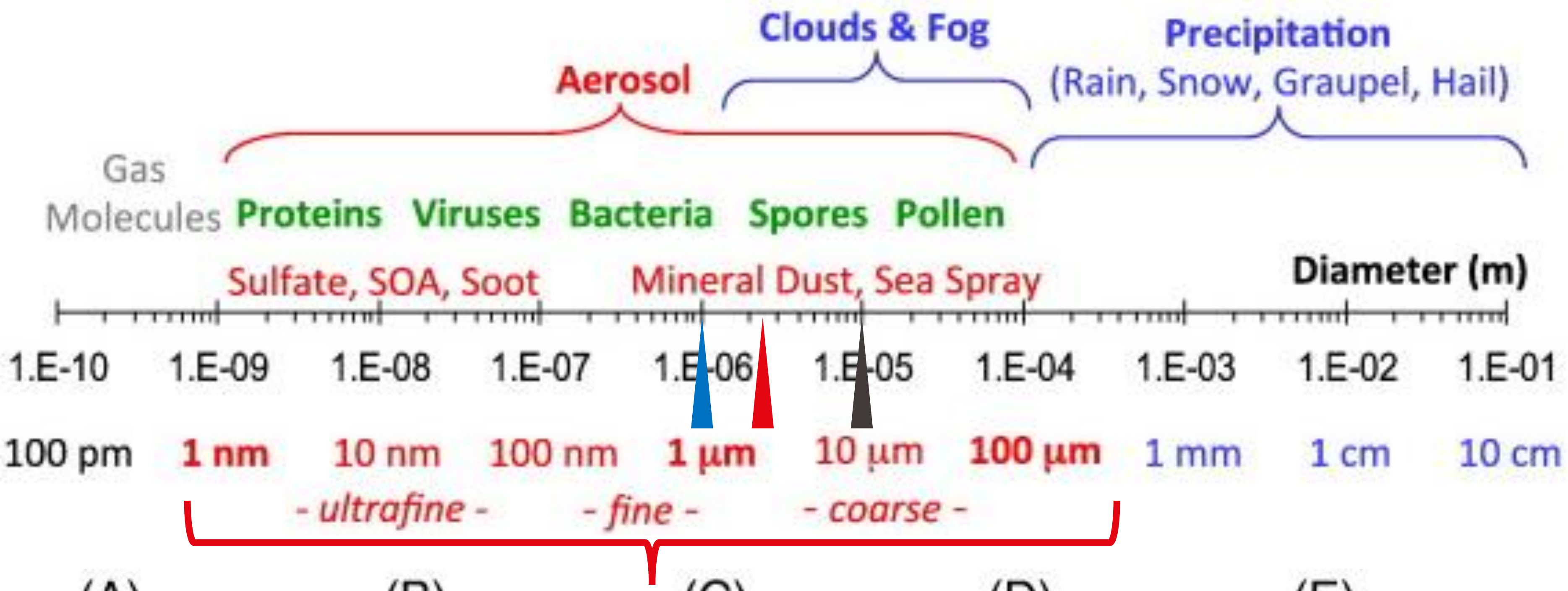


Secondary particles are NOT emitted as particles, but they are formed from gases in the atmosphere through condensation or chemical reactions (in clouds). Examples: Ammoniumsulfate, ammoniumnitrate, secondary organic aerosol

Images are from a Transmission Electron Microscope (TEM).

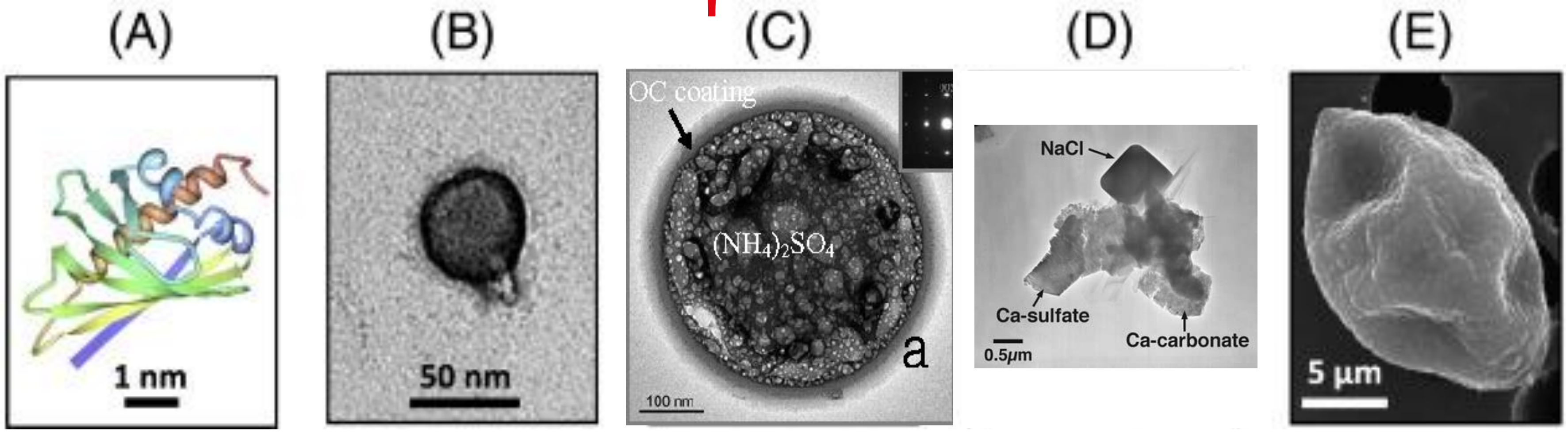
Links to papers: right, left

Size of aerosols



PM_1
$PM_{2.5}$
PM_{10}

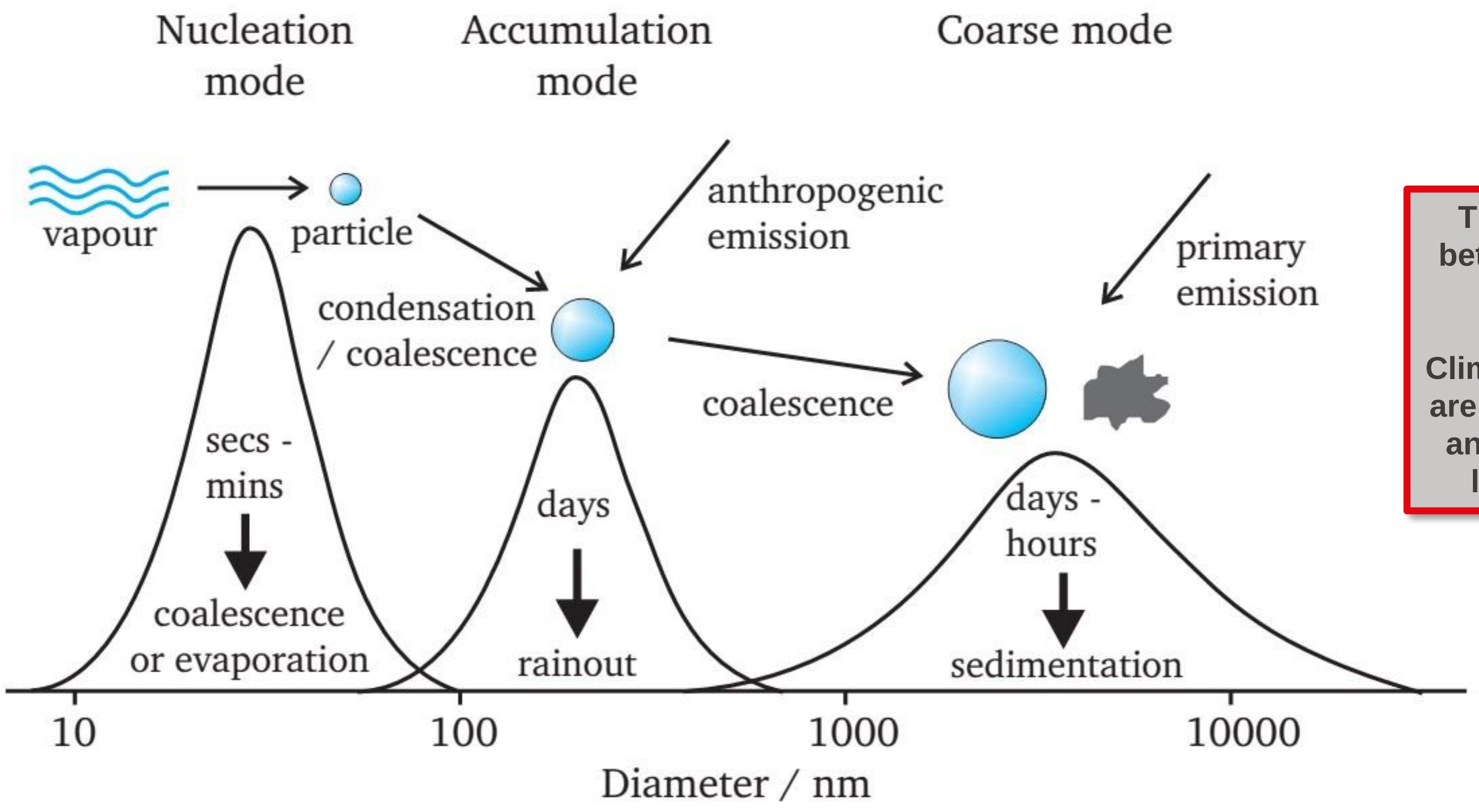
Particulate matter with a diameter equal to or smaller than x µm (air quality)



(A) protein,
(B) virus
(C) Urban particle
(D) Mineral dust
(E) pollen grain

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

Size and Atmospheric Lifetime



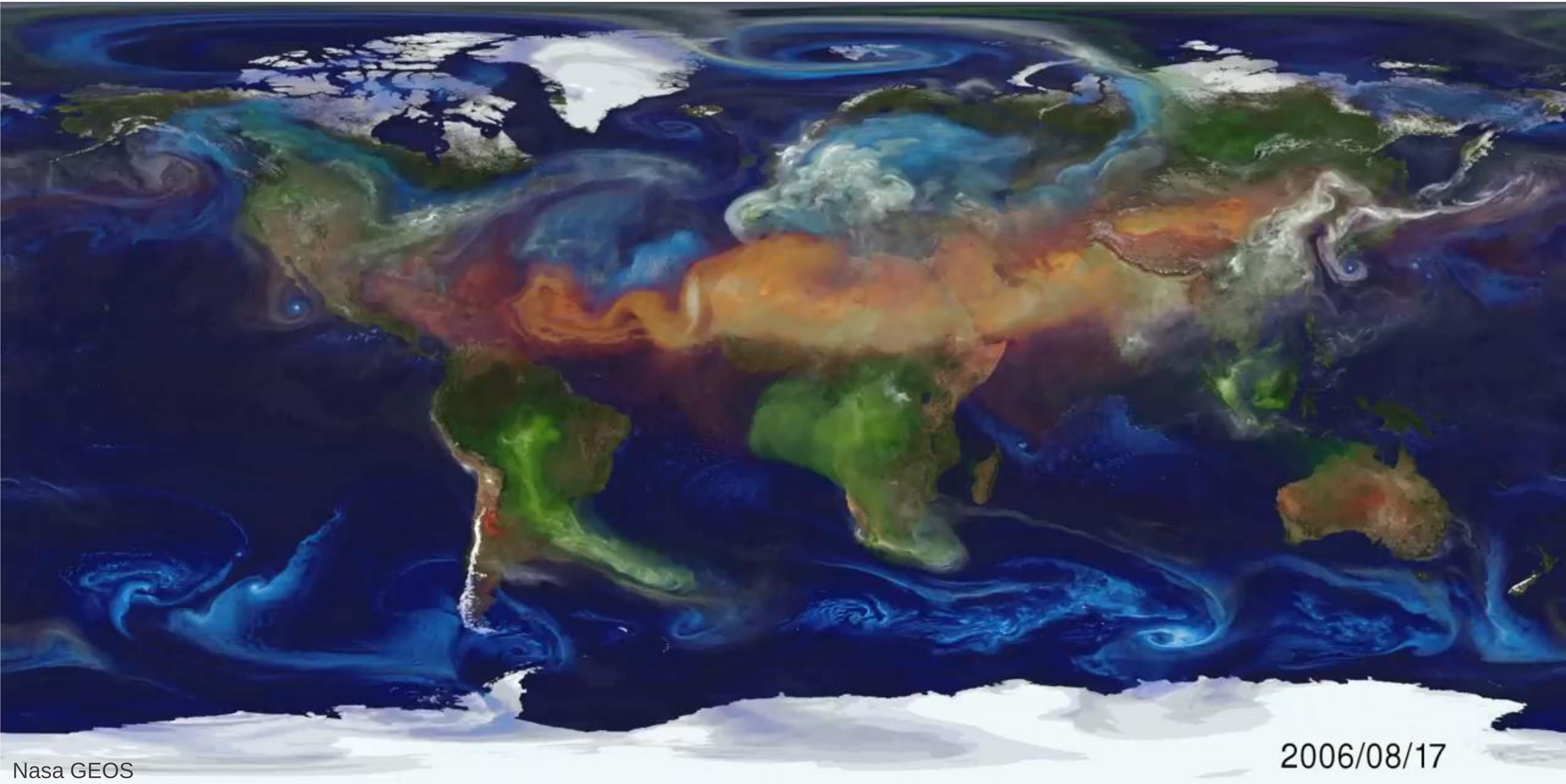
The atmospheric lifetime is between seconds and several weeks.

Climate active aerosol particles are mostly in the accumulation and coarse mode and have a lifetime of days to weeks.

EPFL

Global transport of aerosols

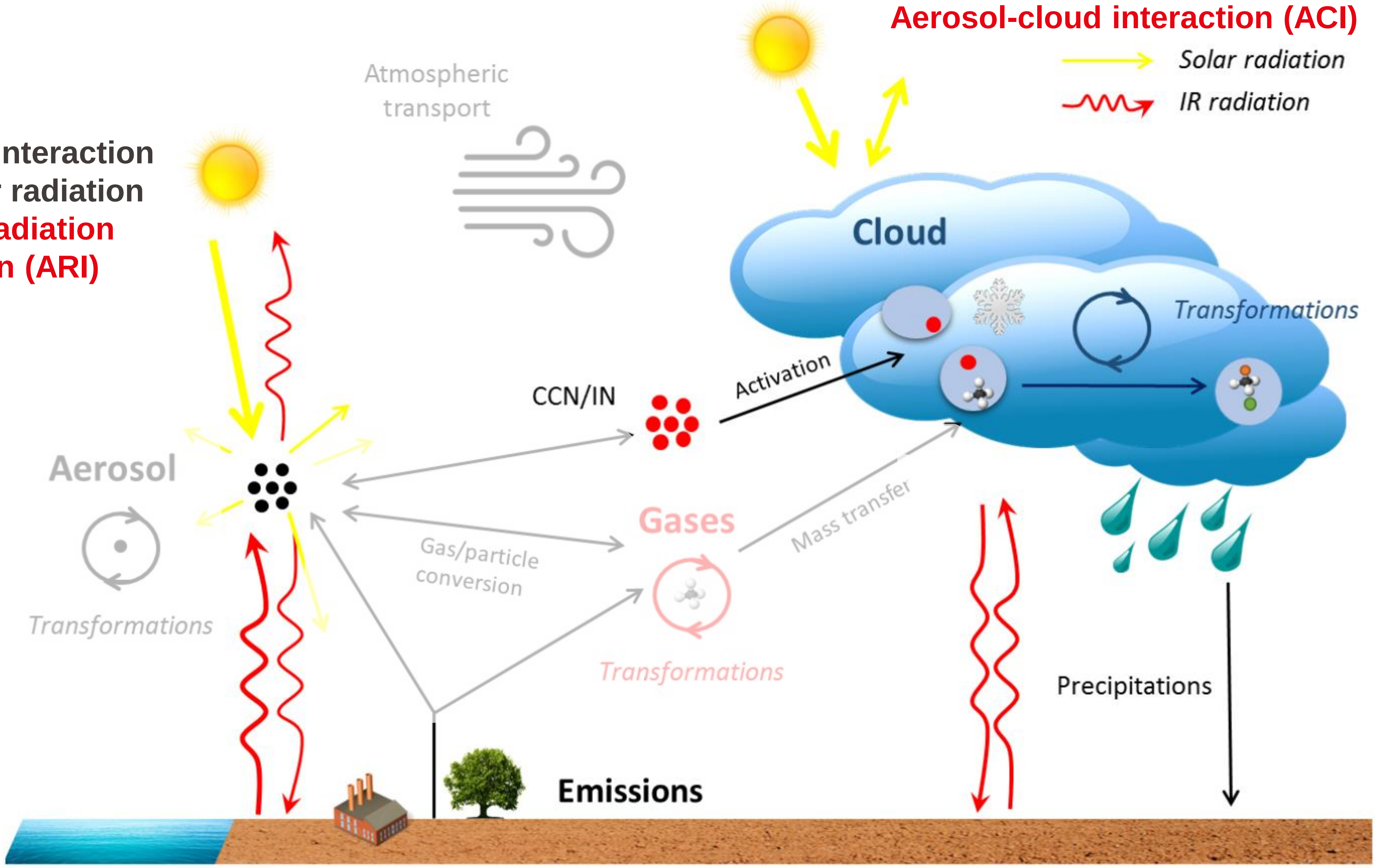
Mineral Dust
Anthropogenic
Forest Fire Emissions
Sea Spray



Aerosol climate effects

B. Indirect interaction with solar radiation through clouds
Aerosol-cloud interaction (ACI)

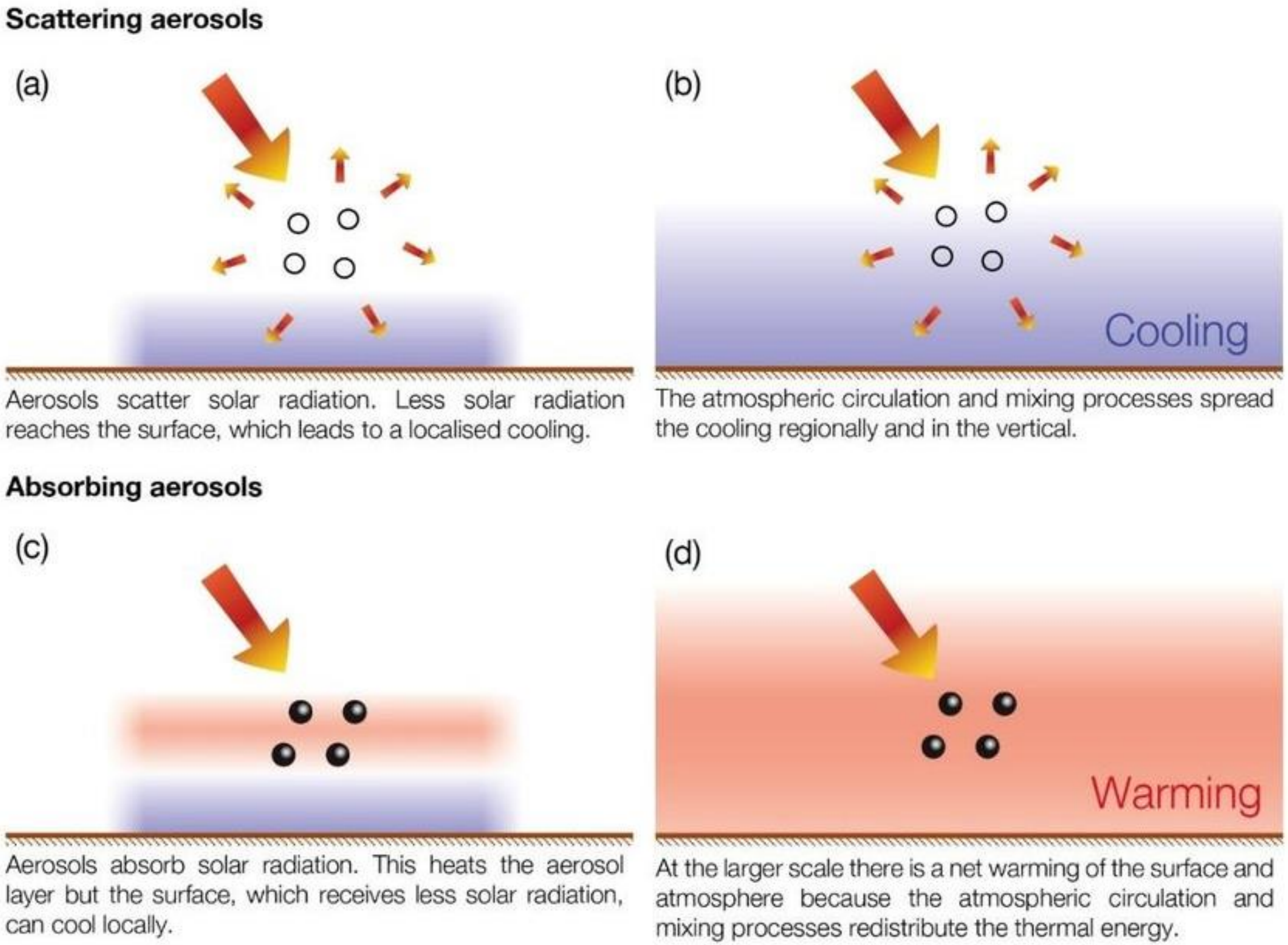
A. Direct interaction with solar radiation
Aerosol-radiation interaction (ARI)



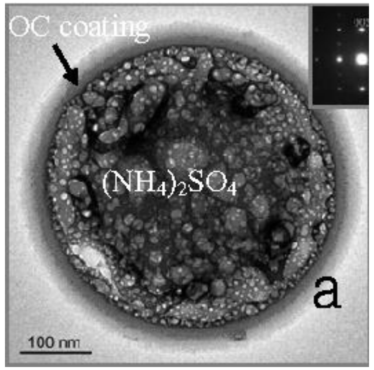
- Baray et al., 2020, https://doi.org/10.5194/amt-13-3413-2020

EPFL

Aerosol-radiation interaction

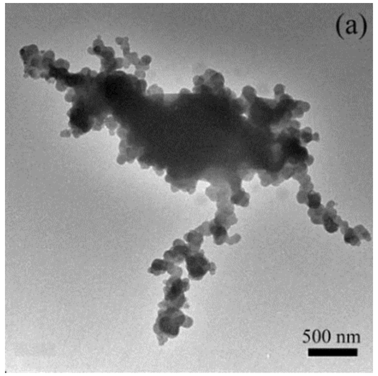


Aerosols reflect solar radiation, thereby shielding (masking) the Earth's surface from radiation



Ammonium, sulfate, nitrate, some organics

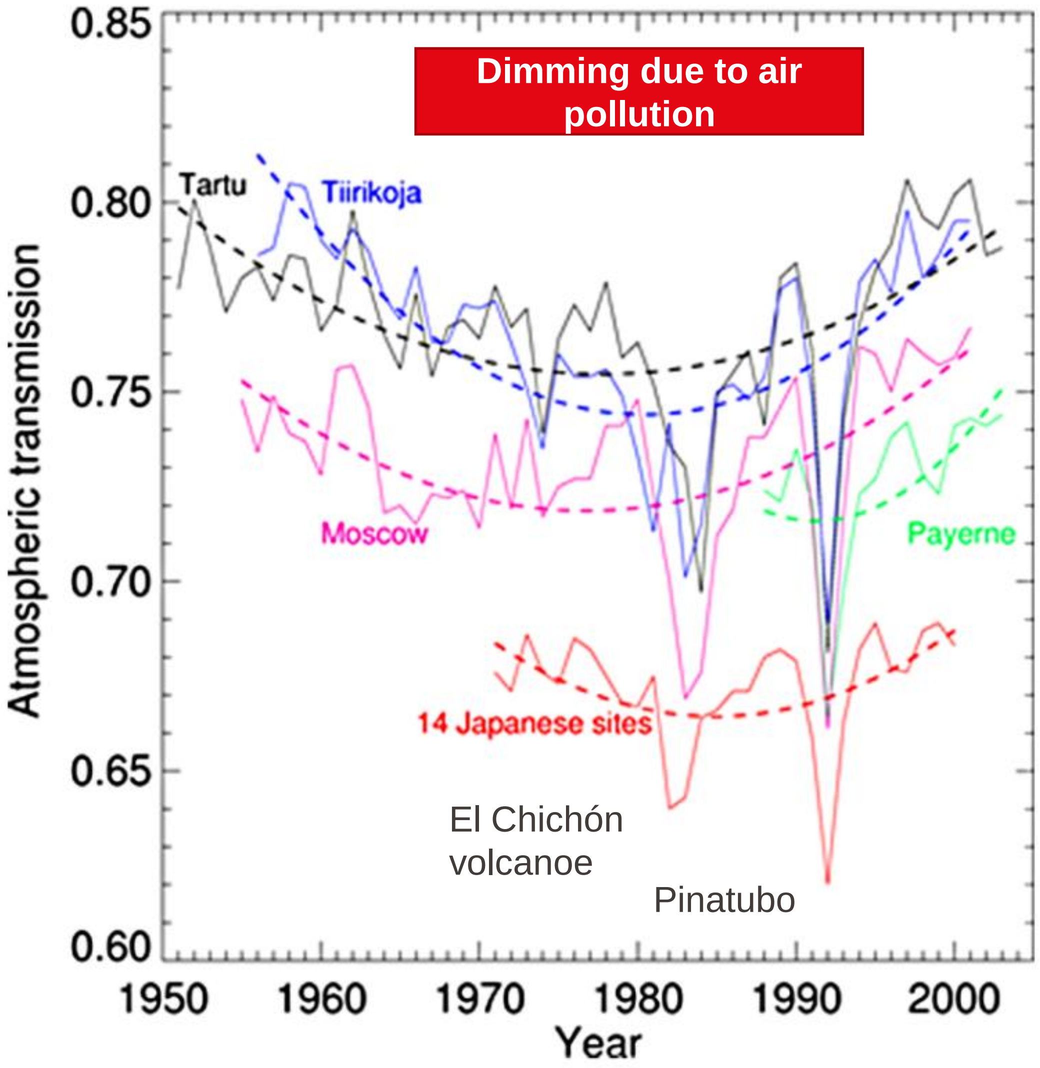
Aerosols absorb solar radiation, thereby warming the air



Soot and some types of mineral dust

- http://www.climatechange2013.org/report/reports-graphic/ch7-graphics/

Aerosol-radiation interaction



Aerosols prevent solar radiation from reaching the Earth's surface, they have a «dimming» effect.

Observed tendencies in surface solar radiation

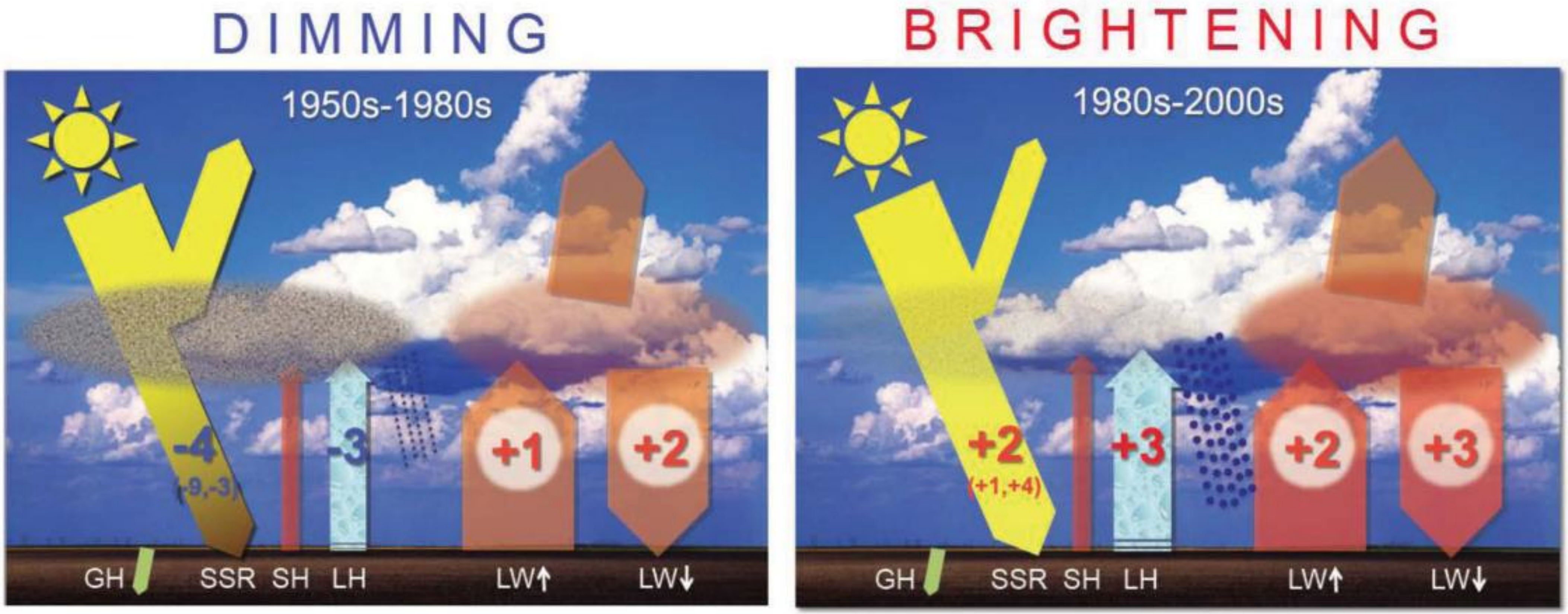
	1950s-1980s	1980s-2000	after 2000
USA	-6 ↘	5 ↗	8 ↗
Europe	-3 ↘	2 ↗	3 ↗
China/Mongolia	-7 ↘	3 ↗	-4 ↘
Japan	-5 ↘	8 ↗	0 →
India	-3 ↘	-8 ↘	-10 ↘

Units in W m^{-2}

- Fuzzi et al., 2015, doi:10.5194/acp-15-8217-2015

[Wild, 2021, https://doi.org/10.1175/BAMS-D-11-00074.1](https://doi.org/10.1175/BAMS-D-11-00074.1)

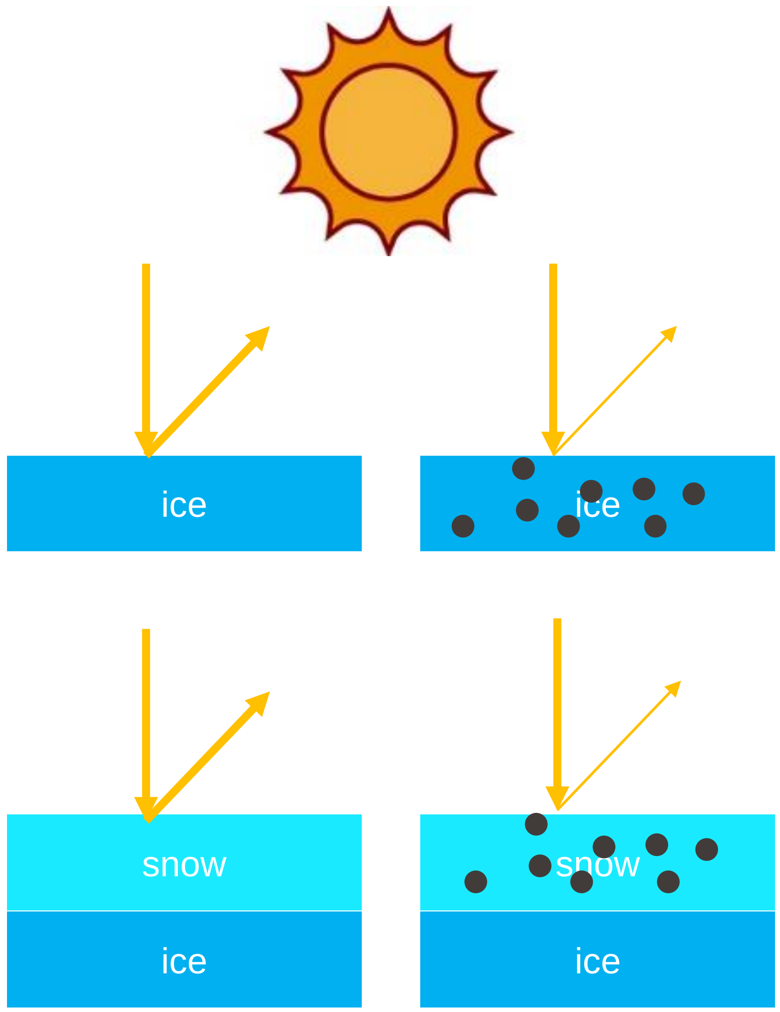
Aerosol-radiation interaction



Units in W m^{-2}

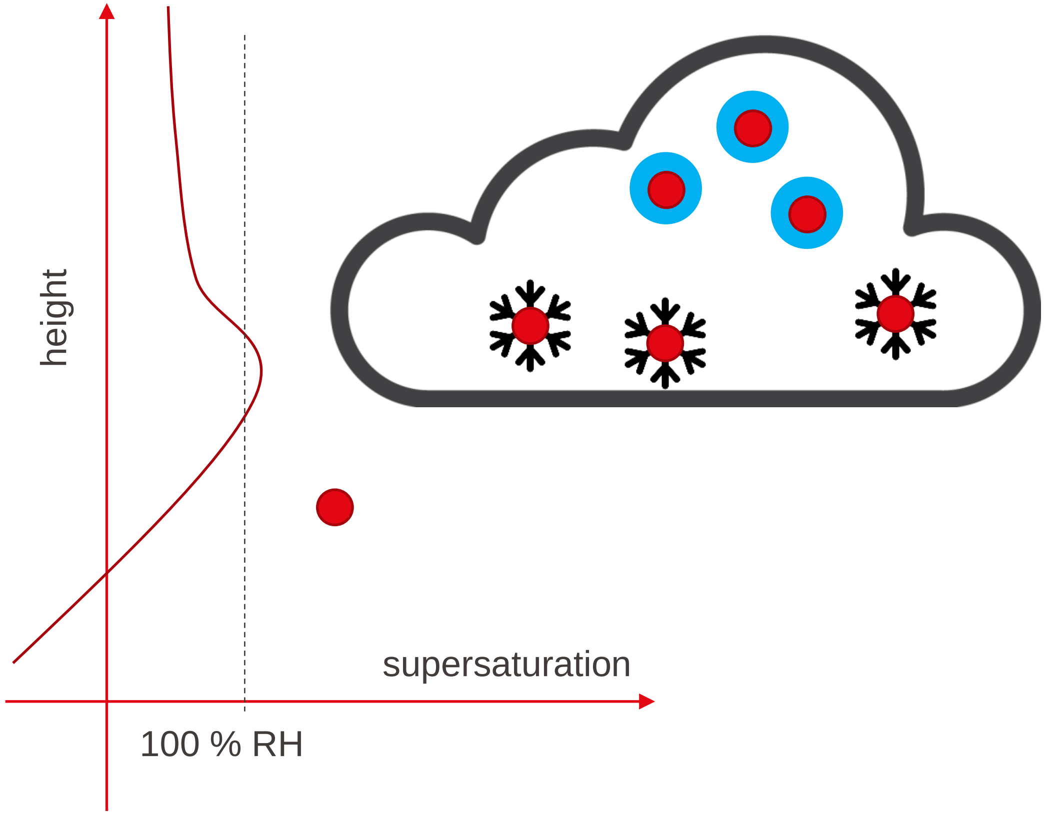
- Wild, 2021, https://doi.org/10.1175/BAMS-D-11-00074.1

Aerosol-radiation interaction on snow and ice



Absorbing aerosol such as black carbon and mineral dust lower the albedo of snow and ice surfaces and can thereby contribute to enhanced melt.

Aerosol cloud interactions



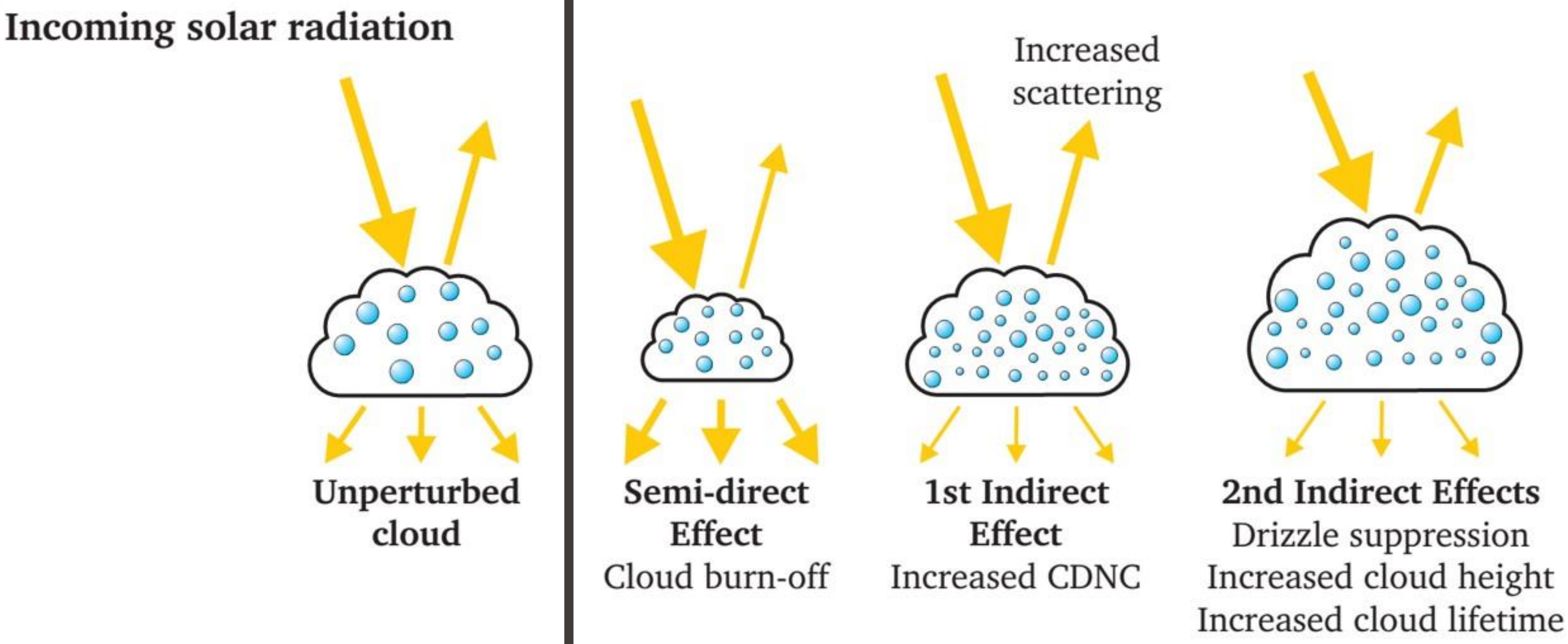
Aerosols act as:
a) cloud condensation nuclei – CCN
b) ice nucleating particles - INP

Aerosols are necessary to form clouds!

Aerosol-cloud interactions

Pristine clouds

Polluted atmosphere and clouds



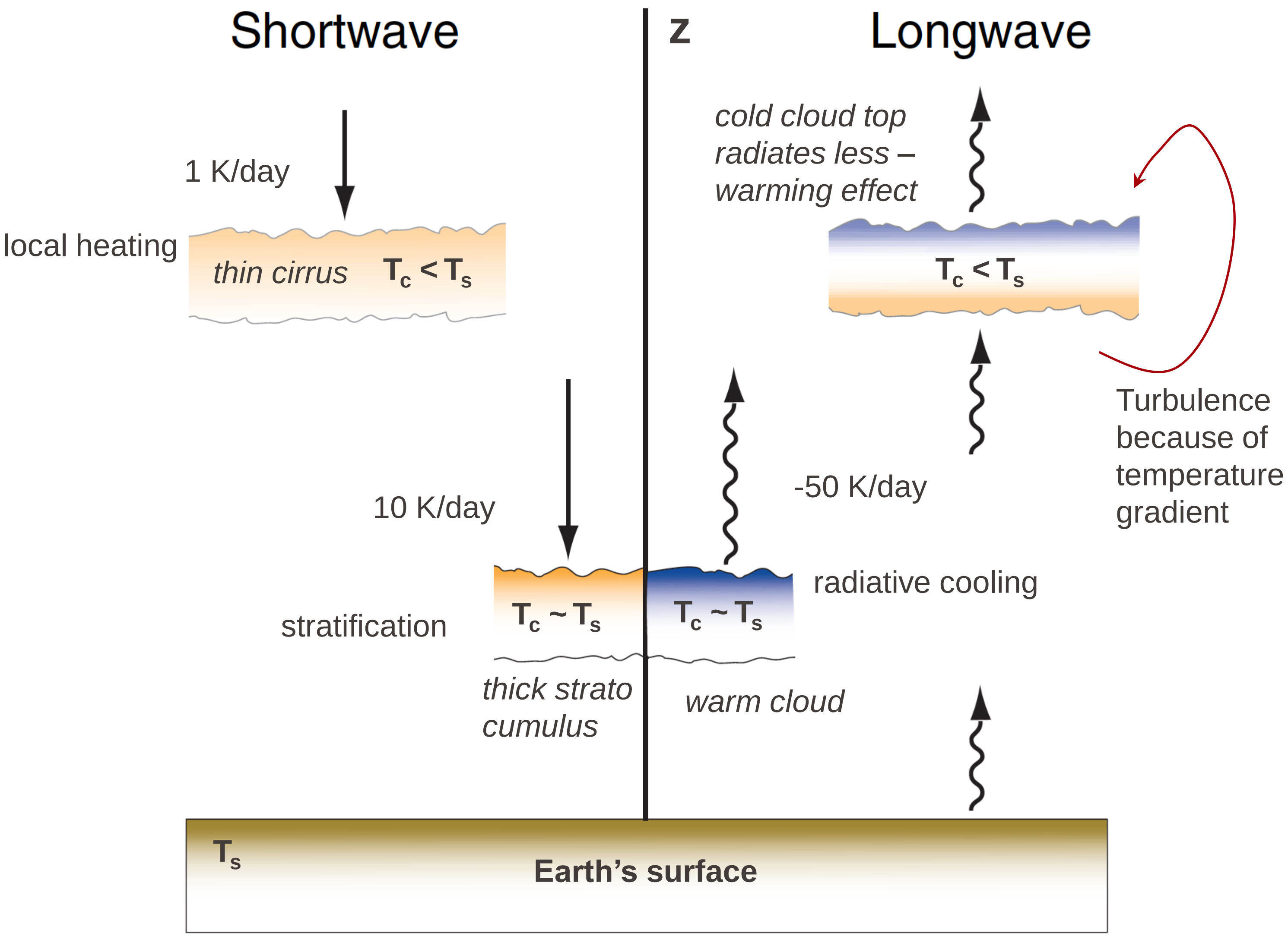
Air becomes warmer and clouds do not form or evaporate

Higher albedo

No big drops

CDNC – cloud droplet number concentration

Cooling and heating in cloud layers



Clouds modify the heating / cooling significantly. They can be considered like blackbodies in the atmosphere.

Longwave cooling is stronger than shortwave heating averaged over a day.

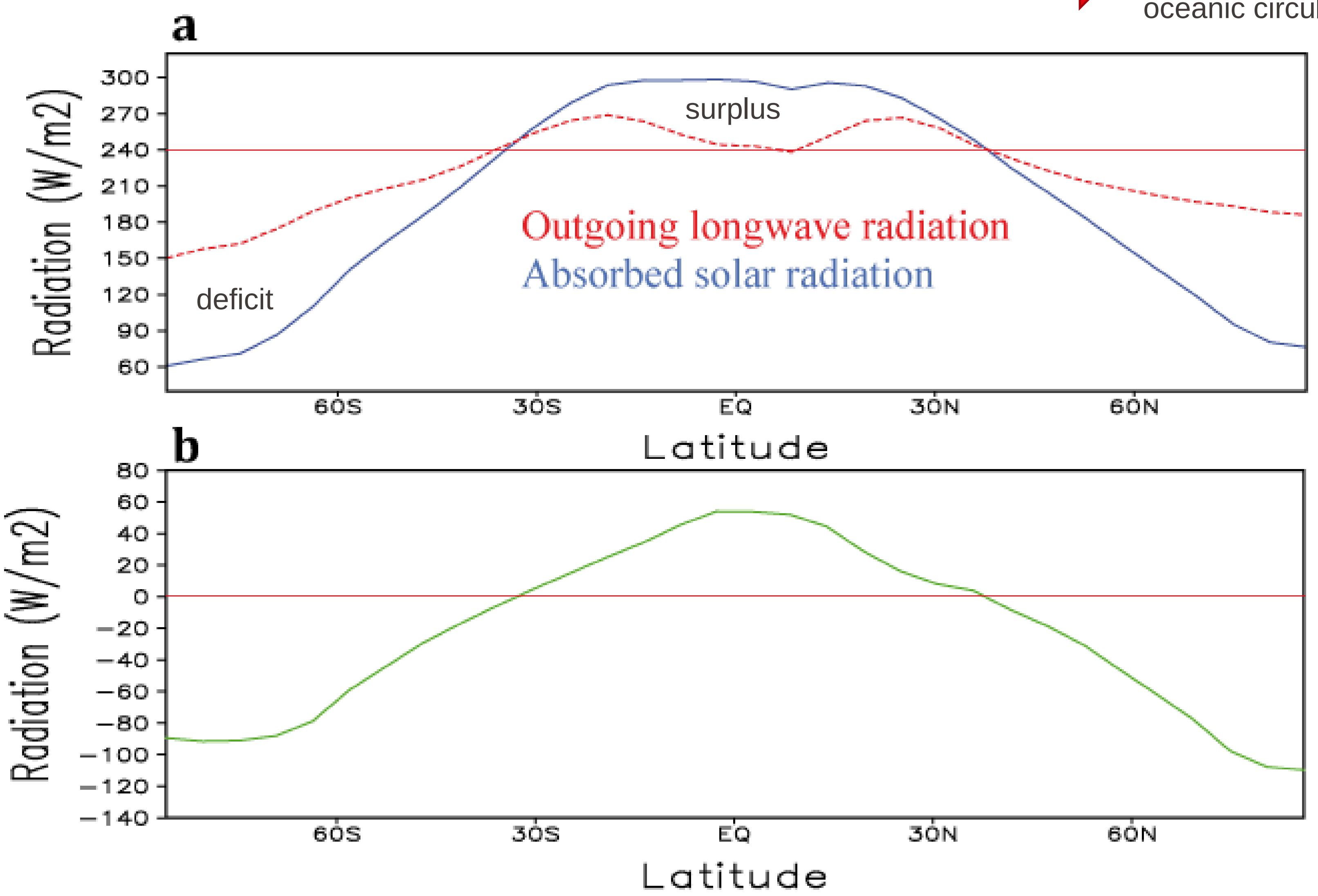
Longwave cooling and heating typically promote vertical instability.

Shortwave heating of cloud tops leads to a more stable stratification.

T_c = Cloud temperature
T_s = surface temperature

Annual average flux density at ToA

Difference drives atmospheric and oceanic circulation

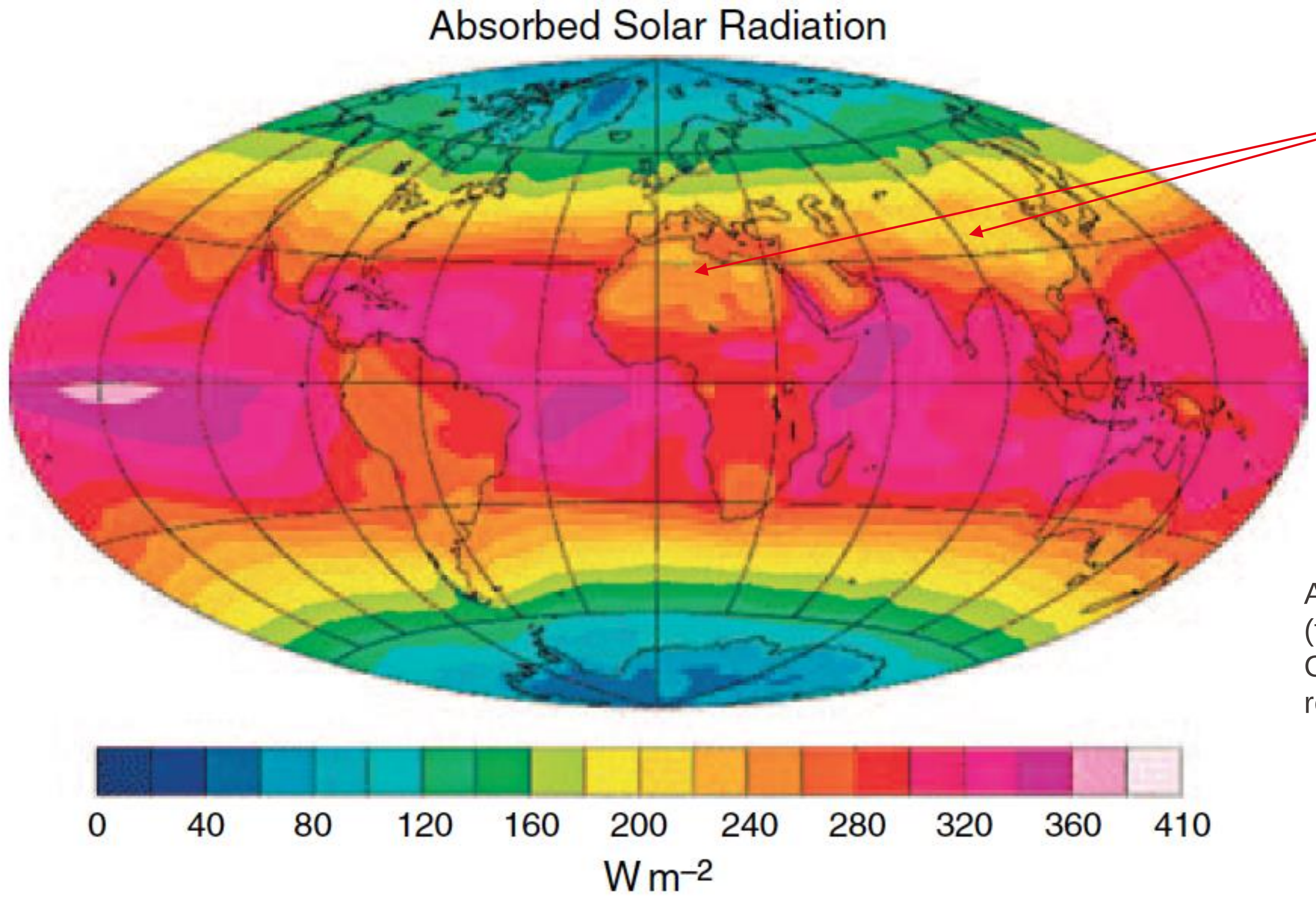


Subtracted the lines from panel a)

- http://www.climate.be/textbook/chapter2_node6.html

TOA = Top of Atmosphere

Top of Atmosphere Radiation Balance

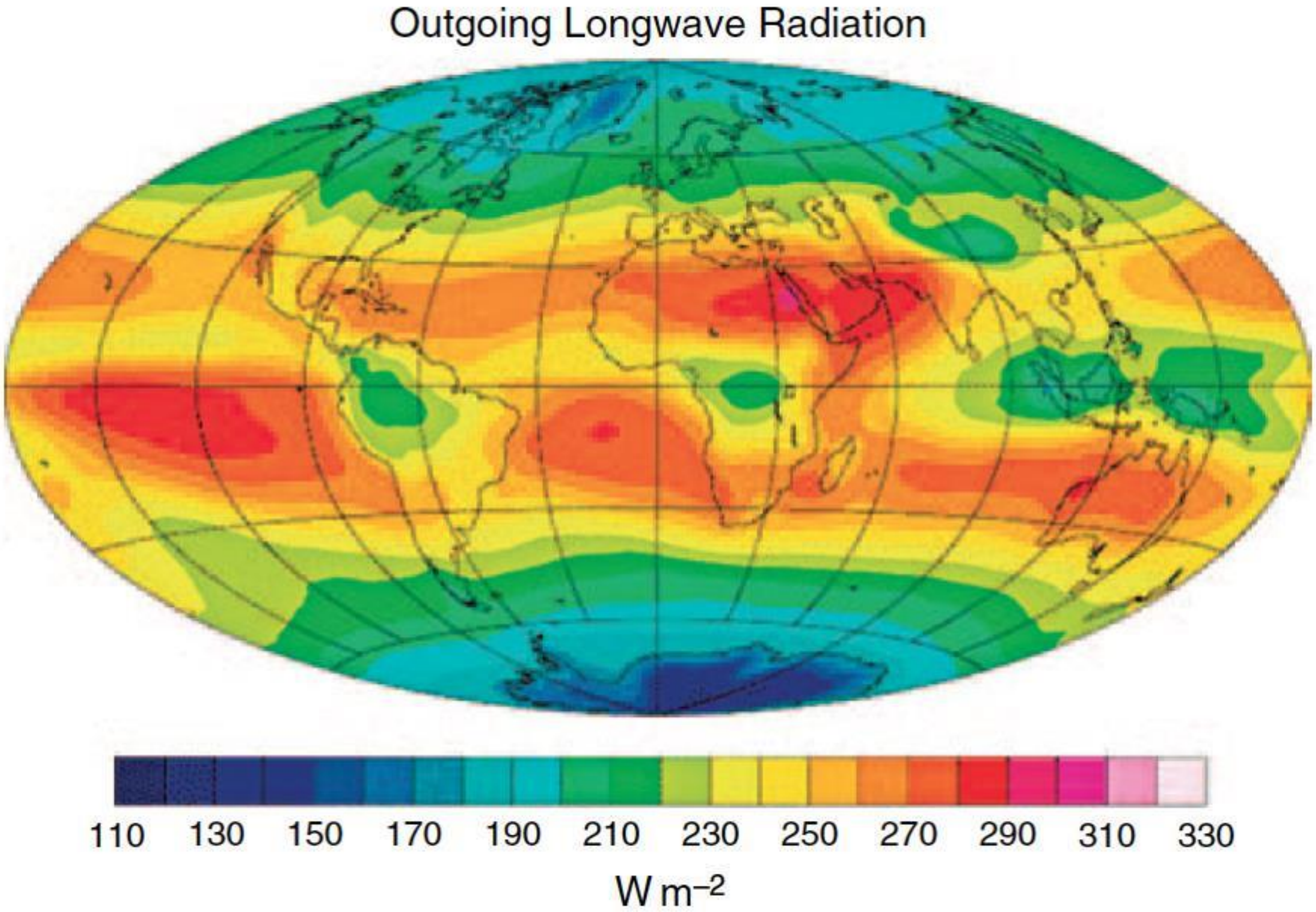


Albedo
difference

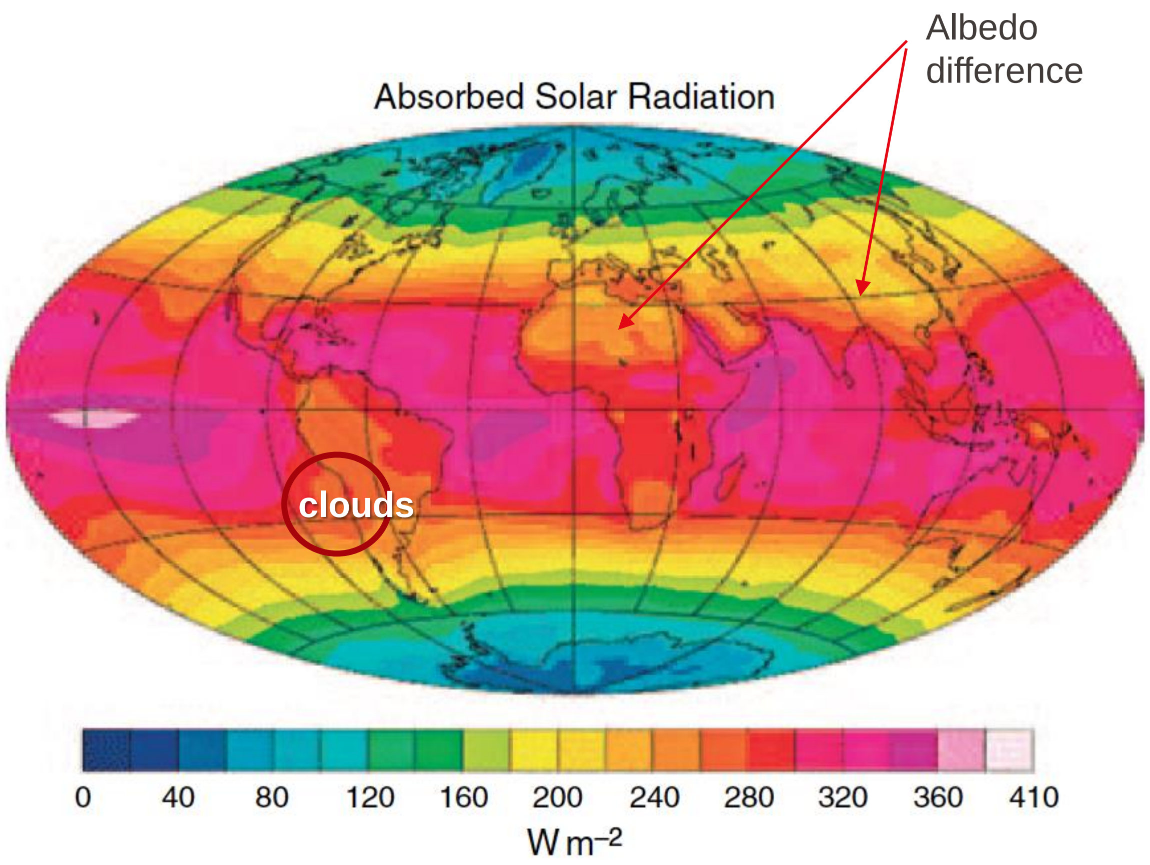
Annual mean net downward shortwave radiation (takes into account: solar declination, local albedo). Clouds reflect more, deserts as well. In polar regions half of the year is dark.

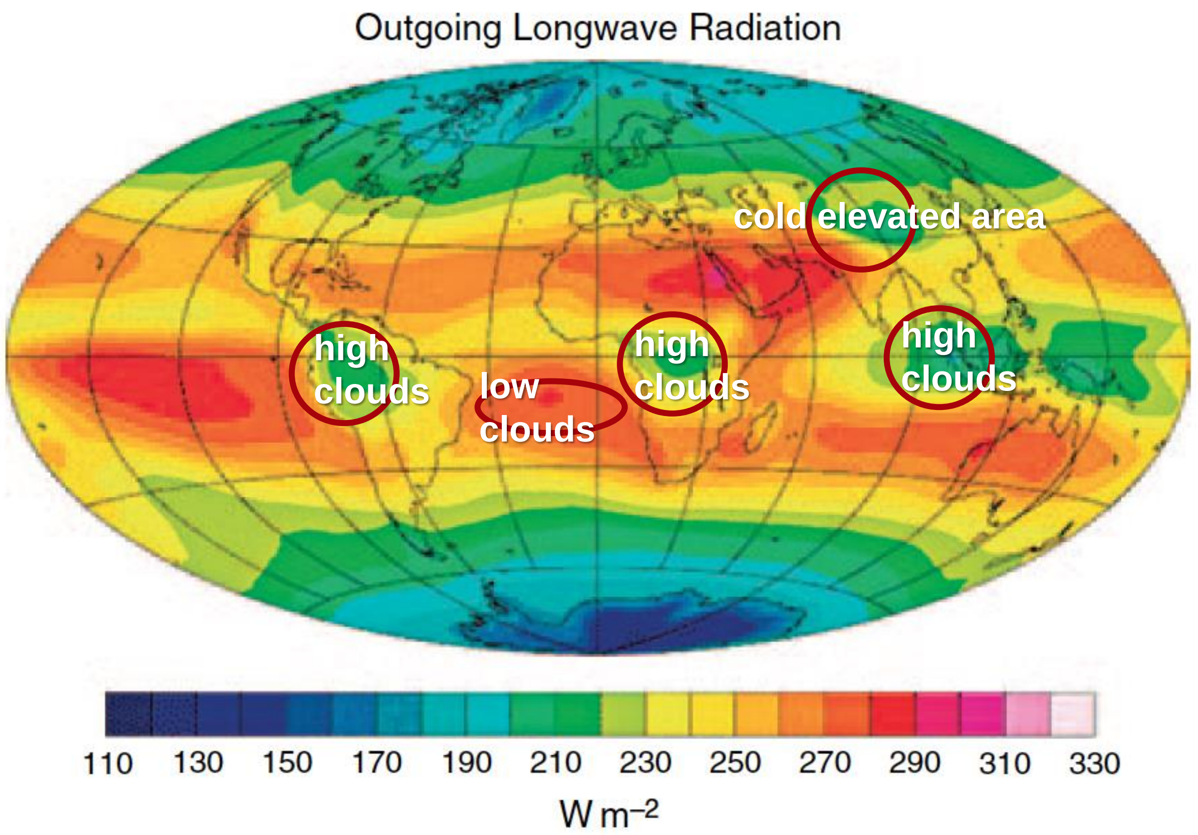
EPFL

Can you indicate regions with high clouds?



Top of Atmosphere Radiation Balance



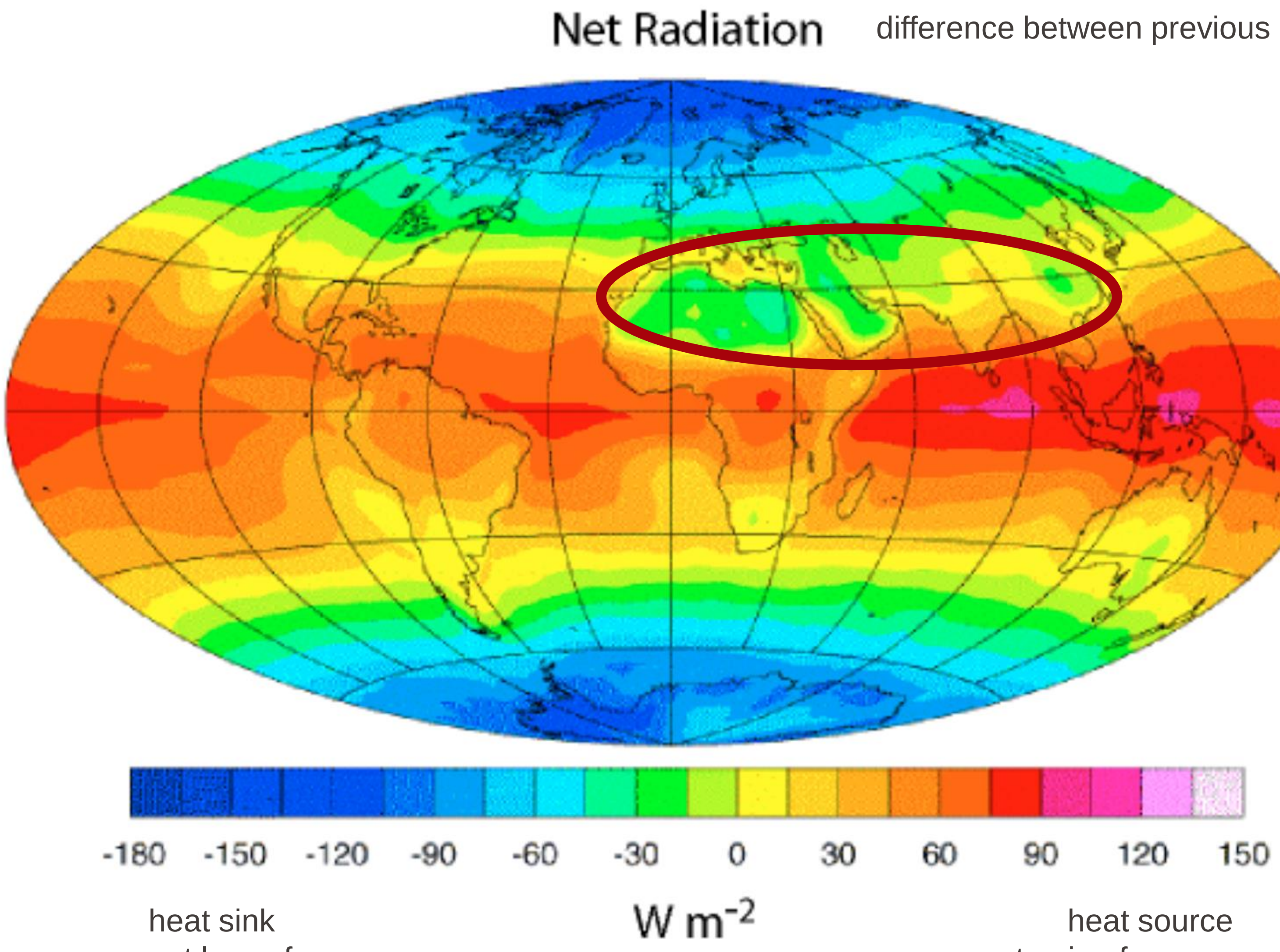


Annual mean net downward shortwave radiation (takes into account: solar declination, local albedo). Clouds reflect more, deserts as well. In polar regions half of the year is dark.

Annual mean net outgoing longwave radiation. More variability in the tropics (cloudy and non-cloudy areas), smaller gradient between equator and poles (cloud effect, clouds are higher and colder in tropics).

Top of atmosphere net radiation

difference between previous plots

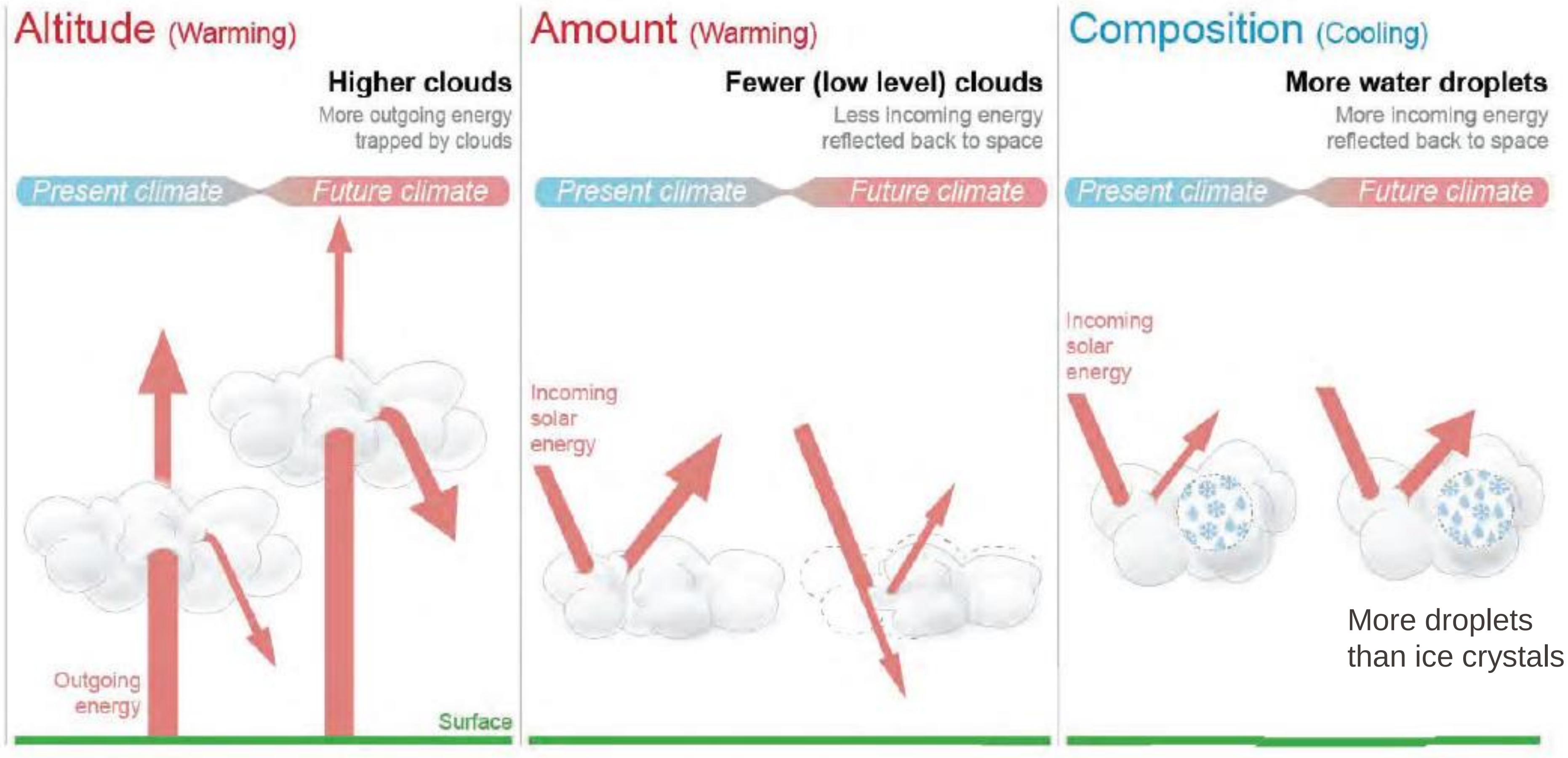


heat sink
net loss of energy

heat source
net gain of energy

The difference between the low and high latitudes drives global atmospheric circulation patterns.

Clouds in a future, warmer climate



More droplets than ice crystals

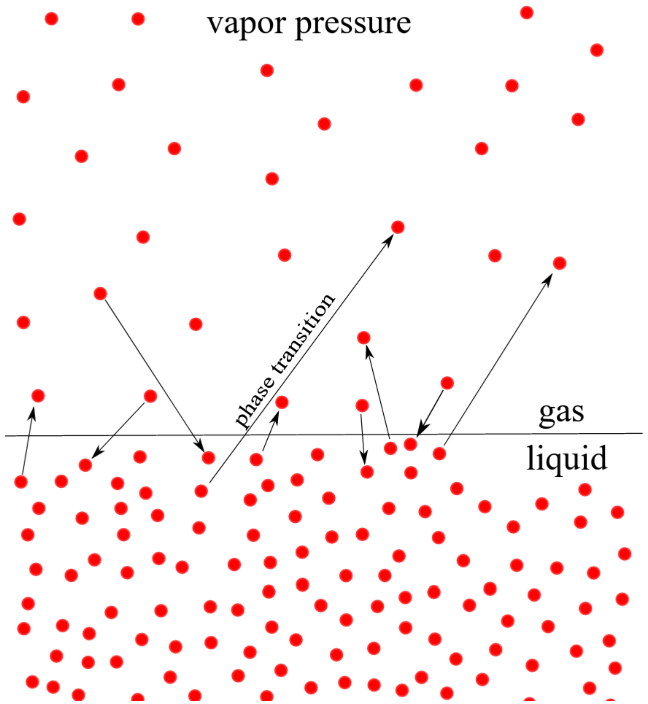
The overall anticipated future effect of clouds is warming.

IPCC, AR6, FAQ 7.2, Fig. 1

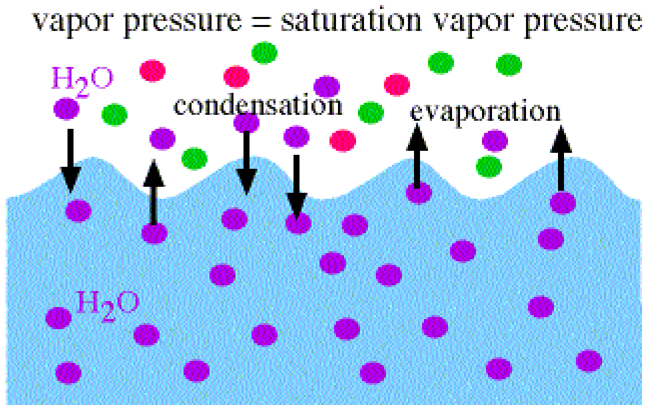
The interaction of climate warming and atmospheric water vapor

- For each 1°C warming, the atmosphere can hold 7% more water vapor.
- Water vapor is the most abundant greenhouse gas.
- Water vapor is part of the hydrological cycle and will lead to precipitation.

Vapor pressure and Saturation vapor pressure



When the number of molecules that condense and evaporate is the same, the system is in equilibrium and we speak of the saturation vapor pressure.



The vapor pressure of a liquid or solid is the pressure exerted by the vapor in equilibrium with the condensed (solid/liquid) phase.

The **equilibrium vapor pressure** e_s for substance *i* is also referred to as its **saturation vapor pressure**, and determines the amount of substance that can be "held" in the gas phase at equilibrium.

https://upload.wikimedia.org/wikipedia/commons/6/67/Vapor_pressure.svg

More moisture in a warmer atmosphere

Clausius-Clapeyron equation: Expresses the variation of the equilibrium vapor pressure e_s with temperature T.

$$\frac{de_s}{dT} = \frac{L_v}{T(\alpha_v - \alpha_l)} \cong \frac{L_v}{T\alpha_v}$$

Ideal gas equation for water vapor

$$e_s\alpha_v = R_vT \quad \Rightarrow \quad \frac{de_s}{dT} \cong \frac{L_v}{T\alpha_v} = \frac{e_sL_v}{T^2R_v}$$

For the small temperature range in the atmosphere we can use the incremental form to good approximation:

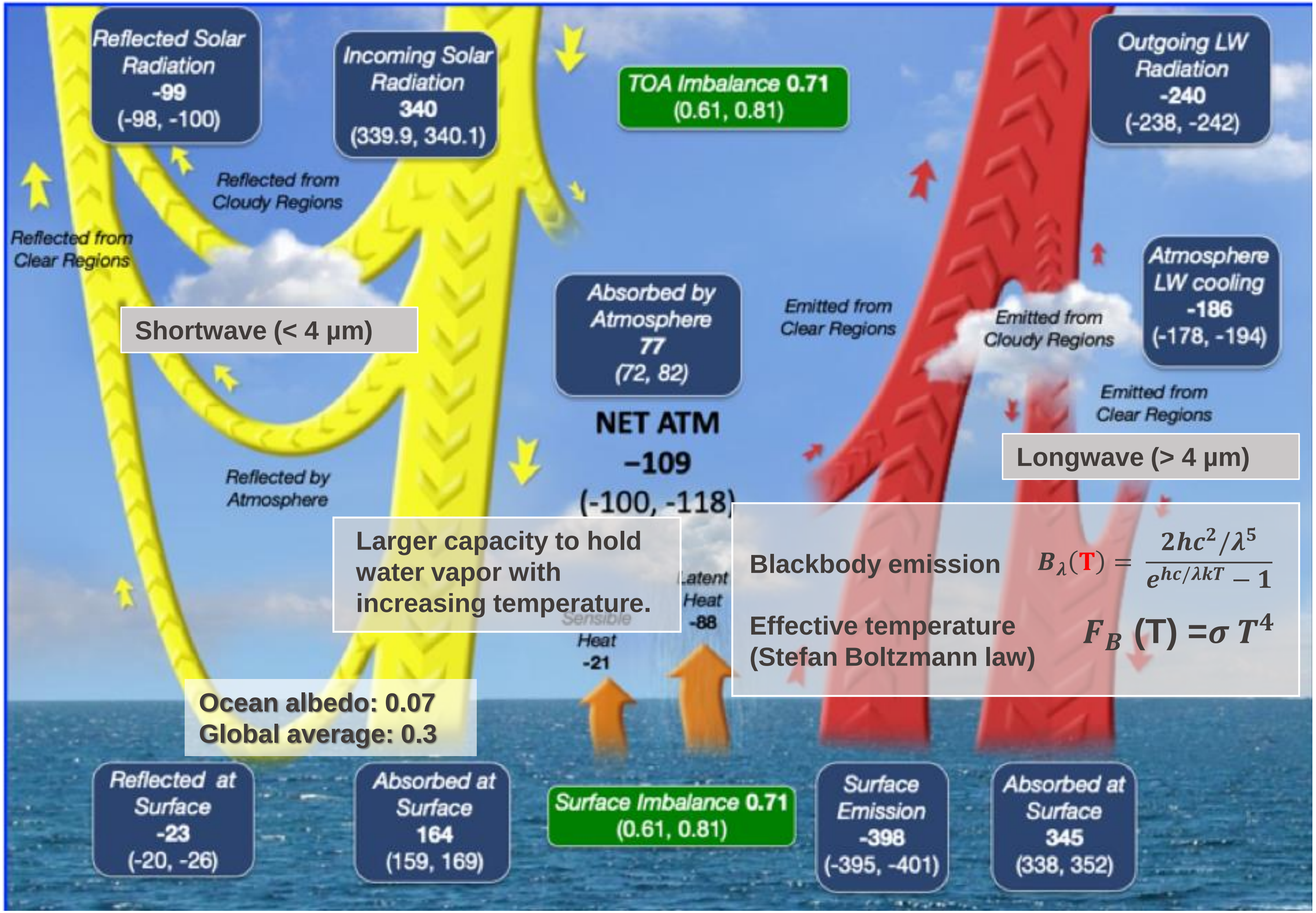
$$\frac{\Delta e_s}{\Delta T} = \frac{e_sL_v}{T^2R_v} \quad \Rightarrow \quad \frac{\Delta e_s}{e_s} = \frac{L_v}{T\,R_v} * \frac{\Delta T}{T} \approx 20\frac{\Delta T}{T}$$

e_s	equilibrium vapor pressure (kg m^{-1}s^{-2})
T	temperature (K)
L_v	latent heat of vaporization (2500 kJ kg^{-1})
α	specific volume of vapor (v) and liquid (l)
R_v	gas constant for water vapor (461.5 J kg^{-1}K^{-1})

In the exercises, show why for each 1°C temperature increase, the atmosphere can hold 7 % more water vapor?

See climate feedback lecture what this means for the lapse rate feedback.

Summary



- At the surface, temperatures would be 32ºC cooler without greenhouse gases like water vapor and CO_2, and clouds. These absorb surface infrared radiation and re-emit most of it back to the surface.
- Globally averaged, the surface has a net surplus of radiant energy while the atmosphere has a net loss.
- To make up for this imbalance, sensible (conduction & convection) and latent heat (evaporation) are transferred from the surface to the atmosphere.

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