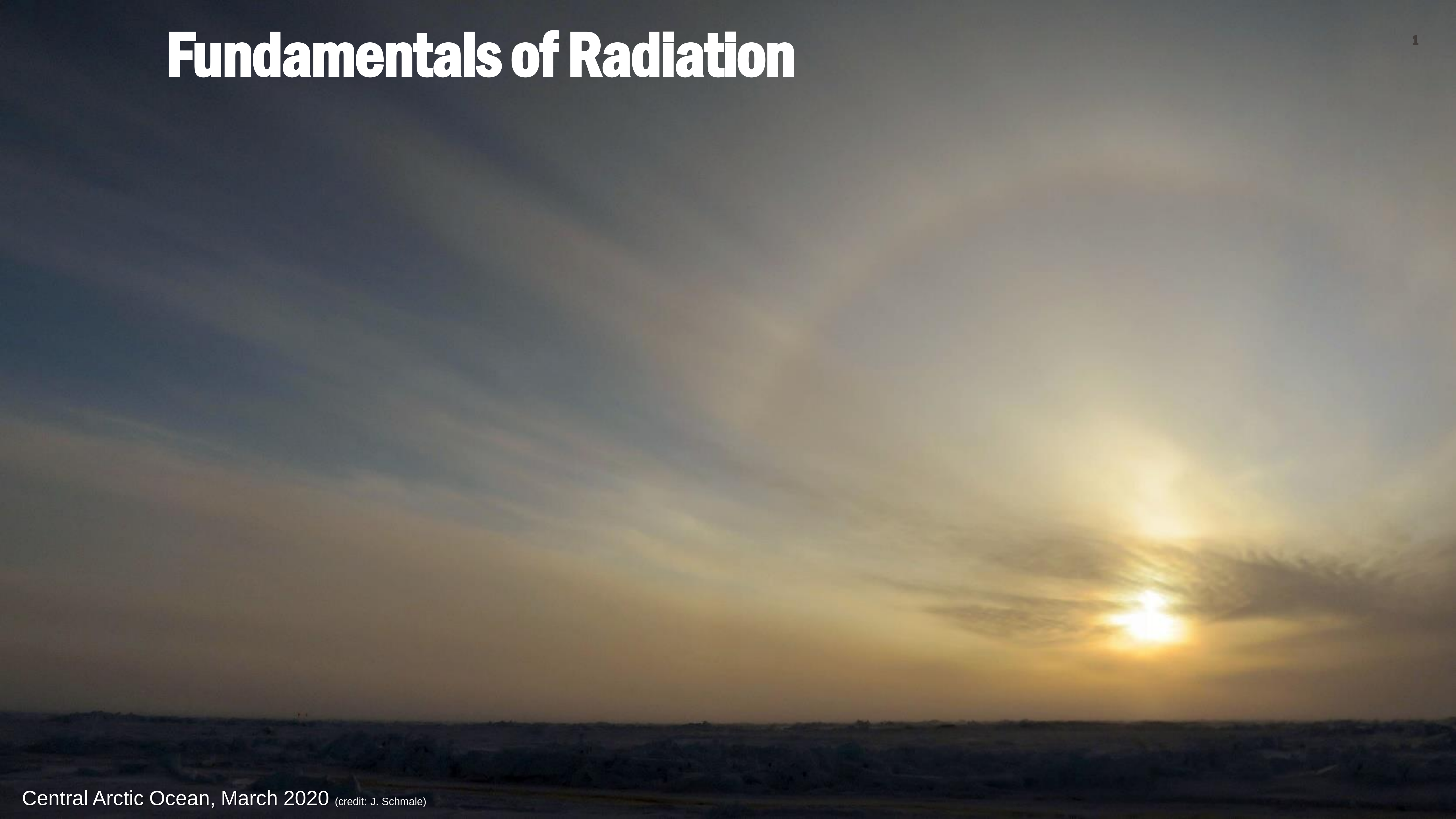
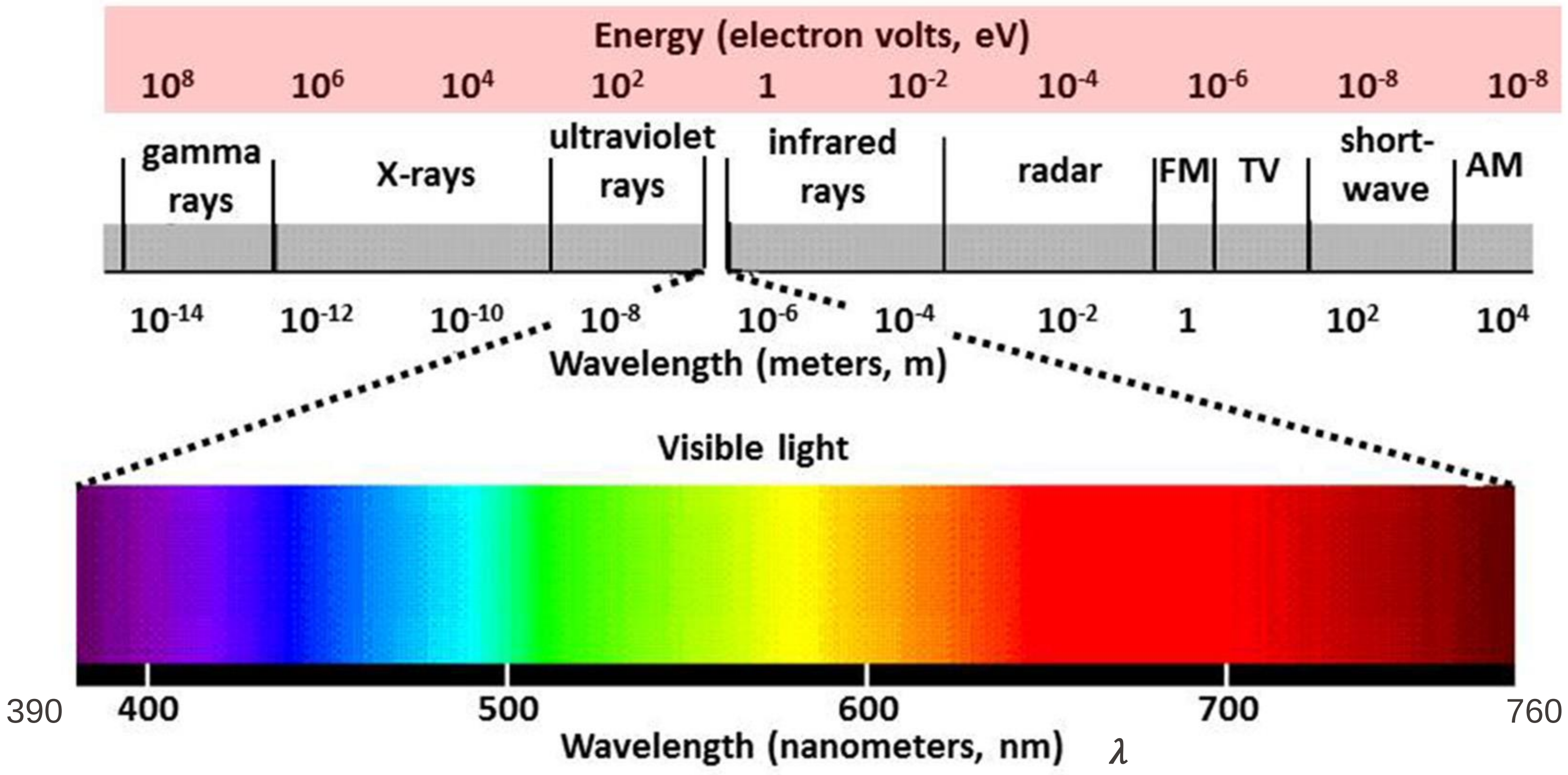
# Fundamentals of Radiation



Central Arctic Ocean, March 2020 (credit: J. Schmale)

# Spectrum of electromagenetic radiation




## Some definitions

**Visible**: 0.39 – 0.76 µm, colors
**Monochromatic**: one single color, i.e. one single wavelength

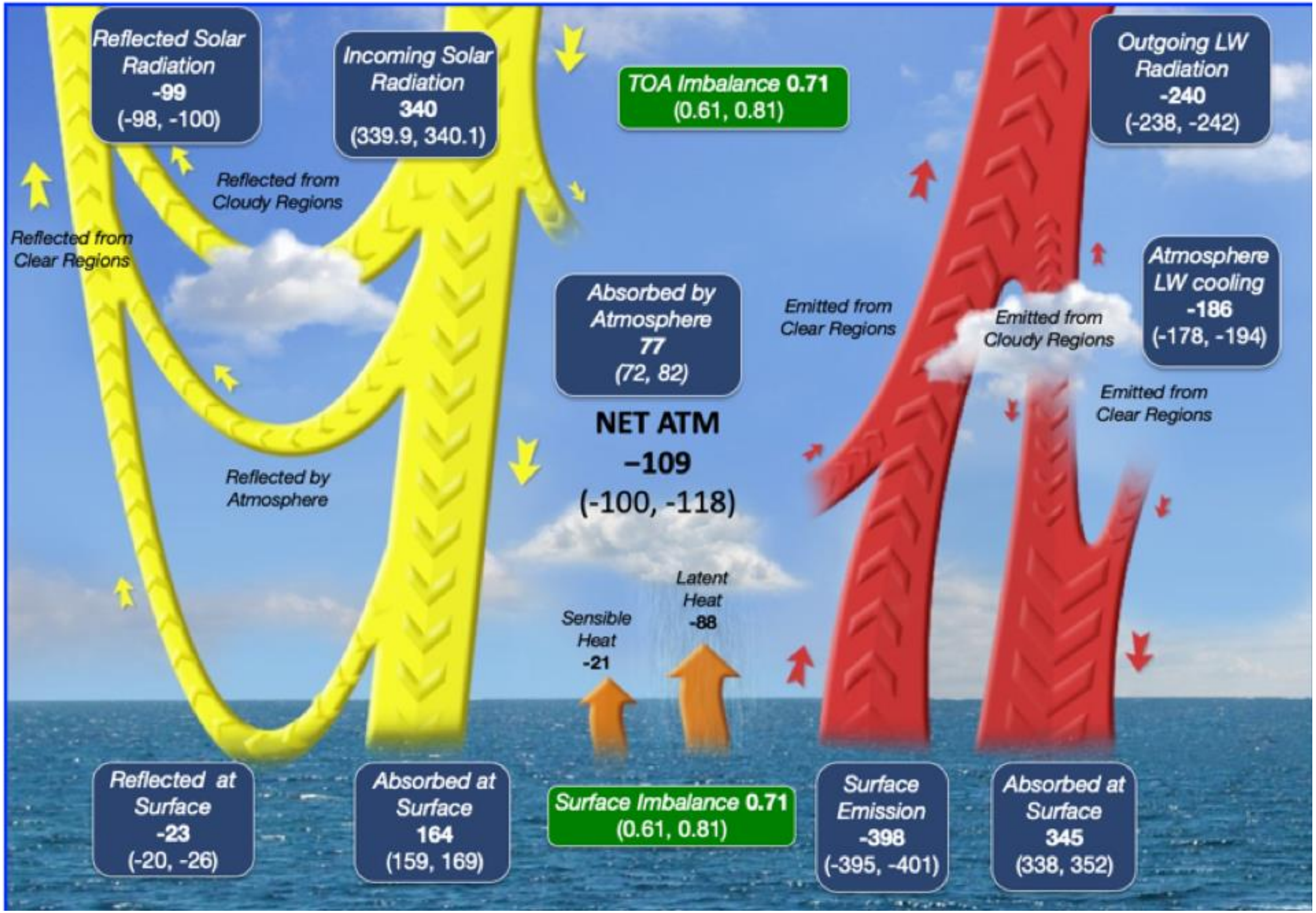
**Solar radiation**: < 4 µm, shortwave
**Terrestrial radiation**: > 4 µm, longwave

**Near infrared**: 0.76 – 4.0 µm (solar radiation)
**Thermal Infrared**: > 4 µm, terrestrial radiation

**Microwave** ($10^{-3}$ – $10^{-1}$ m): not important for Earth's energy balance, but used in remote sensing (radar), can penetrate through clouds

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

# Earth's Energy Balance




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

- 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.
- At the surface, temperatures would be 33ºC cooler without the **natural greenhouse effect** driven by water vapor, $CO_2$, $O_3$ and clouds. These absorb surface infrared radiation and re-emit most of it back to the surface.

**We will learn about:**

→ characteristics of solar and terrestrial radiation,
→ how solar radiation passes through the atmosphere,
→ how terrestrial radiation passes through the atmosphere,
→ why there is a net loss of energy in the atmosphere,
→ how greenhouse gases, aerosols and clouds interact with radiation.

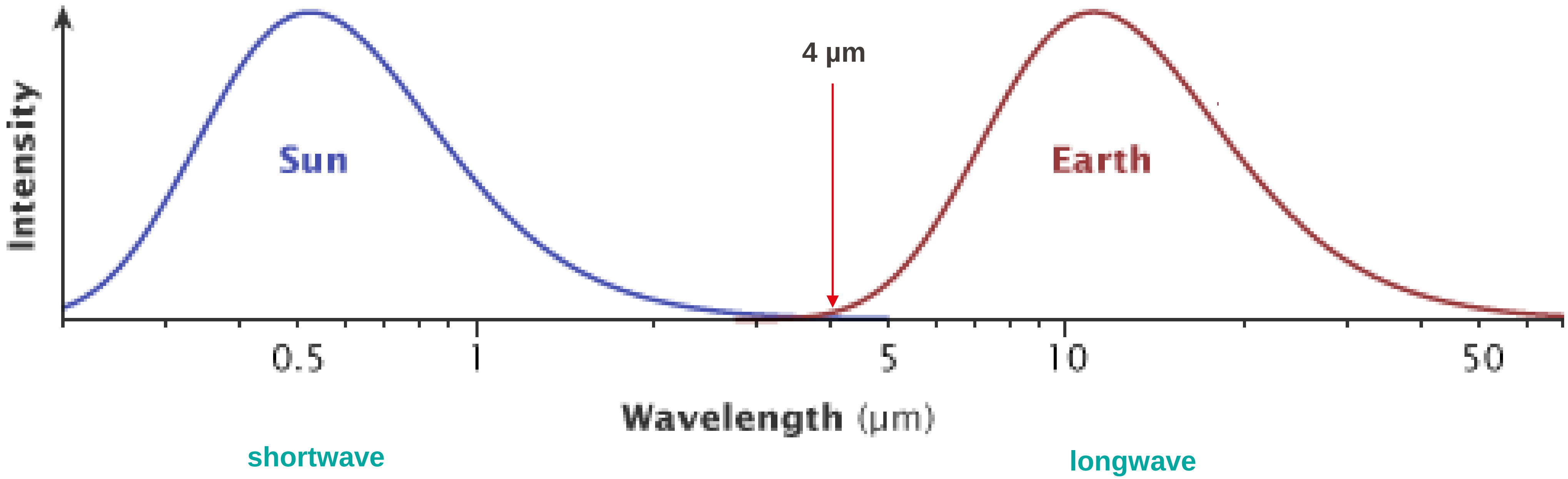
# Some definitions

- **Radiation**: emission or transmission of energy in the form of waves or particles through space or through a material medium
- **Irradiance/Flux Density**: radiant flux (Watts) ***received*** by a ***surface*** per unit area, Symbol: *F*; Unit: W $m^{-2}$
  - **Spectral irradiance** is the irradiance of a surface per unit frequency or wavelength; Unit: W $m^{-2}$ $nm^{-1}$ or W $m^{-2}$ $Hz^{-1}$
  - **Insolation/solar irradiance**: The incident radiant energy emitted by the sun which reaches a unit area over a period of time, typically measured over a horizontal area at the Earth's surface or at the top of Earth's atmosphere. Units: W $m^{-2}$

- **Radiance**: is the radiant flux emitted, reflected, transmitted or received by a given surface, per unit solid angle per unit projected area, Symbol: *I*; Units: W $m^{-2}$ $sr^{-1}$
  - **Radiant intensity**: radiant flux emitted, reflected, transmitted or received, per unit solid angle, Units: W $sr^{-1}$
  - **Spectral intensity**: is the radiant intensity per unit frequency or wavelength, Units: W $sr^{-1}$ $Hz^{-1}$ or W $sr^{-1}$ $nm^{-1}$

# Solar and terrestrial emission spectra






- cf. Figure 4.7, Wallace and Hobbs, 2006

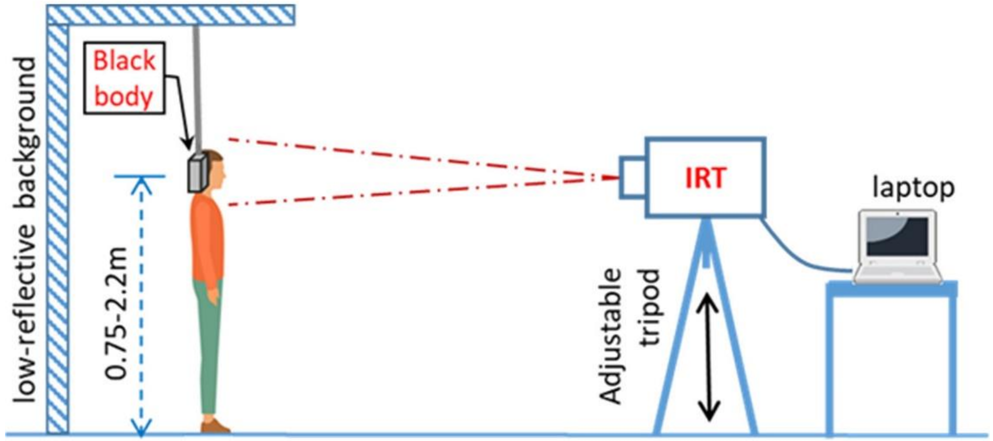
# Blackbody radiation

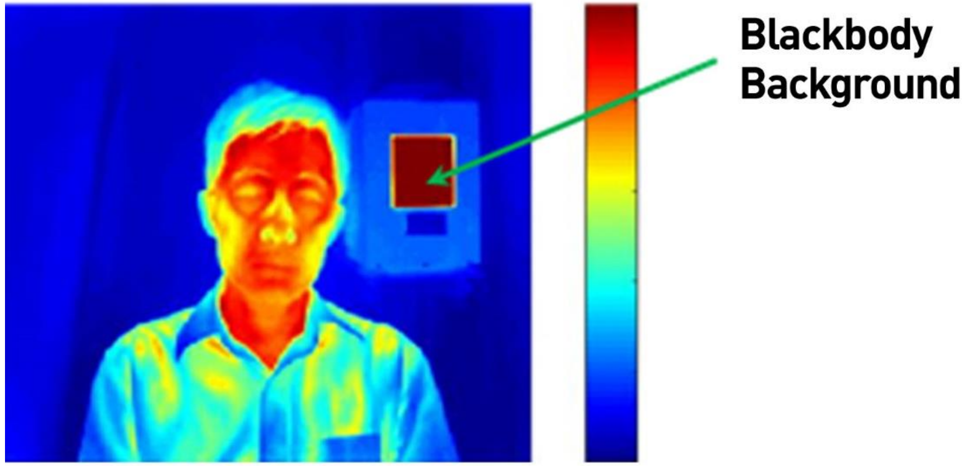
<u>Definition of blackbody</u>: matter or object that absorbs all radation incident on it, no reflection. Examples: coal, cave

**Blackbodies emit radiation**. The radiation *emitted* by a blackbody is *isotropic (same intensity independent of location/direction)* and depends only on the ***temperature of the body****,* not on the composition of the blackbody, nor on whether any radiation is incident on the blackbody. The blackbody is losing energy by emission of radiation, so heat must be supplied to keep its temperature constant.

Most objects are not blackbodies. Their emissions can nevertheless be approximated by using blackbody radiation laws.

<u>Recent example of using blackbody radiation: temperature measurements as covid-19 check</u>




- https://www.fda.gov/

# Blackbody radiation: Planck function

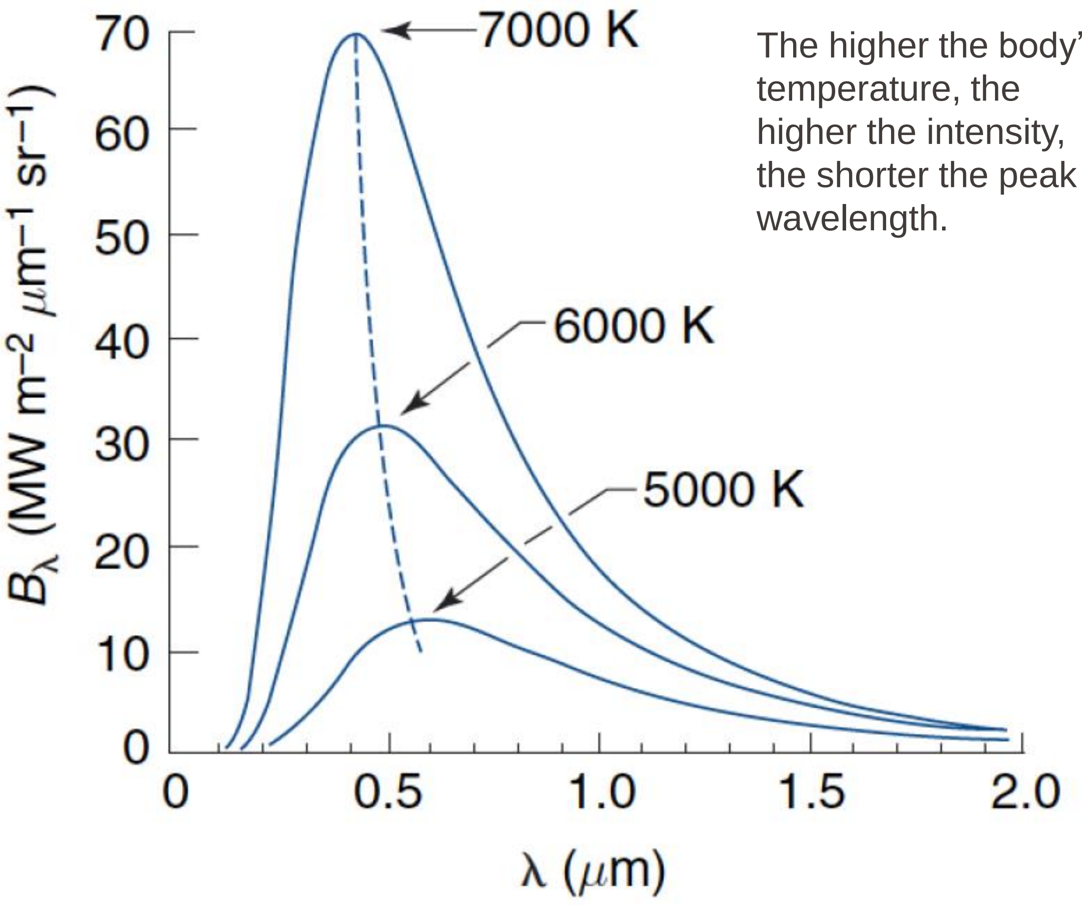
## A critical climate feedback

Monochromatic intensity of a blackbody ($B_\lambda$)

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

k = Boltzmann's constant, 1.380649 x $10^{-23}$ J $K^{-1}$
h = Planck's constant, 6.63 x $10^{-34}$ J s
c = speed of light, 299,792,458 m $s^{-1}$
T = Temperature of blackbody (K)
sr = solid angle (steradian)
$\lambda$ = wavelength

**The Planck function states that the emission intensity of a blackbody depends on the body's temperature and the wavelength considered.**




The higher the body's temperature, the higher the intensity, the shorter the peak wavelength.

Fig. 4.6: Emission spectra of a blackbody at three different temperatures

# Blackbody radiation: Wien's displacement law

<u>**Peak wavelength**</u>

Obtained by differentiating $B_\lambda(T)$ and setting equal to 0:

$\frac{dB_\lambda(T)}{d\lambda} = 0$ for $\lambda = \lambda_{max} \rightarrow T$ = const. = $2.897 \times 10^{-3}$ (m K)

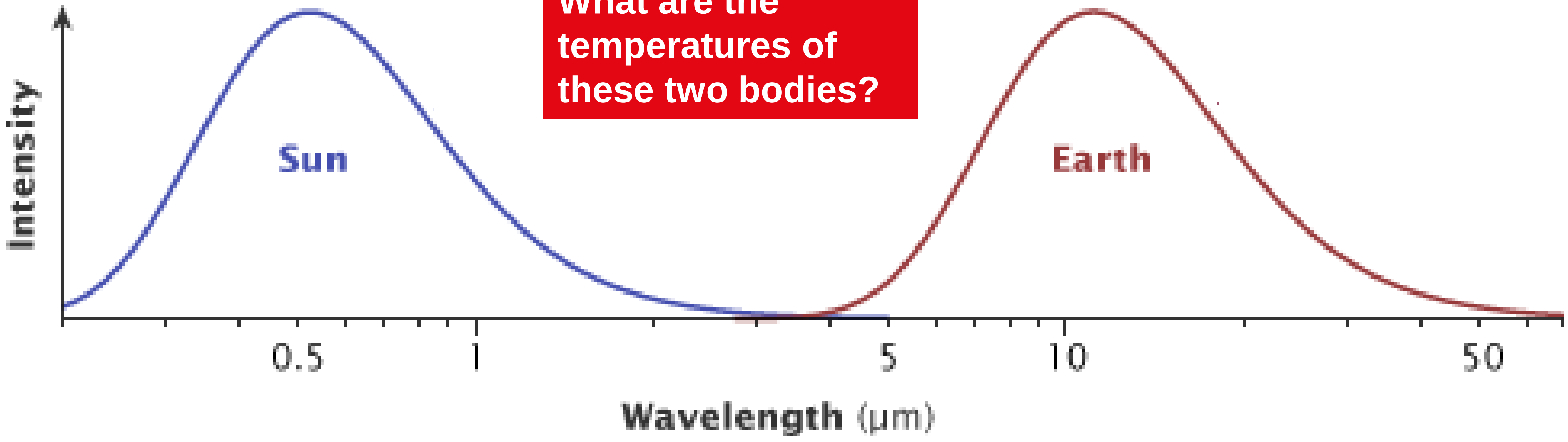
$\lambda_{max}$ = wavelength of maximum intensity

**Wien's displacement law**

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

**With Wien's displacement law, we can calculate the temperature of a body, if we know its emission spectrum.**

**What are the temperatures of these two bodies?**



# What are the temperatures of the two bodies?

**Peak wavelength**

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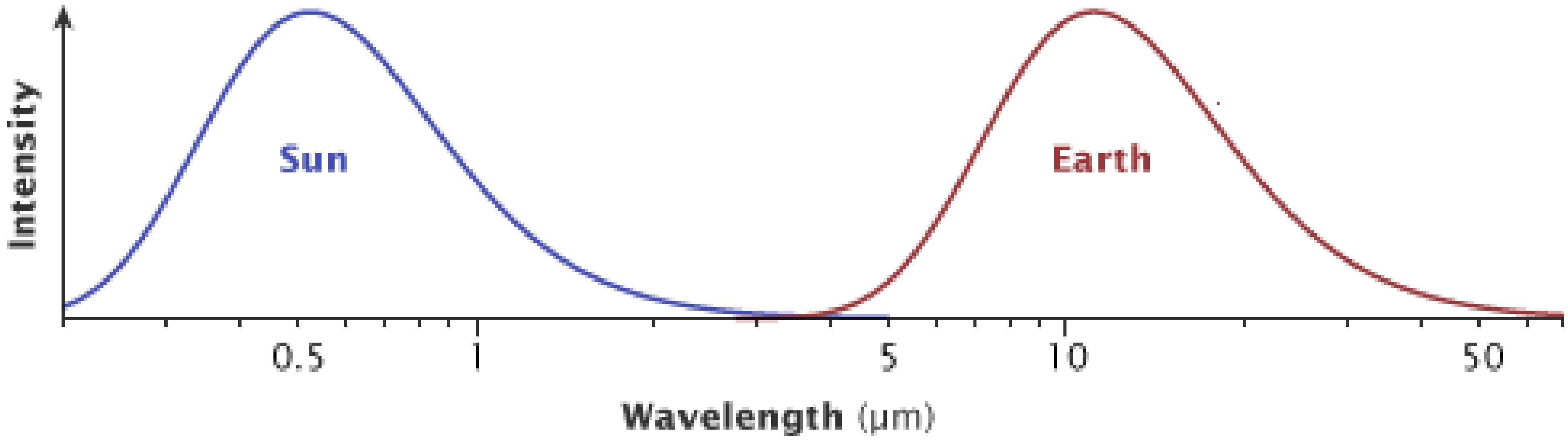
**Wien's displacement law**

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

1



# Blackbody radiation: Stefan-Boltzmann law

In the exercises, you will calculate the equivalent blackbody temperature of Earth.

Integration over all wavelengths

$$B(T) = \int_0^\infty B_\lambda(T)d\lambda \sim T^4$$

Integration over all angles of a hemisphere covering a horizontal surface (B(T) is independent of direction): **total flux density (irradiance)** $\boldsymbol{F_B}$

$$\boldsymbol{F_B}\ \mathbf{(T)} = \pi \mathrm{B(T)} = \pi \int B_\lambda(T)d\lambda = \boldsymbol{\sigma T^4}$$

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

**Knowing the flux density $F_B$ of a blackbody, we can calculate the equivalent blackbody temperature or effective emission temperature ($T_E$). $T_E$ is the temperature a blackbody would need to emit radiation at, at the measured rate F. If the body is a blackbody then $T_E$ and T of the body are equal.**

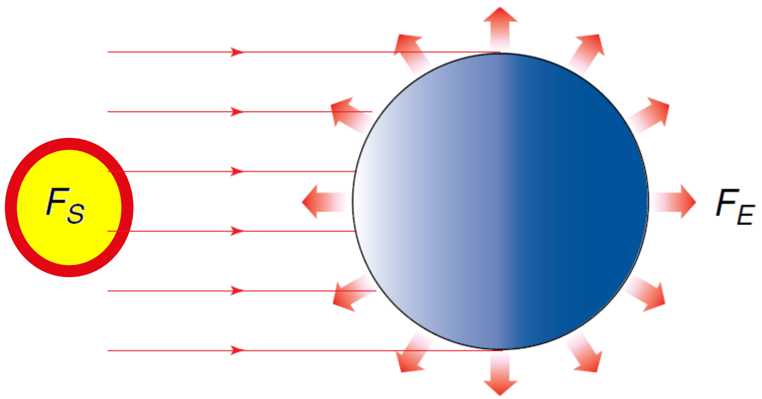
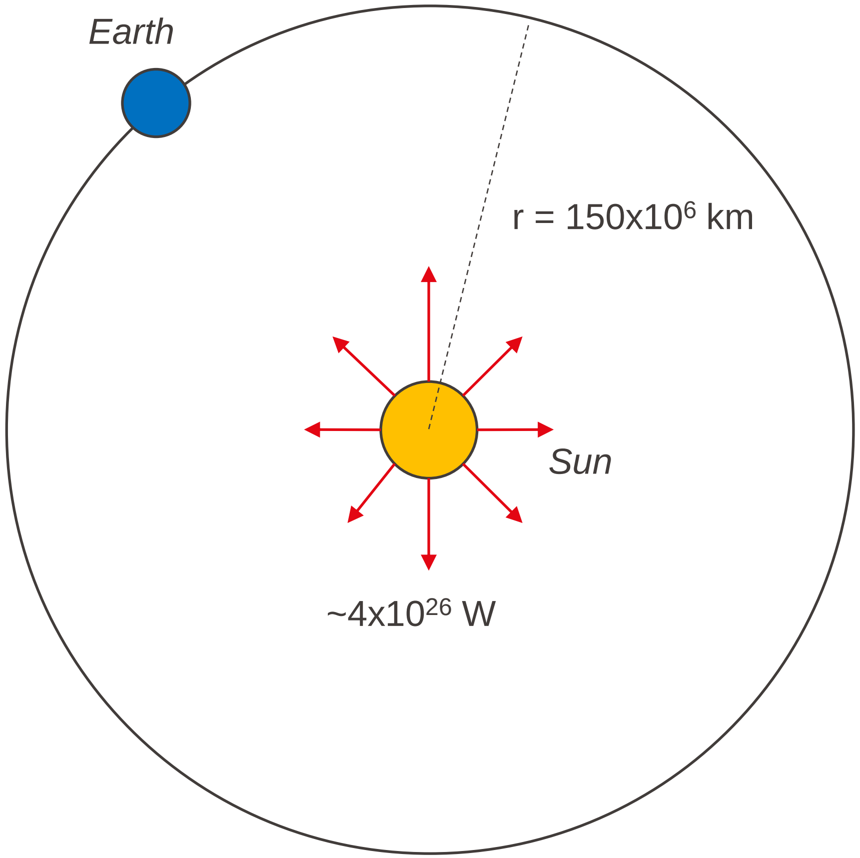



**Fig. 4.8** Radiation balance of the Earth. Parallel beam solar radiation incident on the Earth's orbit, indicated by the thin red arrows, is intercepted over an area $\pi R_E^2$ and outgoing (blackbody) terrestrial radiation, indicated by the wide red arrows, is emitted over the area $4\pi R_E^2$.

- Wallace and Hobbs, 2006

# Solar constant






Sphere with radius r has a surface area $4\pi r^2$

So the flux density received by Earth is: $4 \times 10^{26} / 4\pi r^2$ → **solar constant**

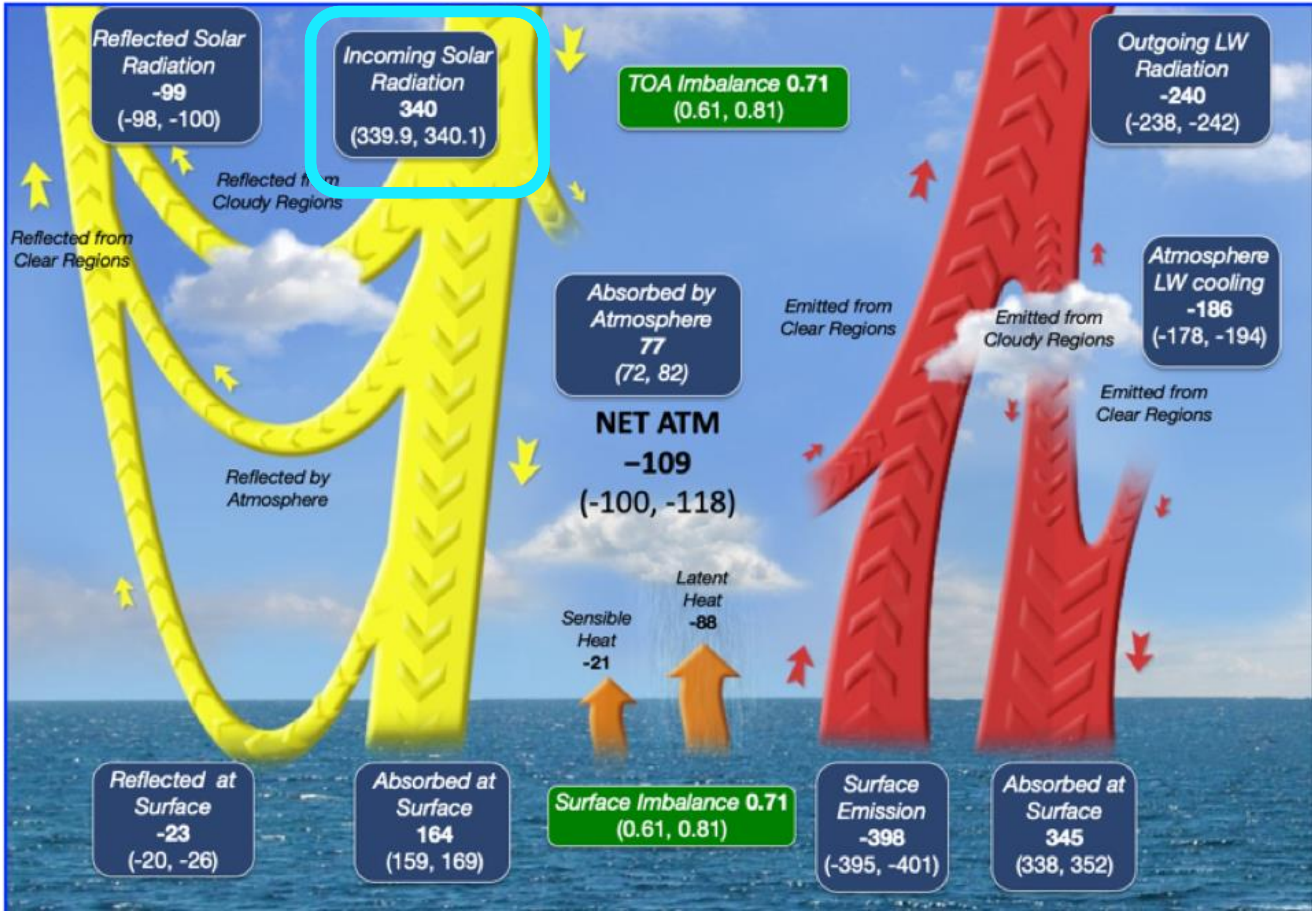
The solar constant is defined as the rate at which solar energy is received by a surface oriented perpendicular to the Sun's direction at the distance of the Earth's orbit. It is measured to be 1370 W $m^{-2}$.

$$\boldsymbol{S_0 = 1370\ W\ m^{-2}}$$

Is it constant?

- Different for each planet.
- Earth's orbit is eccentric (r varies by $\pm$1.75 %). Closer to the sun in January, farthest in July. The constant is defined for the average distance.
- It varies as the sun rotates (29-day cycle), bringing sunspots groups across the Earth-facing side of the Sun.
- It varies by 0.1 % over the 11-year solar cycle, with a maximum at sunspot maximum (next 2025).
- It increases as the Sun ages (1 % every 100 million years).

# Earth's Energy Balance




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

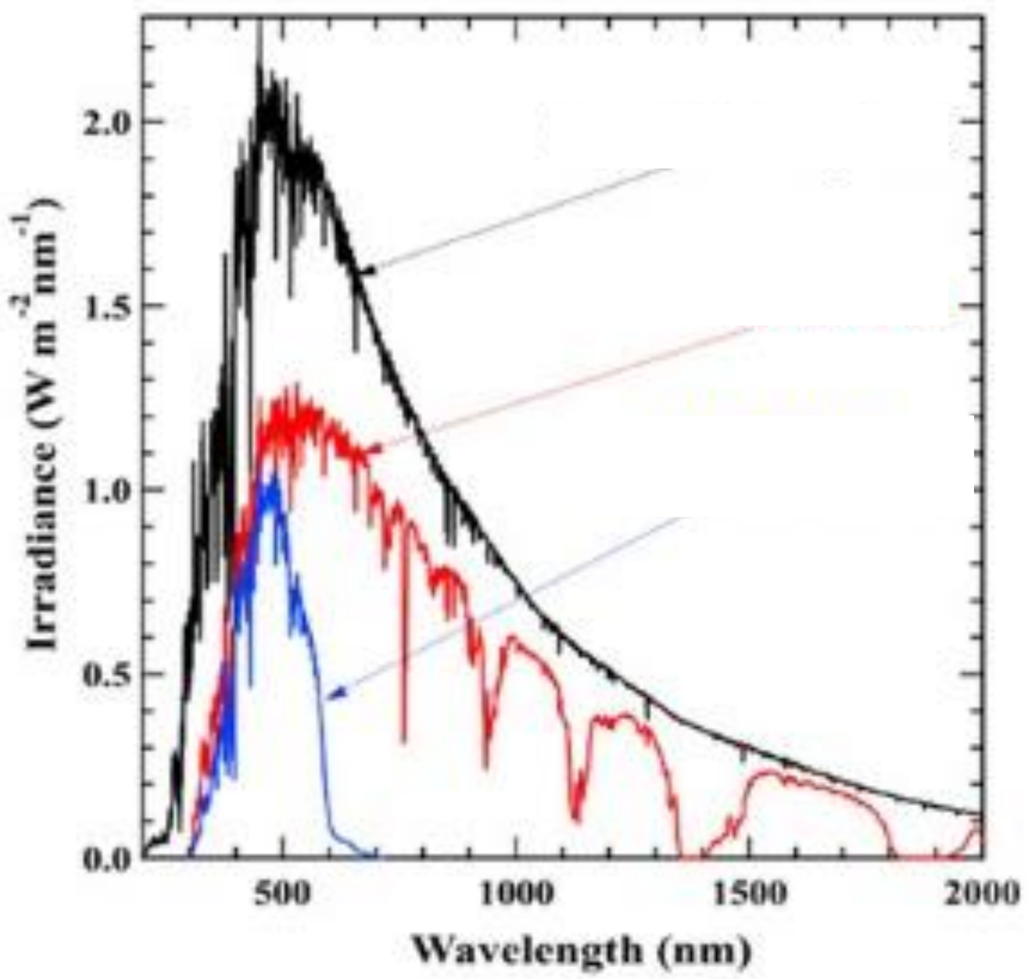
Solar constant is 1370 W m$^{-2}$

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

→ See exercises

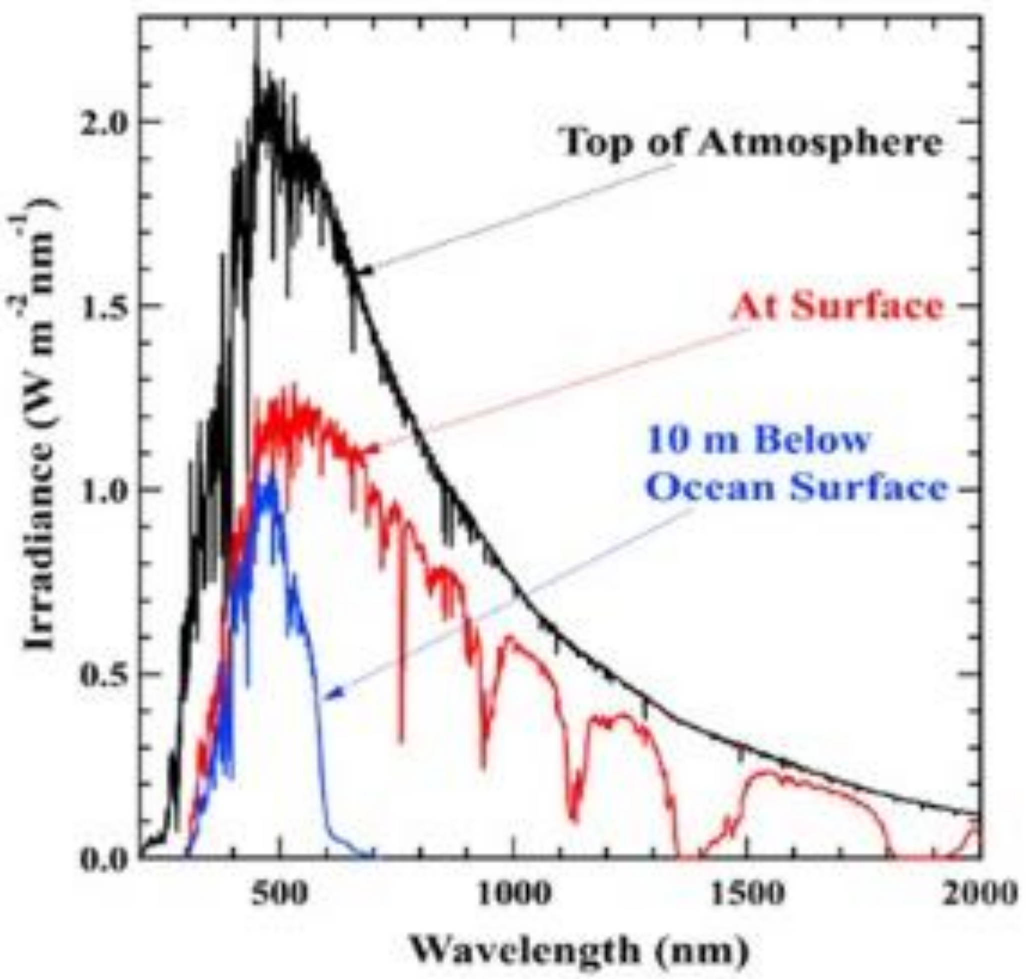
# Transfer of solar radiation through the atmosphere





# Transfer of solar radiation through the atmosphere






There is less radiation reaching the Earth's surface compared to the top of the atmosphere, meaning there must be interaction between solar radiation and Earth's atmosphere.

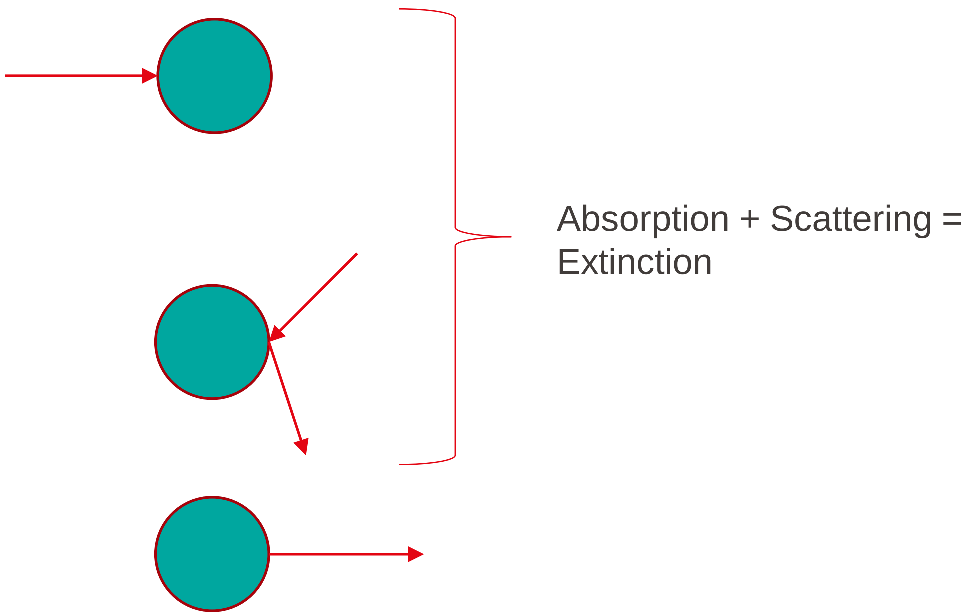
# Interaction of radiation with atmospheric constituents (gases, particles)

## Definitions

1. **Absorption**: A photon is destroyed. Its energy is distributed by collision into other forms of energy (vibration, rotation…). The frequency of subsequently emitted raditation is independent of the frequency of the absorbed photon.

2. **Scattering/Reflection**: The photon changes direction but not frequency.

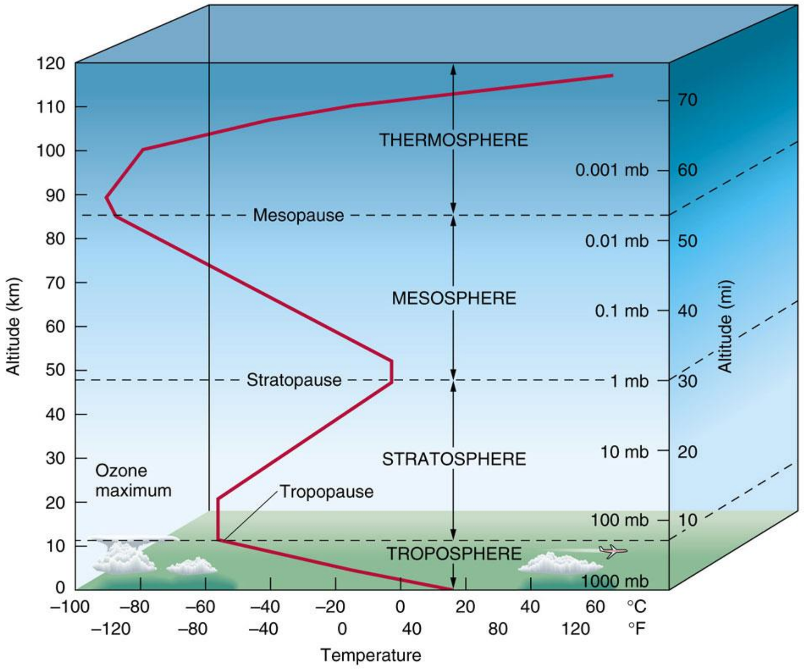
3. **Emission**: A photon is created. The molecule emitting the photon loses internal energy (vibrational, rotational…) equivalent to the energy of the photon.




Processes have different importance:

Shortwave: Absorption + Scattering (mostly gases, particles, clouds)
Longwave: Absorption + Emission (mostly greenhouse gases, clouds)

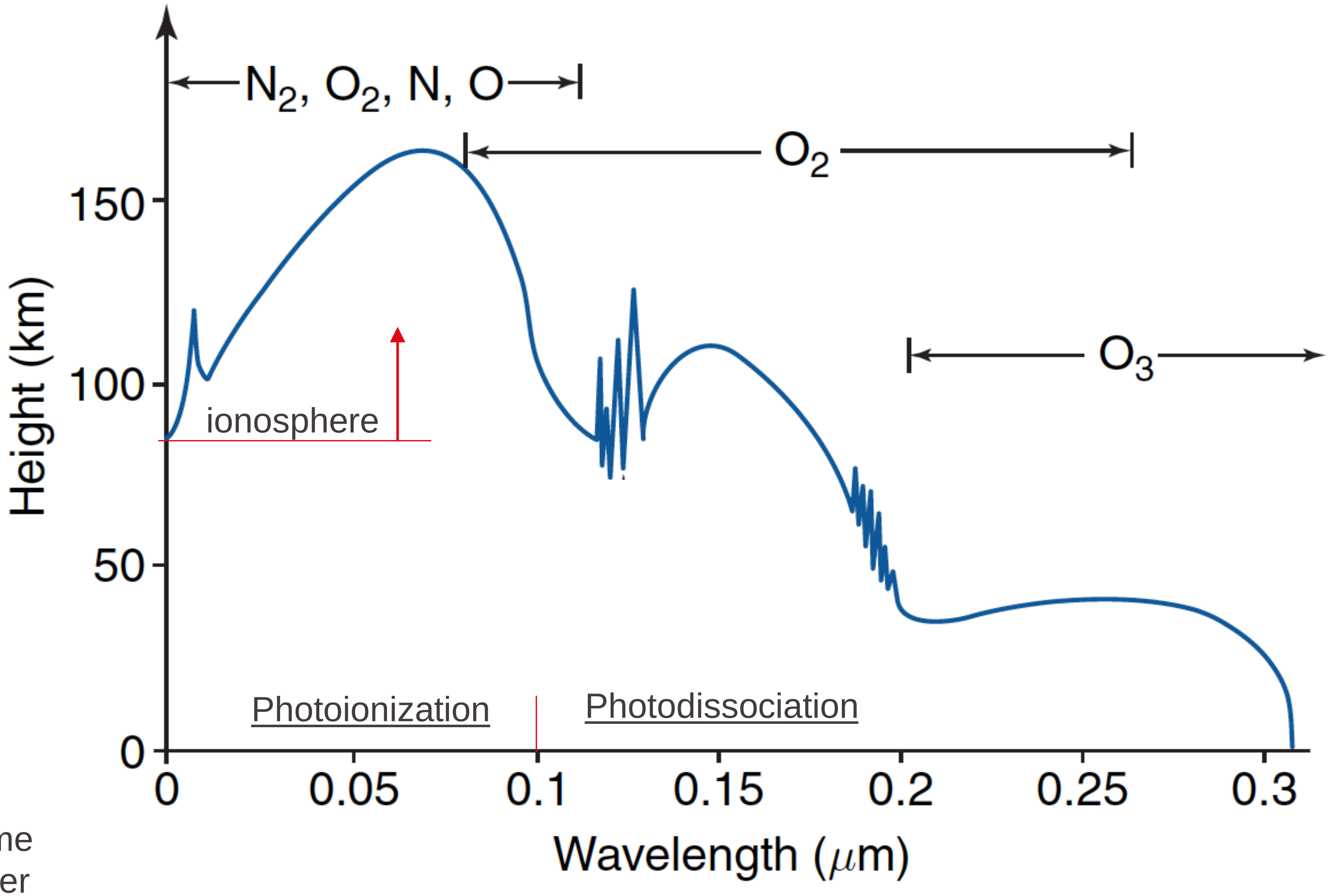
# Absorption by gases




**Absorption continua** in **x-ray and UV range** caused by:

- Photoionization (remove electrons from atoms, extreme ultraviolet $\lambda \leq 0.1\ \mu m$, happens in ionosphere, i.e upper part of thermosphere)
- Photodissociation (break molecules, ultraviolet $\lambda \leq 0.31\ \mu m$, happens down to stratosphere, $O_2$ breakup important for $O_3$ production)

→ energy is converted into kinetic energy (temperature increase of gas)

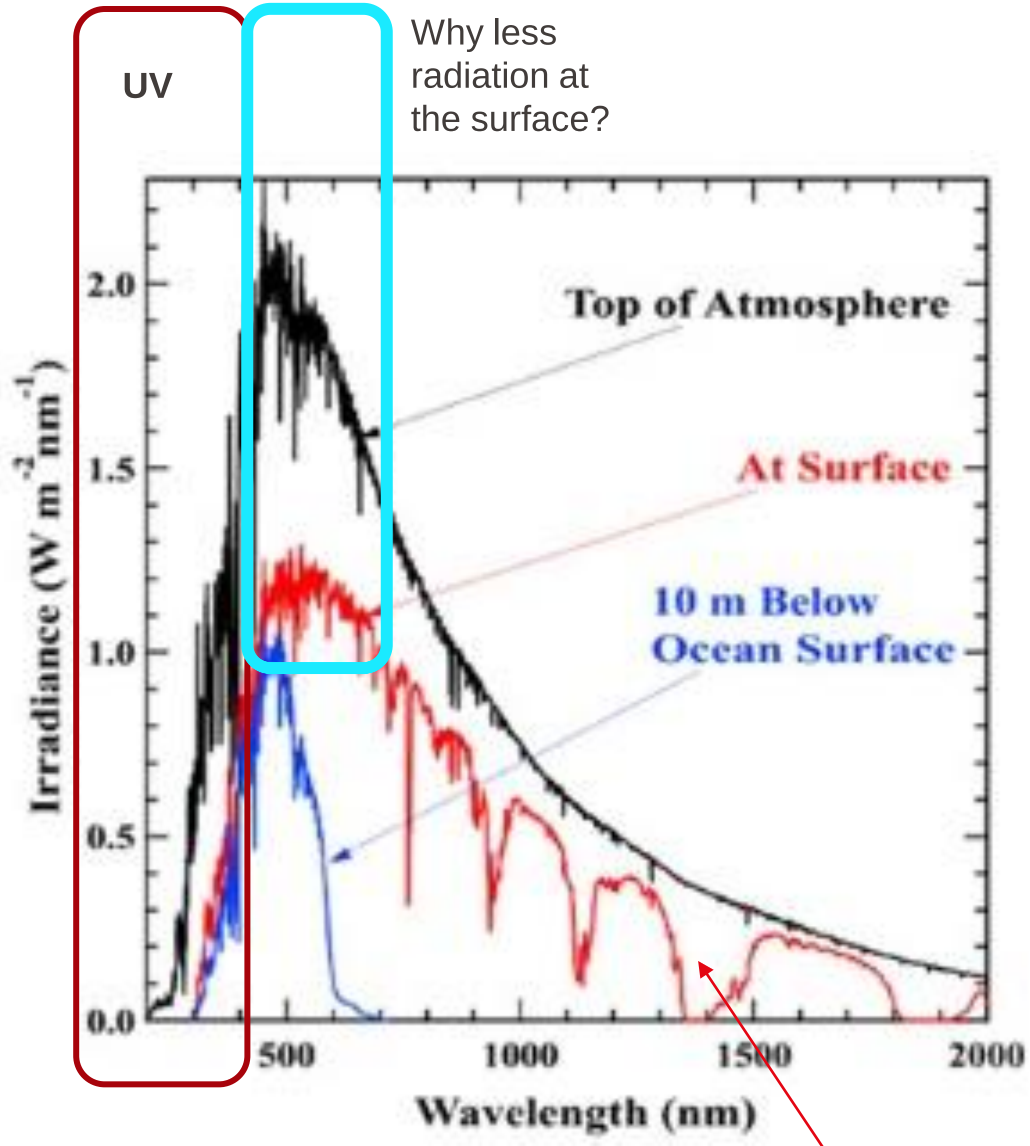



Depth of penetration of solar UV radiation (Fig. 4.20, Wallace and Hobbs,2006)

**Depletion of UV radiation in atmosphere, important for life!**

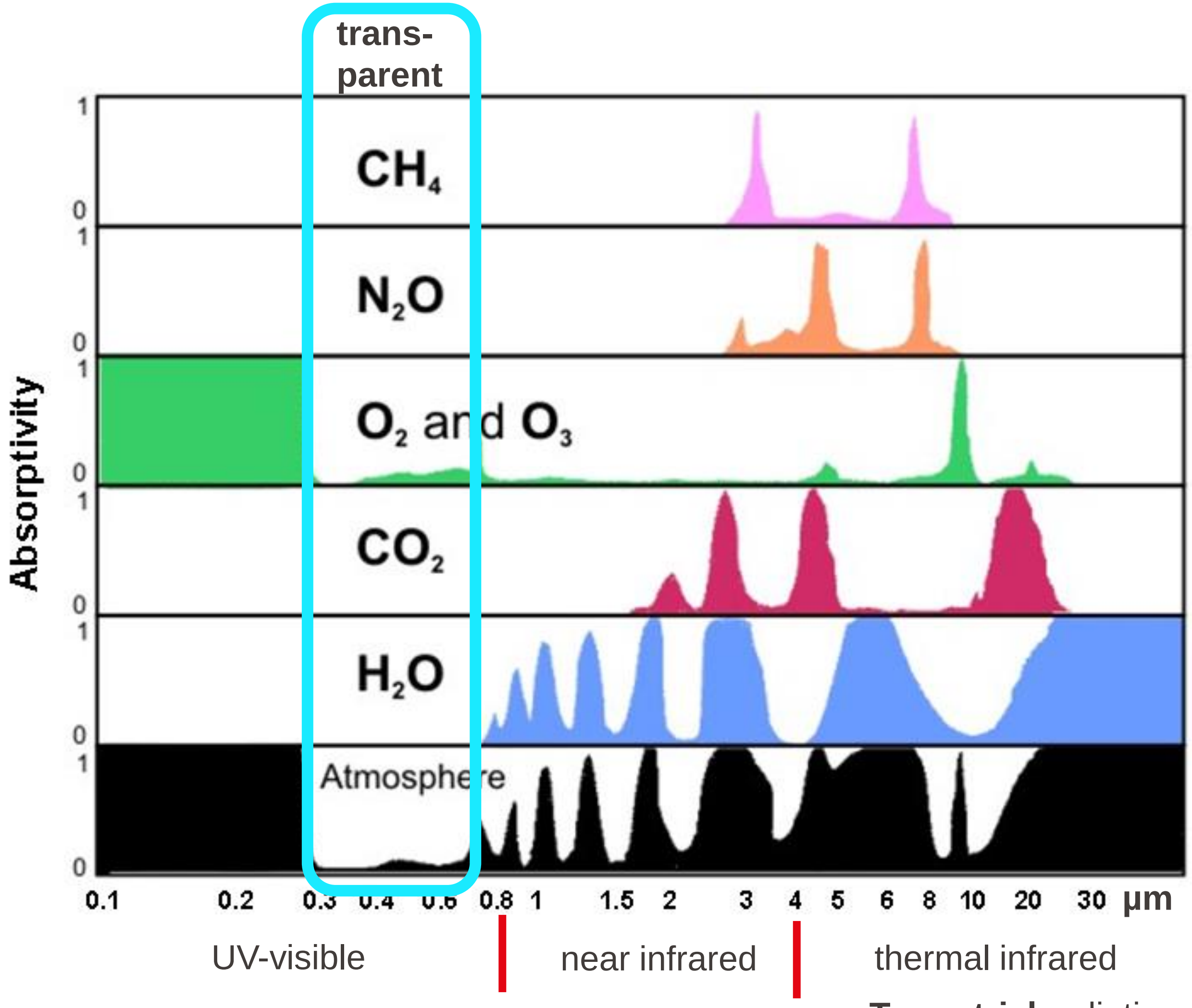
# Absorption by gases

Why less radiation at the surface?



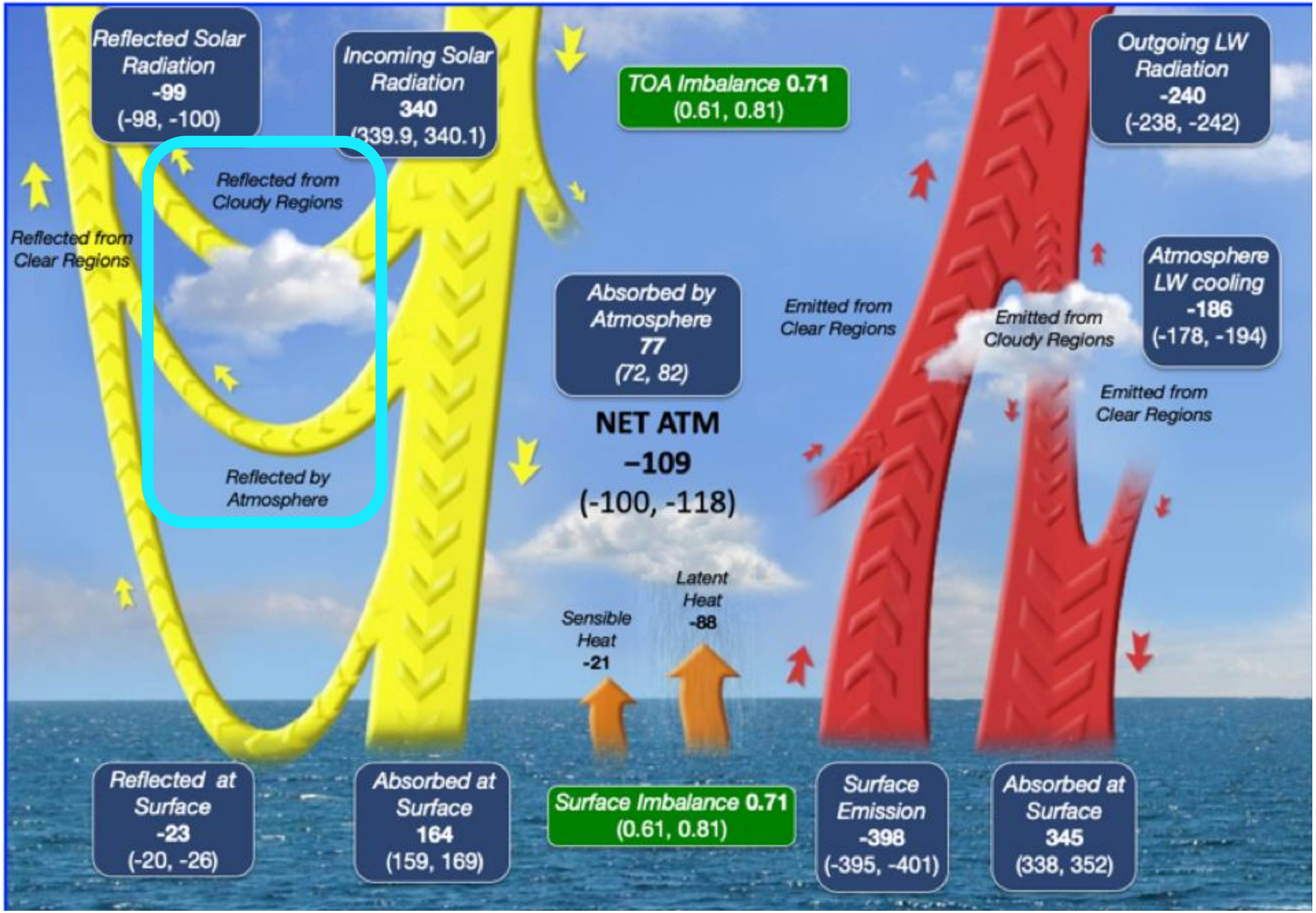

More going on.

**Absorption lines,** mostly in **visible and infrared** spectrum, caused by a change in internal energy state of a gas molecule.




**Terrestrial** radiation

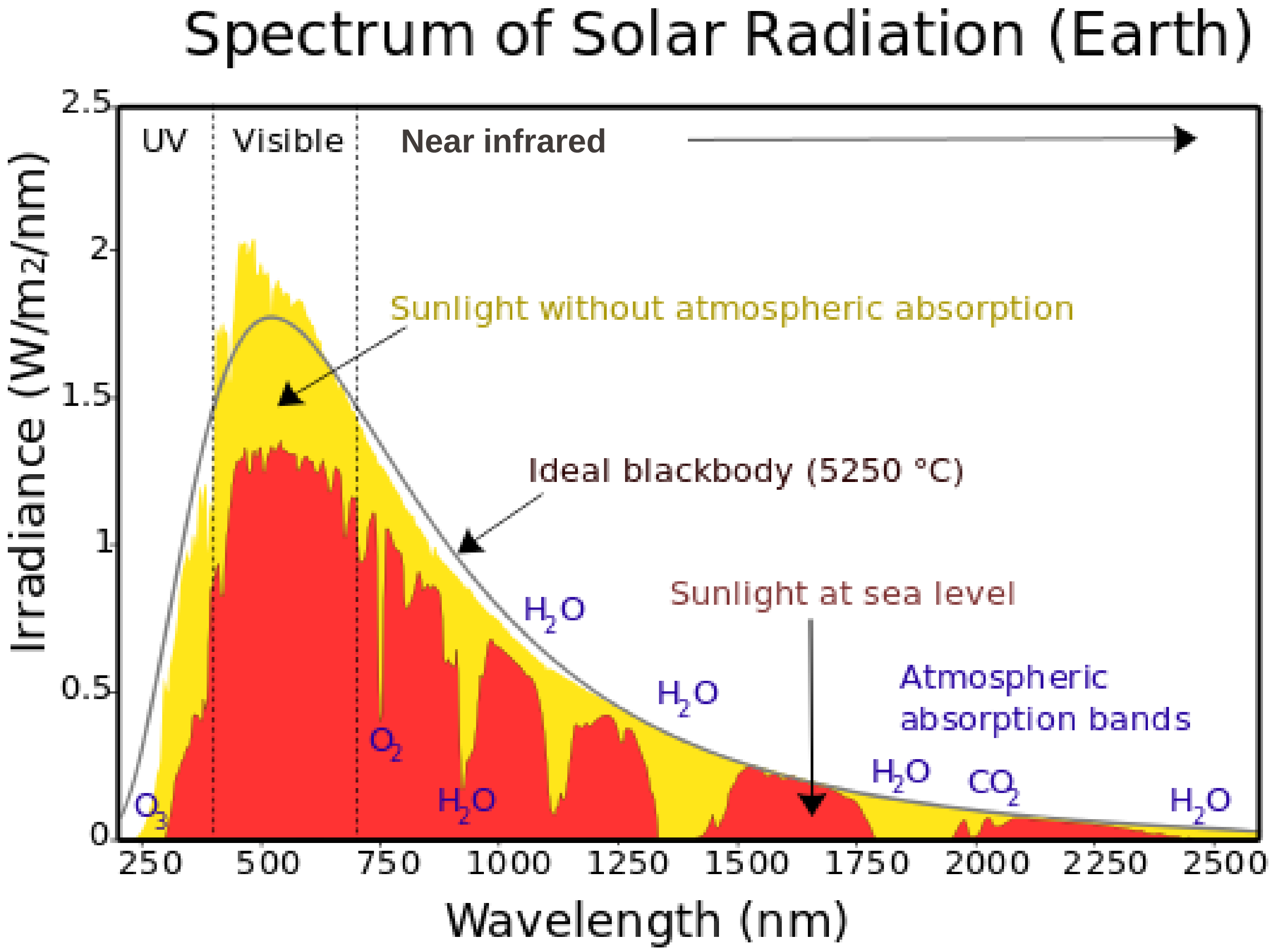
# Earth's Energy Balance

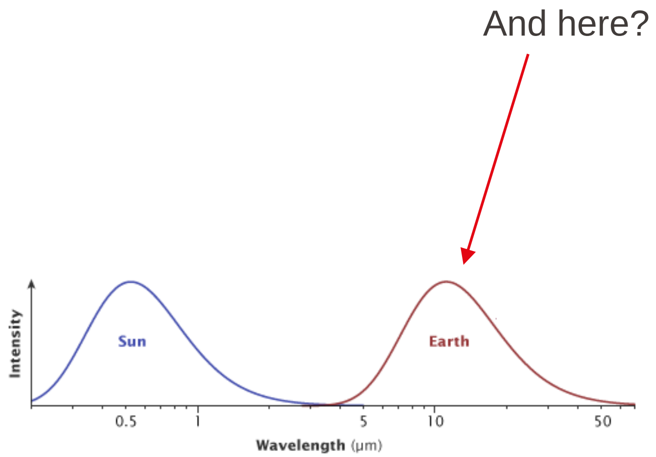



https://ceres.larc.nasa.gov/science/

Reflection is also important.

# Absorption by gases

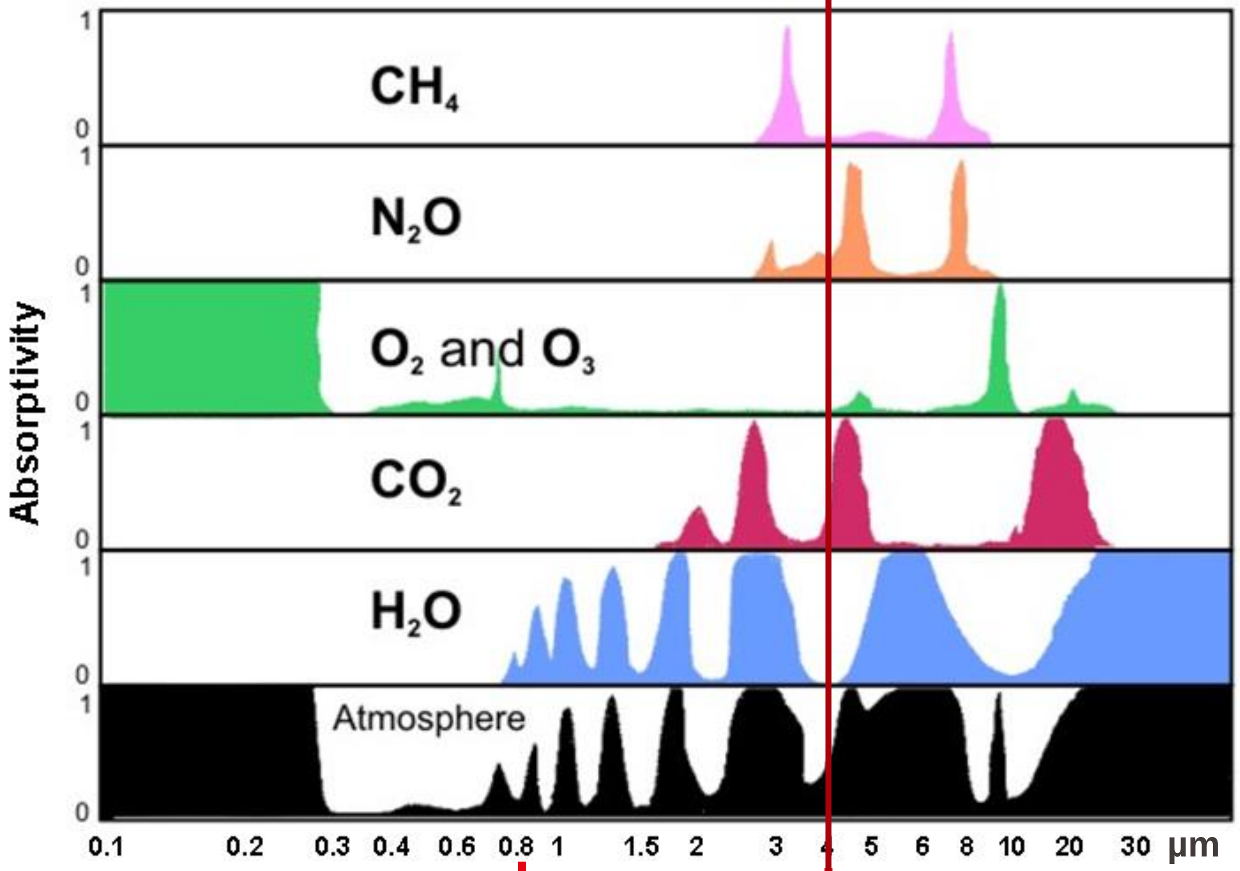



- https://www.e-education.psu.edu/meteo300/node/686

# Absorption by gases

**Strong absorption by greenhouse gases!**




UV-visible | near infrared | thermal infrared

**terrestrial** radiation

# Greenhouse gases



Fundamental consideration:

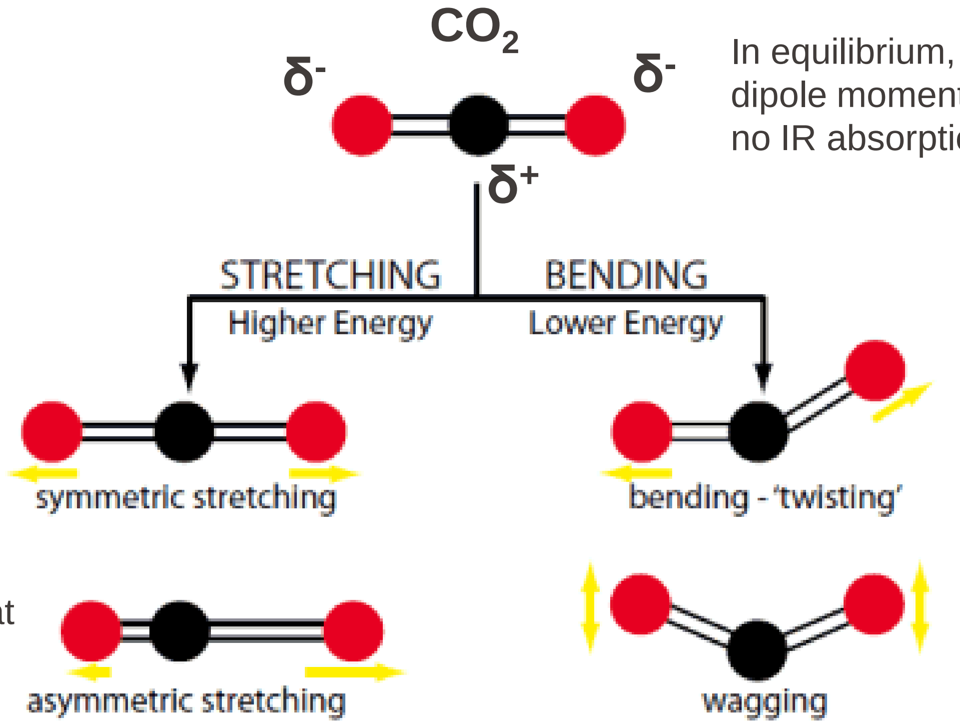
1. **Temperature** is a measure of the average energy of **molecular motion** in matter: to and fro translation, intramolecular vibration, and rotation. The sum of these motions' energies can be described as the "thermal energy". Thermal energy and, hence, **temperature can change as** various forms of energy, including electromagnetic energy, interact with the sample and **change the average energy of motion**.
2. **Molecular vibrations** (and some energetic rotations) have energy level spacings that **correspond to energies in the IR region** of the electromagnetic spectrum. Thus IR radiation absorbed by molecules causes **increased vibration**.
3. **Collisions** between these energized molecules in the atmosphere transfer energy among all the molecules, which increases the average thermal energy and, hence, **raises the temperature**.

- https://www.acs.org/content/acs/en/climatescience/greenhousegases/properties.html

# Greenhouse gases

4. For molecular vibrations **to absorb IR** energy, the **vibrational motions must change the dipole moment** of the molecule. **All molecules with three or more atoms meet this criterion and are IR absorbers.**
5. While the Earth's (dry) atmosphere is predominantly composed of non-IR absorbers, $N_2$ (78%), $O_2$ (21%), and Ar (~0.9%), **the 0.1% of remaining trace gases contains many species that absorb IR**.
6. Earth's atmosphere is not dry and can contain several % of water vapor. **Water vapor is the main greenhouse gas.**
7. The presence of "natural" (i.e. not influenced by human action) water vapor, $CO_2$, $CH_4$, $N_2O$ and other greenhouse gases are **responsible for the natural greenhouse effect.**

In equilibrium, no dipole moment, no IR absorption.




molecular vibrations of $CO_2$

In equilibrium, no dipole moment, no IR absorption.

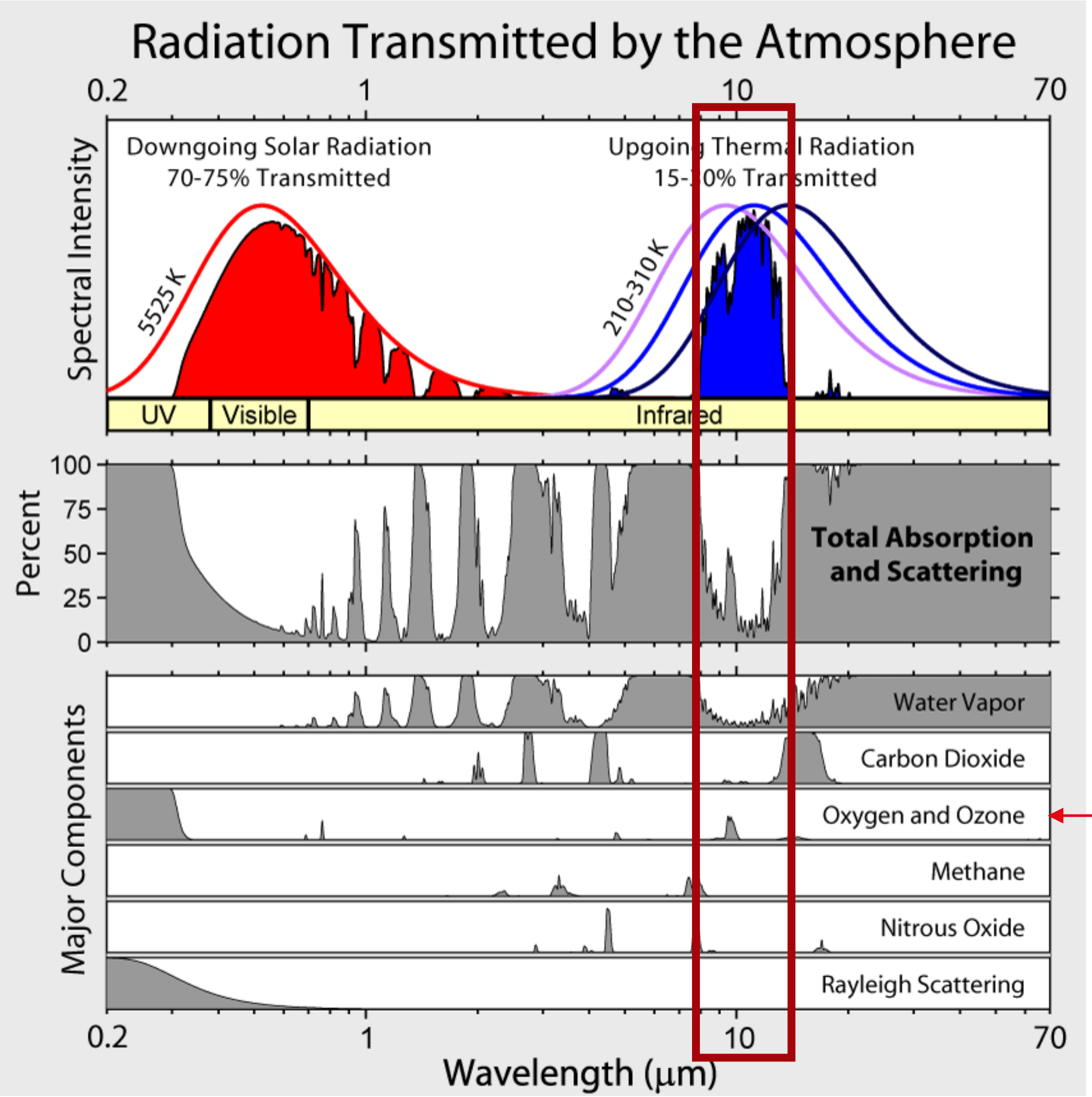
Absorption at 4 µm

Absorption at 15 µm

**Dipoles** means that a molecule has negative and positive charges, and the averaged centers of the charges do not co-incide. This leads to a dipole moment, capable of IR absorption. $O_2$ and $N_2$ are not dipoles.

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

# Atmospheric «windows»




The window is between 8-9 and 10 - 12 µm, roughly.

The result of the presence of greenhouse gases is that only a small part of the longwave surface emission makes it to space.

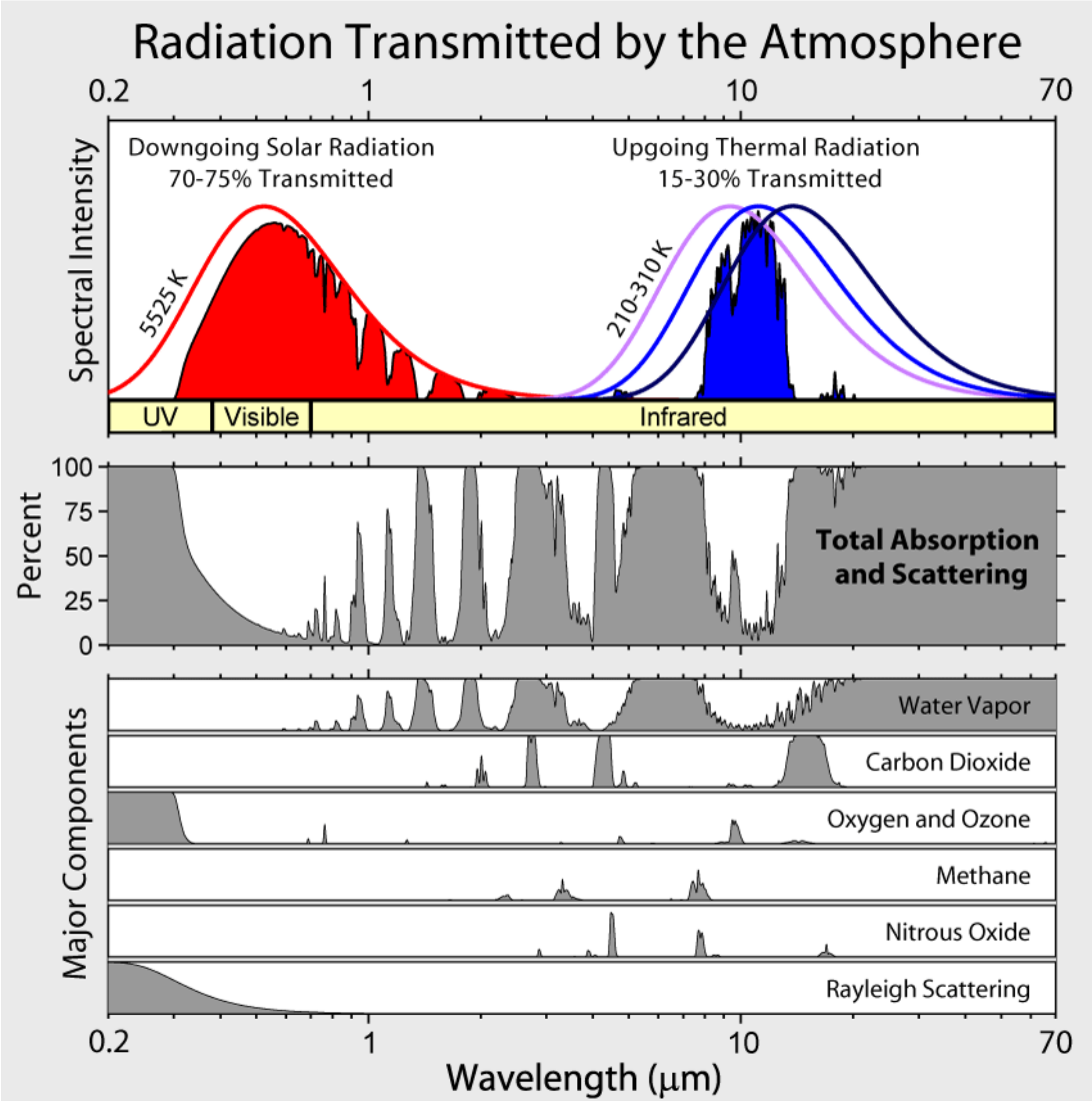
Different greenhouse gases work together to close “atmospheric windows” in the longwave part of the spectrum. They are located at the window edges.

Ozone absorbs at 9.6 µm.

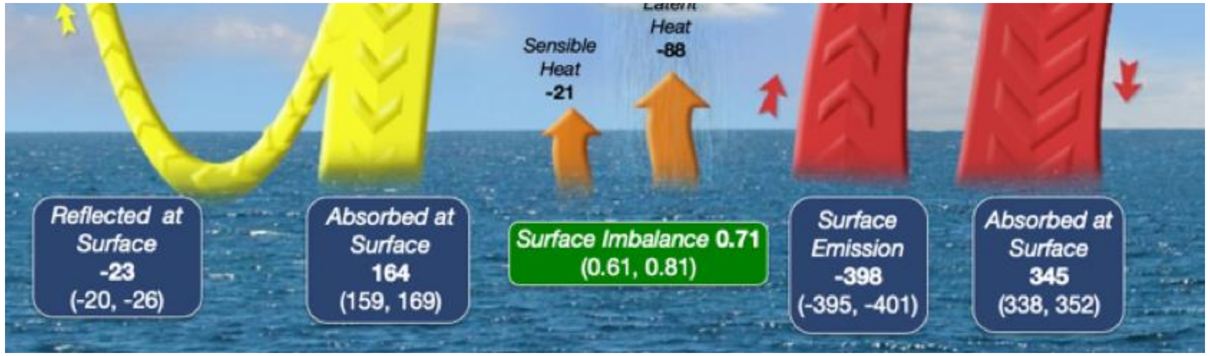
Source: Wikipedia

# Greenhouse effect

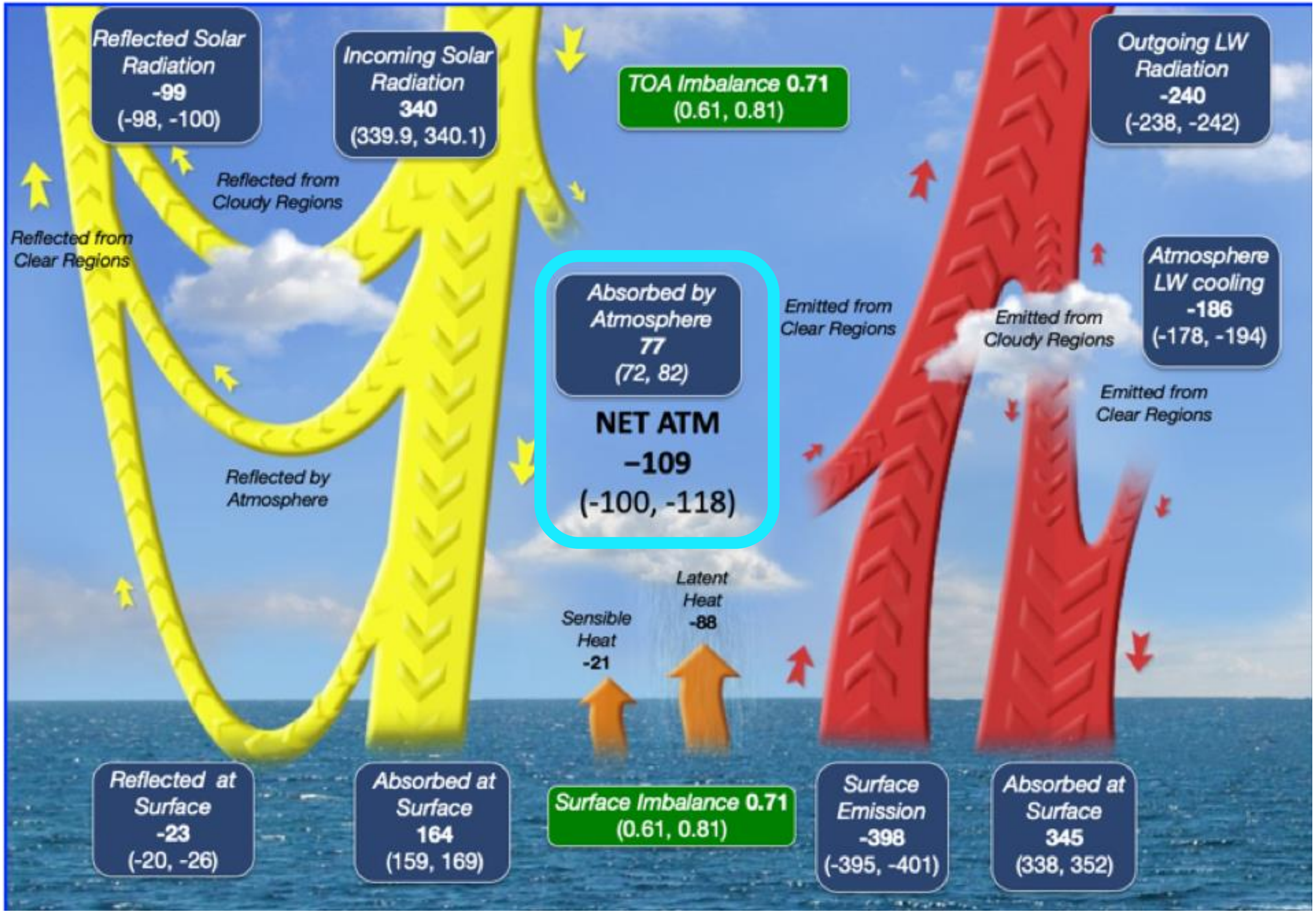





1. Solar radiation is transmitted through Earth's nearly transparent atmosphere (transparent to shortwave radiation).
2. Earth's surface absorbs the solar radiation and warms.
3. The Earth emits thermal IR radiation (blackbody radiation).
4. The atmosphere is much less transparent to thermal infrared radiation and absorbs it.
5. The absorbed radiation leads to warming of the atmosphere, which in turn emits thermal IR radiation in all directions, but also partly downwards.
6. So the net thermal IR flux from the Earth (as blackbody) to space is greatly recuded. This diminishes the radiative cooling of the Earth's surface and leads to surface warming.



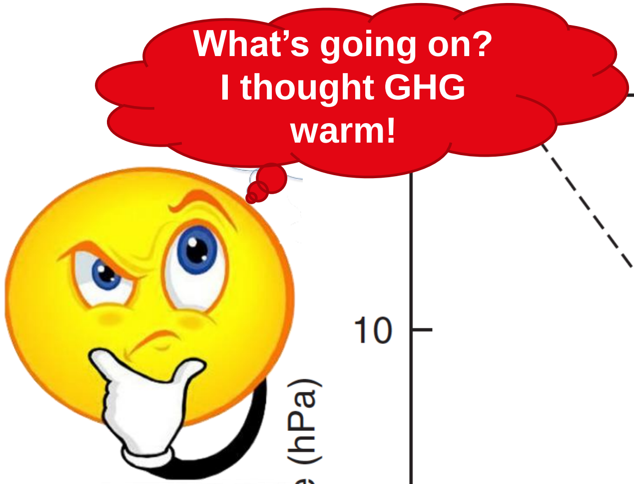
# Earth's Energy Balance

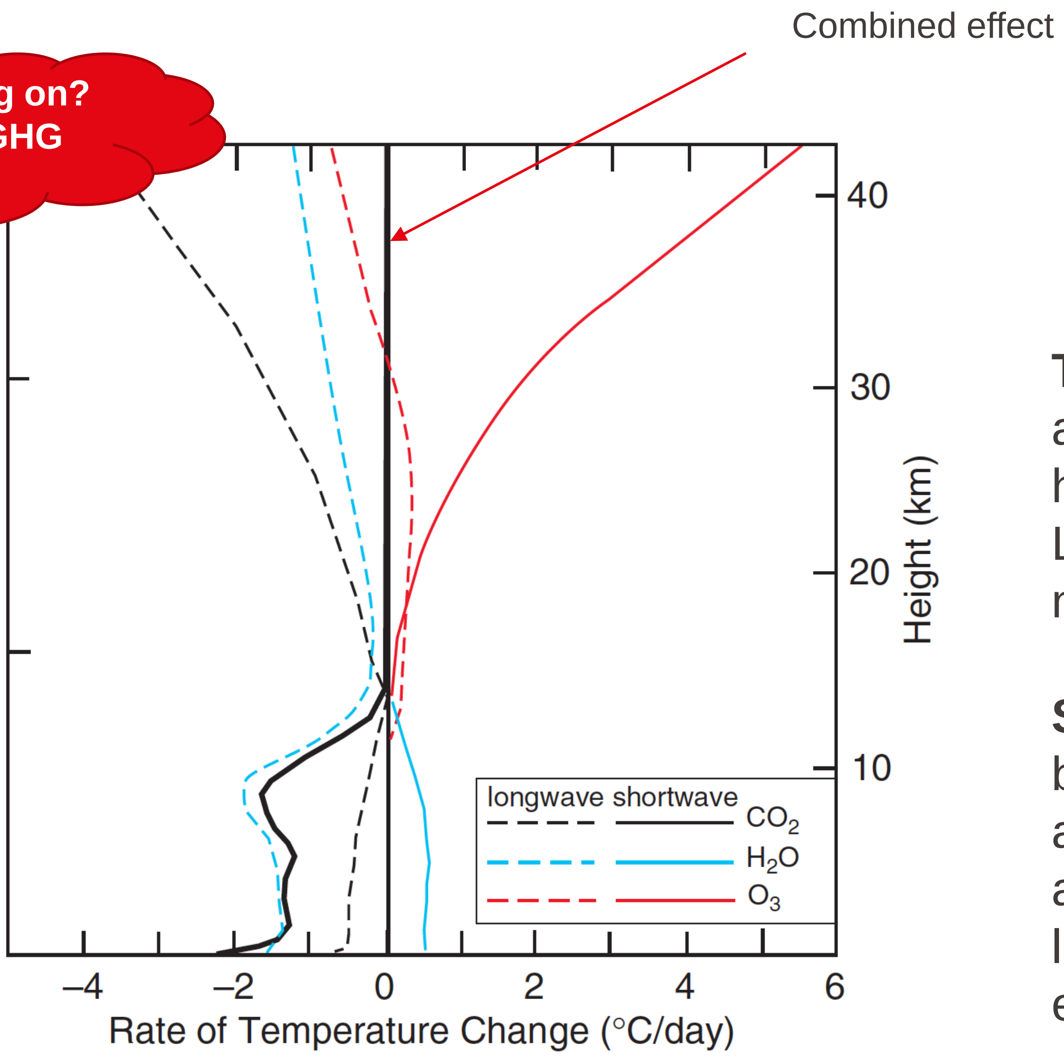



https://ceres.larc.nasa.gov/science/

Net atmospheric loss of energy.

# Heating and cooling from radiative transfer




Climate model from the 60s (**Manabe** and Strickler (1964)

- Longwave & shortwave
- Average Earth cloudiness assumption
- 3 greenhouse gases

**Troposphere**: Cooling due to $H_2O$, mainly, and $CO_2$. Effect of $H_2O$ decreases with height along with smaller mixing ratio. Longwave $CO_2$ effect and shortwave $H_2O$ nearly cancel each other.

**Stratosphere**: Equilibrium due to warming by $O_3$ (UV absorption, and a little bit of IR absorption at 9.6 µm) and cooling by $H_2O$ and $CO_2$ (dominant cooling agent through longwave emission). Model assumes equilibrium in the stratosphere.

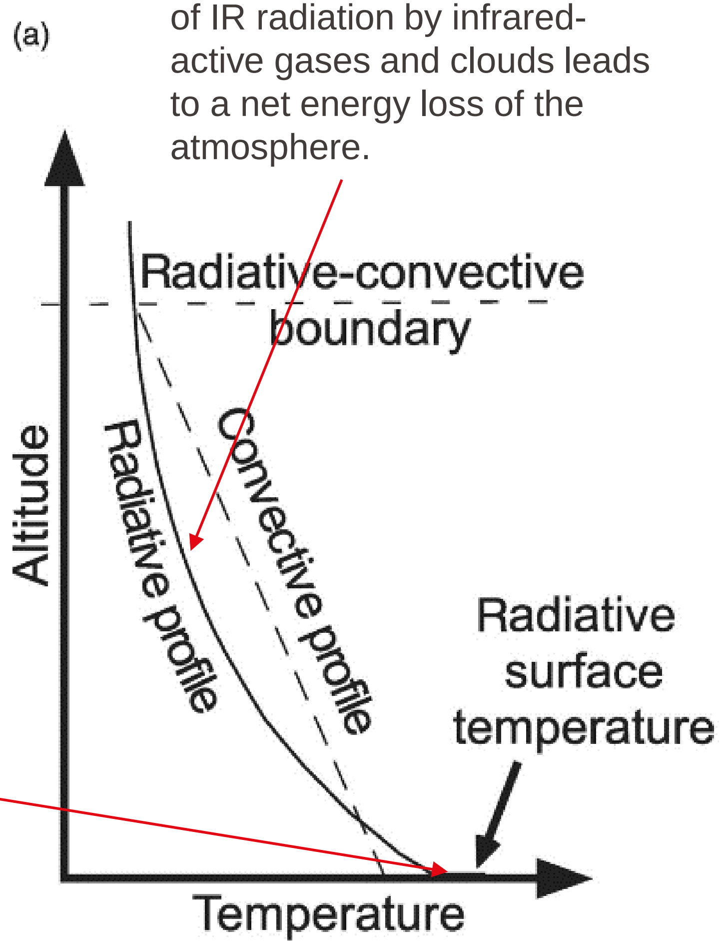
- Wallace and Hobbs, Fig. 4.29, original publication: https://journals.ametsoc.org/view/journals/atsc/21/4/1520-0469_1964_021_0361_teotaw_2_0_co_2.xml?tab_body=pdf

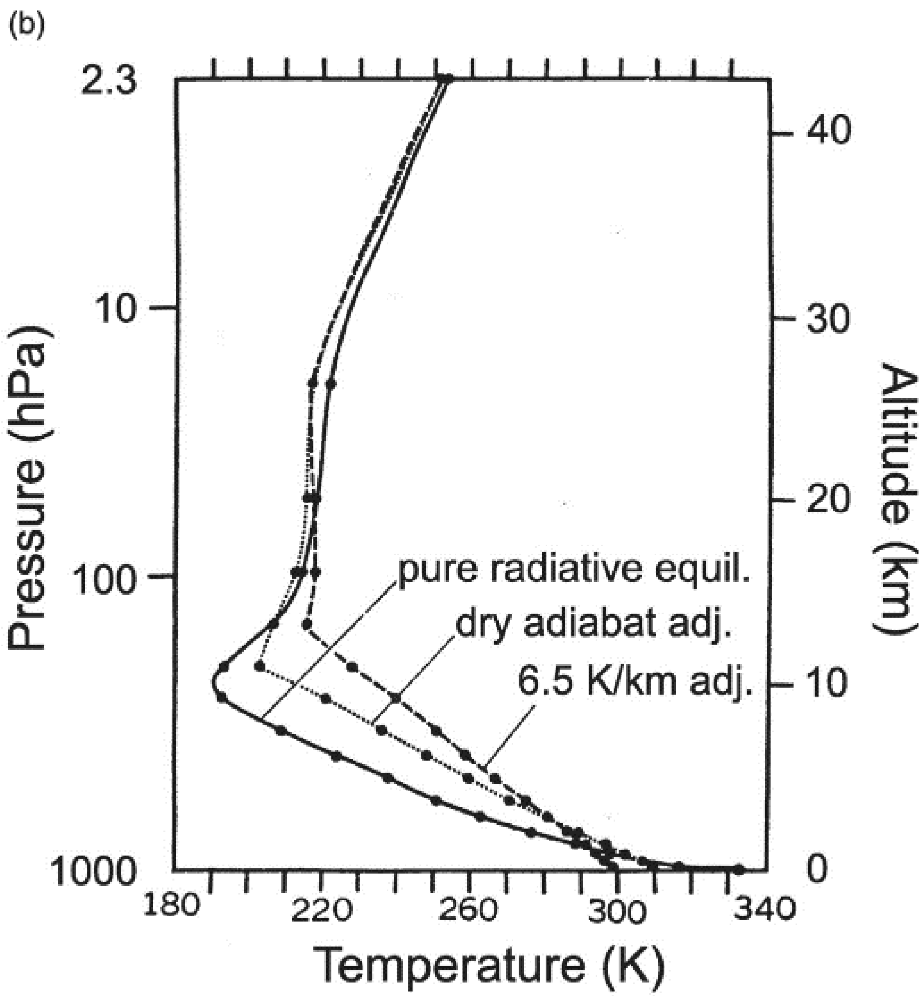
# Convective - radiative equilibrium



Because the density of the atmosphere increases close to the surface, the layers become optically thicker and physically thinner. Hence, removing heat near the surface becomes difficult.
If only radiative equilibrium were responsible for the energy balance, Earth's surface would be very hot!

Further aloft in the troposphere, the re-emission of IR radiation by infrared-active gases and clouds leads to a net energy loss of the atmosphere.



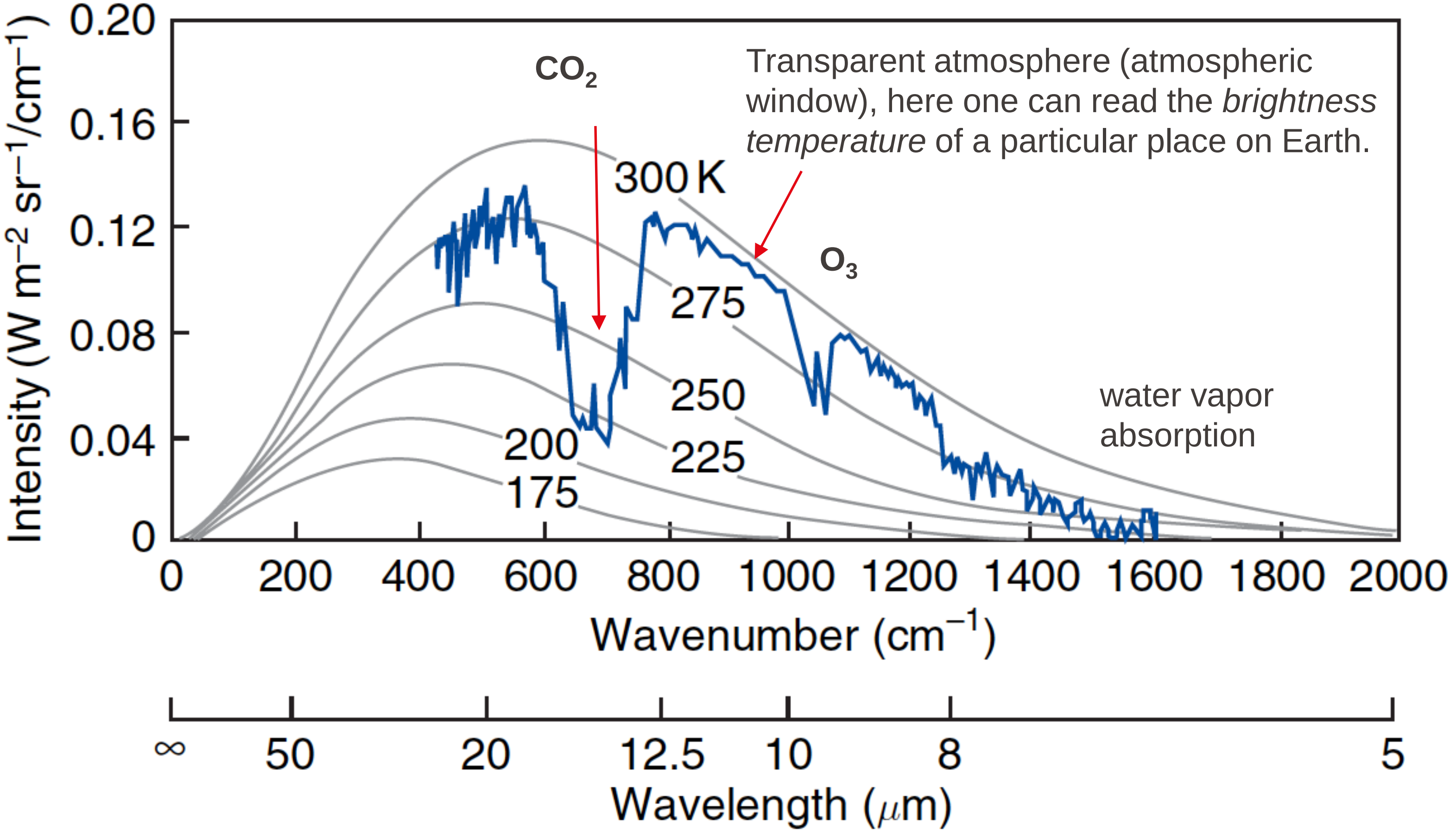

In fact, convective transport of sensible and latent heat of water vapor cools the surface and warms the troposphere and leads to the observed lapse rate of -6.5 K / km.

equil. = equilibrium
ajd. = adjustment

Catling, D., & Kasting, J. (2017). Principles of Planetary Atmospheres. In *Atmospheric Evolution on Inhabited and Lifeless Worlds* (pp. 1-168). Cambridge: Cambridge University Press. Wallace and Hobbs, 2006, Ch. 4.3.6

# Earth's emission seen from space

**Greenhouse gases reduce the emission by Earth at the top of the atmosphere!**




In this graph, the radiation emitted by the Earth's surface retrieved at the TOA (e.g on a satellite) is shown. It is about 40 % less than emitted at the surface.
The grey lines show blackbody emissions for different temperatures.

Where the "measured" spectrum is close to the curve of a high blackbody temperature, atmospheric "windows" are present.

Absorption bands show low brightness temperatures, because the maximum absorption (extinction) happens further up in the atmosphere, where it is colder.

The greenhouse effect is the difference between the blue and ~300 K curve.

Wallace and Hobbs: Fig. 4.31

# Summary of greenhouse effect processes



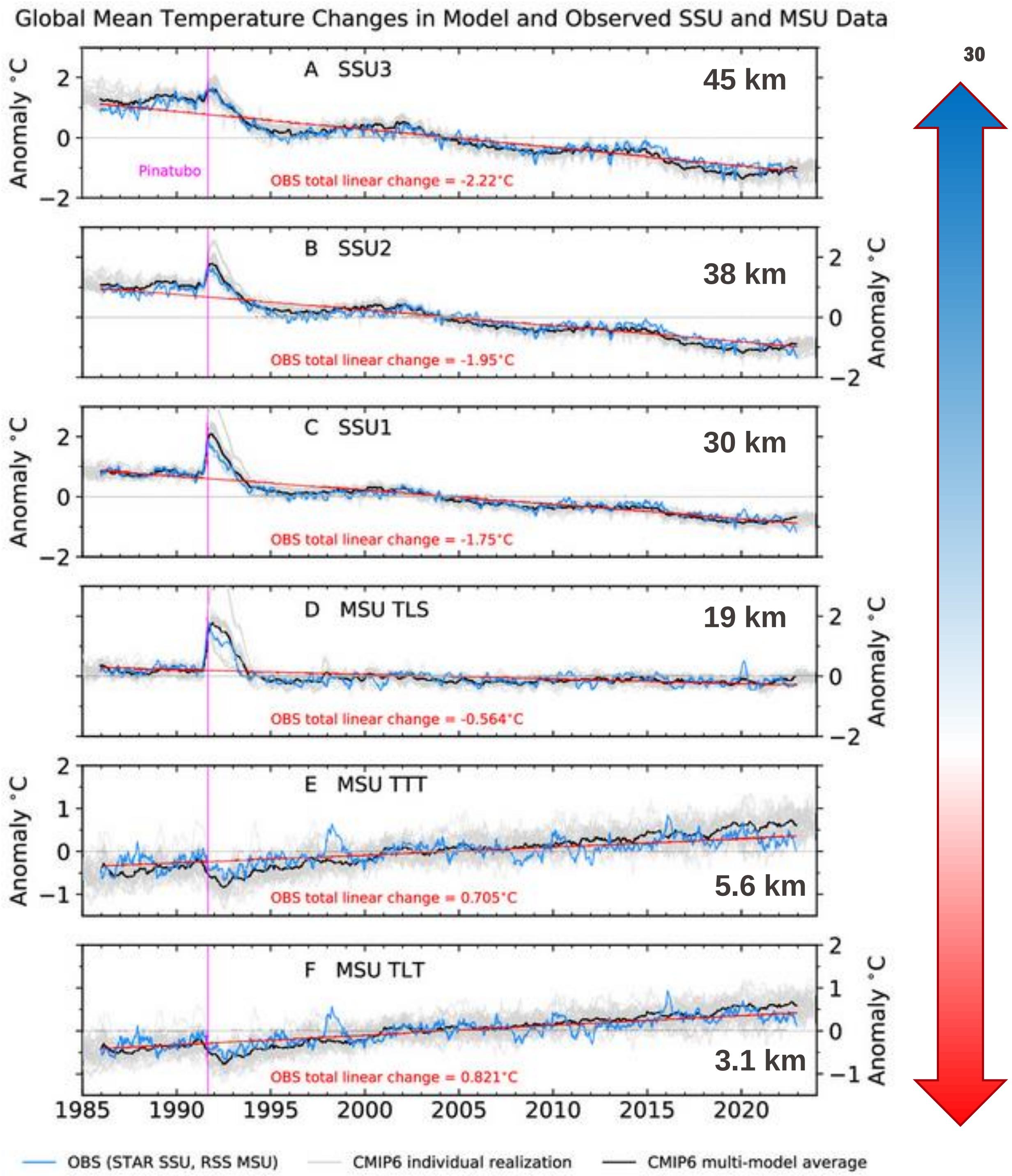
- In summary the greenhouse effect induced by infrared-active gases consists of three elements:

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.

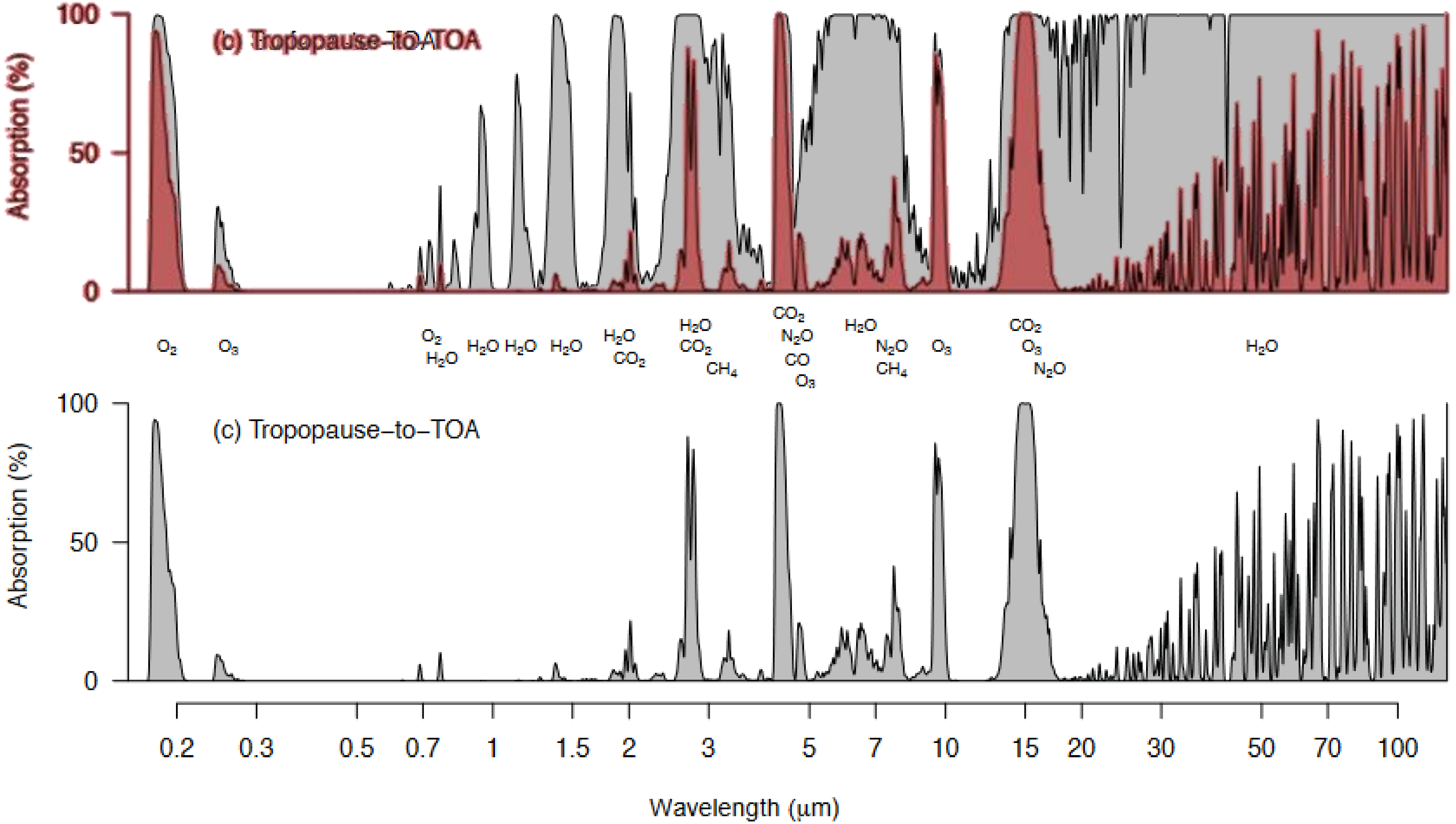
# Stratospheric cooling



- 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

# What about the effect of particles and clouds?