EPFL

Exercises #1

# Sustainability, climate and energy

# Today's goals

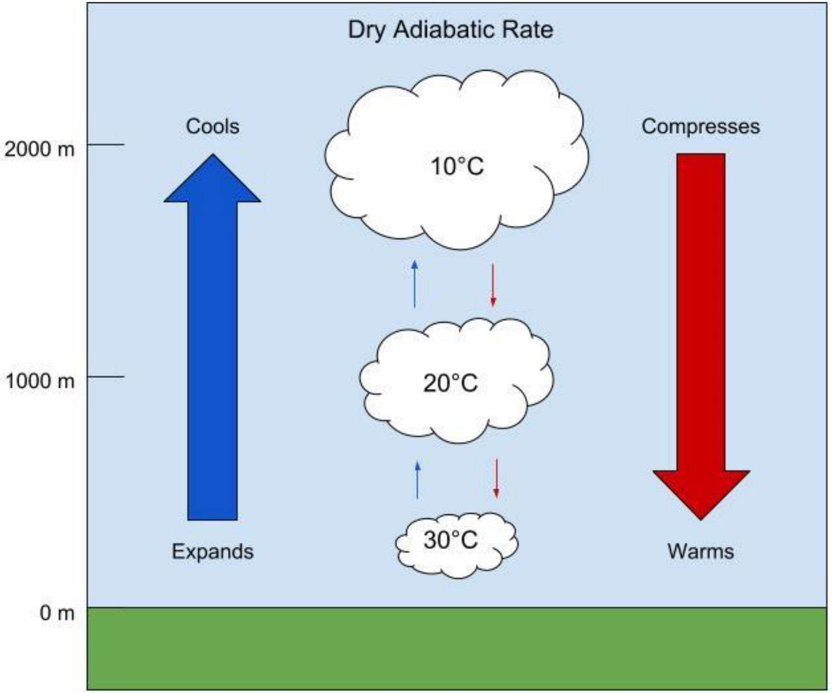
- Some important notions:
  - Lapse rate
  - Latent heat
- Radiative balance
- A joint debunking of climate-skeptic article

# Lapse Rate: control of atmospheric stability climate feedback

- The lapse rate (Γ) is the rate at which temperature (*T*) decreases with height (*z*), in K/km:

$$\Gamma = -\frac{dT}{dz}$$

- **Dry adiabatic lapse rate DALR** *(adiabatic means that there is no heat exchange with the surroundings, only internal energy change due to expansion or compression).*
- Warm and dry parcels expand and rise ; then they fall due to cooling and compression, until reaching equilibrium with surrounding air.
- DALR is ~9.8 K/km *(function of gravitational acceleration and heat capacity of dry air).*




*Source: A. Nugent et al., atmospheric processes and phenomena*

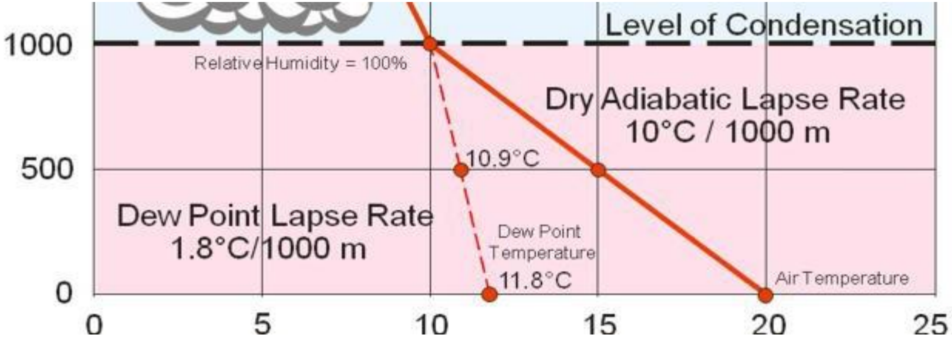
# Lapse Rate: control of atmospheric stability climate feedback

- **Dew point lapse rate (DPLR)**: rate at which the dew point temperature decreases with altitude.
- Dew point is the temperature at which air becomes saturated with water vapor and condensation begins.
- When air reaches the dew point, the relative humidity *RH* is 100%. It depends on pressure and temperature.
- DPLR is ~1.8 K/km.
- Simplified formula to calculate the dew point $T_d$ :

$$T_d \approx T - \frac{(100 - RH)}{5}$$

- Example: air mass with $T$ = 30°C and RH = 60%

$T_d$ = 22°C




*RH* = 60%

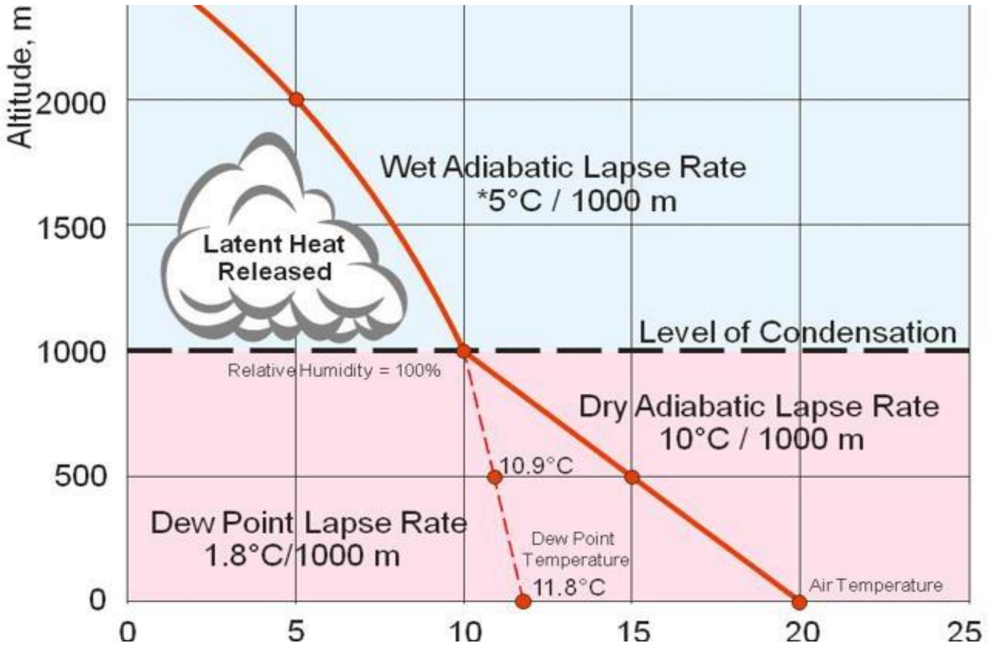
Source: Creative Commons

# Lapse Rate: control of atmospheric stability climate feedback

- When DALR and DPLR meet at altitude, it defines where RH becomes 100% and clouds start to form (if CCN or INP are around…)

  = level of condensation

- **Wet adiabatic lapse rate (WALR)**: water droplets start to form and release latent heat in the atmosphere, thus reducing the cooling rate of rising air parcels.
- WALR ranges from 4 to 7 K/km, depending on air temperature and pressure. It is less than DALR.
- Warm humid air: close to 4 K/km
- Cold dry air: close to 7 K/km



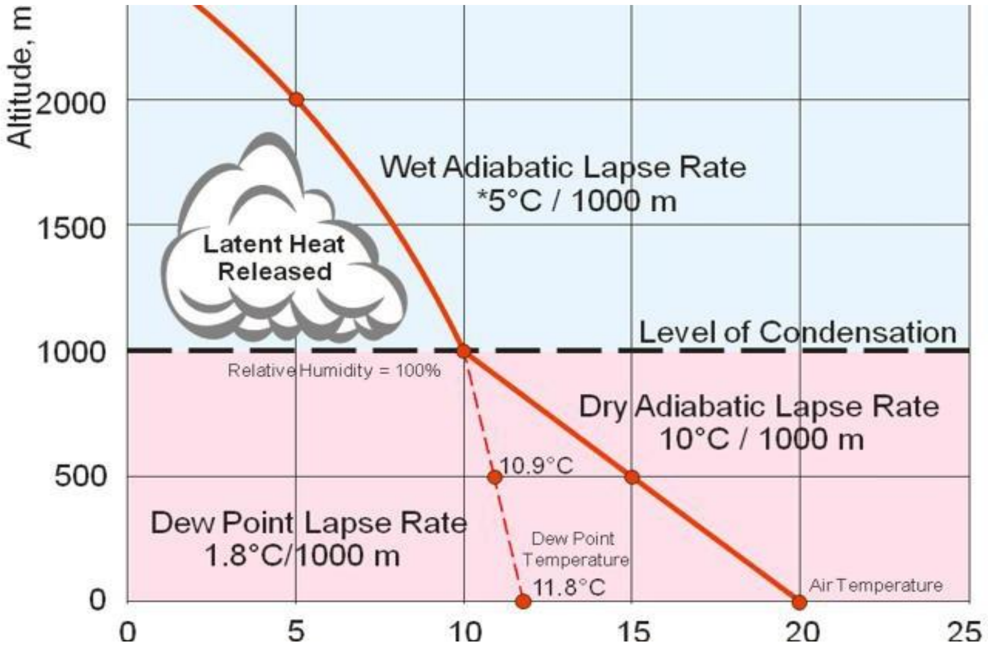

RH = 60%

Source: [Creative Commons]

# Lapse Rate: control of atmospheric stability climate feedback

**Environmental lapse rate**, which is a mix of DALR, DPLR and WALR.

Under average atmospheric conditions, it is roughly 6.5 K/km.




RH = 60%

Source: [Creative Commons]

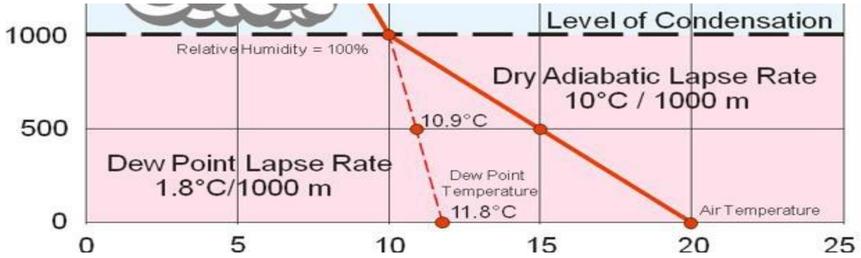
# Exercise: determine the altitude of cloud formation

Relevant information:

$$T_d \approx T - \frac{(100 - RH)}{5}$$

RH being the relative humidity

Dry ALR = 9.8 K/km
DewPoint LR = 1.8 K/km
Wet ALR = 5 K/km




- **Ground air temperature is 10°C**
- **Relative humidity at ground is 60%**
- **At what altitude *z* (in km) would clouds form ?**

# Exercise: determine the altitude of cloud formation

**Relevant information**:

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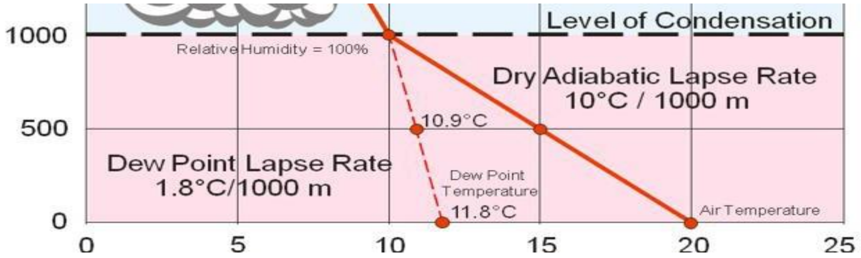



- **Ground air temperature is 10°C**
- **Relative humidity at ground is 60%**
- **At what altitude *z* (in km) would clouds form ?**

**Solution**:

- Dew point temperature at surface: 10 – ( 100 – 60 ) / 5 = **2°C**
- Meeting point between DPLR and DALR: 10 – ( 9.8 * *z* ) = **2** – ( 1.8 * *z* )
- *z* = ( 10 – 2 ) / ( 9.8 – 1.8)

**Z = 1 km**

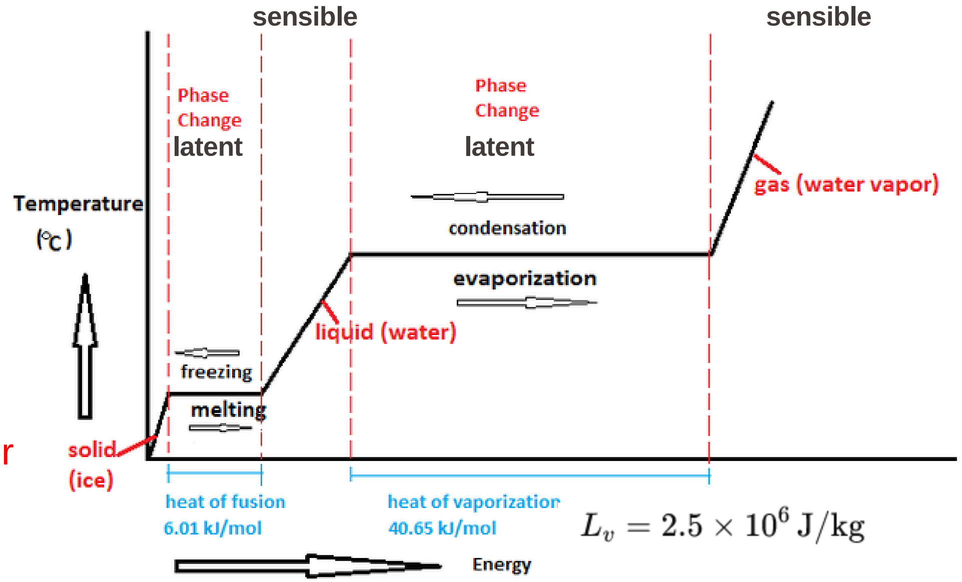
# Latent and sensible heat

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

**Latent heat**: energy is transferred **without change of body's temperature**. There is a change of the physical state of the body between solid, liquid and vapor. In the case of water: melting of ice, evaporation over the oceans, condensation in clouds, solidification with snow fall.

**Sensible heat: Change of body's temperature**, without a change in physical state. It can be «felt», like increasing or decreasing air or water temperature.

For water




$$L_v = 2.5 \times 10^6 \ \mathrm{J/kg}$$

Source: https://commons.wikimedia.org/wiki/File:Water_Phase_Change_Diagram.png

# Exercise: latent heat release and evolution of air parcel

**Relevant information**:

Energy $Q$ released by condensation: $Q = L_v \times m_{\text{condensed water}}$

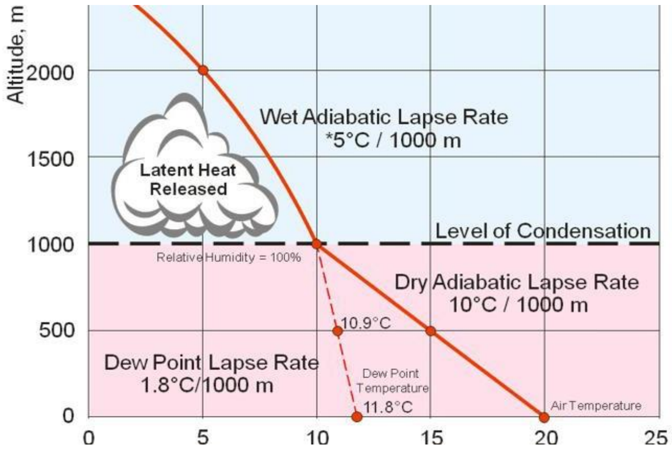
where $L_v = 2.5 \times 10^6\ \text{J/kg}$

Temperature change: $\Delta T = \dfrac{Q}{c_p \times m_{\text{air}}}$

where $c_p$ is the heat capacity of air: 1.005 kJ/kg-K

And $m_{air}$ is the mass of the air parcel

DALR = 9.8 K/km
DPLR = 1.8 K/km
WALR = 5 K/km




- **In the case before, a ground air parcel at 10°C and 60% RH rises and condensates at 1 km**
- **Let's assume that the air parcel weights 1kg and contains 5 g of $H_2O$**

- **What is the temperature of the air parcel at 1 km, <u>before condensation</u> ?**
- **What is its temperature <u>after condensation</u> ?**
- **Assuming that the air parcel will keep rising until freezing, at what altitude *z* (in km) would precipitation form ?**

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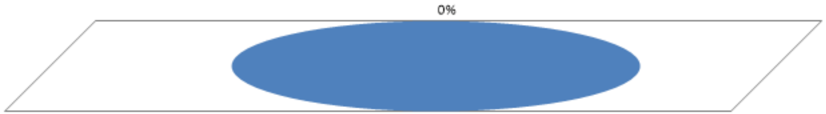

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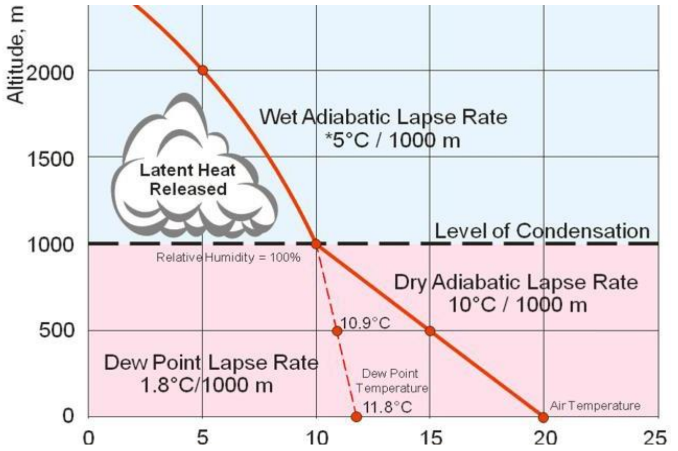


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- **What is the temperature of the air parcel at 1 km, <u>before condensation</u> ?**

**Solution**:

- Use DALR and ground T or DPLR and ground DP T: 10 – ( 9.8 * 1) = **0.2°C**

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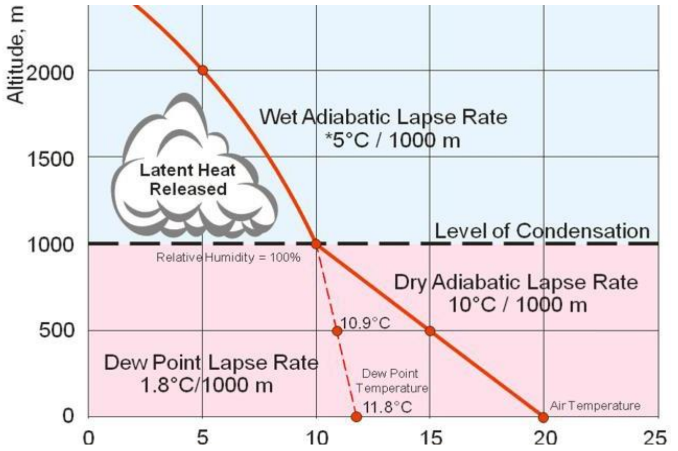


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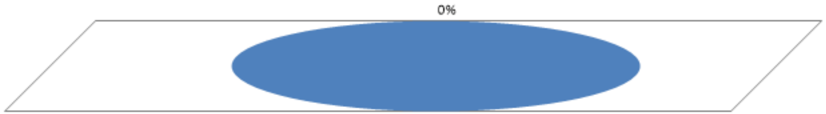

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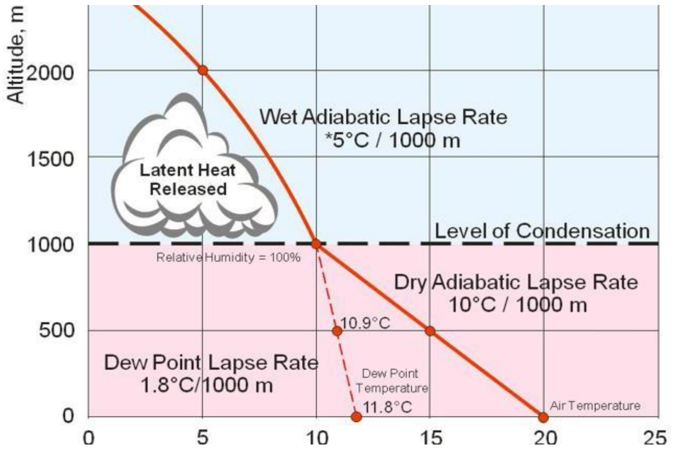


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- **What is its temperature after condensation ?**

Solution:

- $Q = L_v \times m_{\text{condensed water}}$ Q = 2.5*10^6 x 0.005 = **12,500 J**
- $\Delta T = \dfrac{Q}{c_p \times m_{\text{air}}}$ ΔT = 12,500 / (1005 * 1) = **12.4 K** T = 0.2 + 12.4 = **12.6°C**

# Exercise: latent heat release and evolution of air parcel

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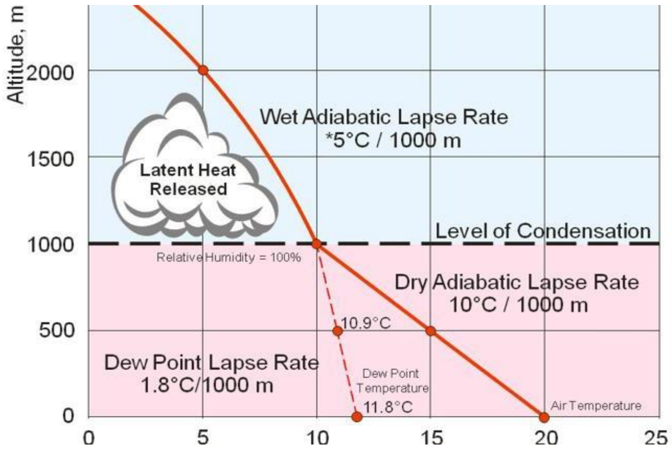


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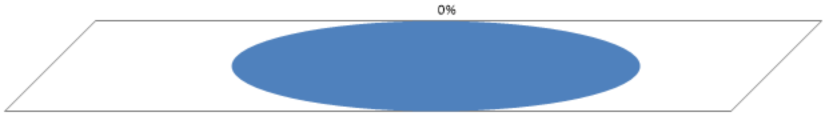

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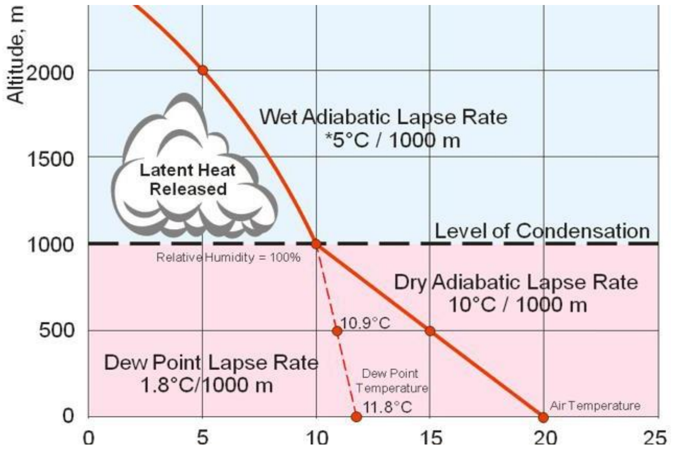


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**Solution**:

- Use WALR and T after condensation. Assume air rises until reaching 0°C: Δz = 12.6 / 5 = **2.5 km**

z = 2.5 + 1 = **3.5 km**

# What summer temperature at Halley VI in 2100 ?

British research station constructed on the Brunt ice shelf

- Mean summer temperature in 2025: -6.6°C
- Under extreme IPCC scenarios, expected warming of 1°C per decade.
- **What would be the mean summer temperature in 2100 at Halley VI ?**

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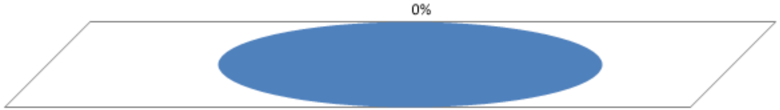
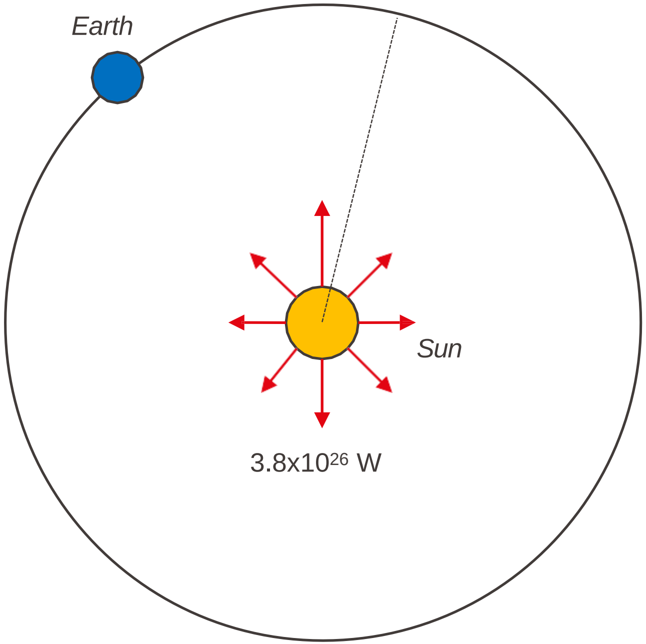


# Today's goals

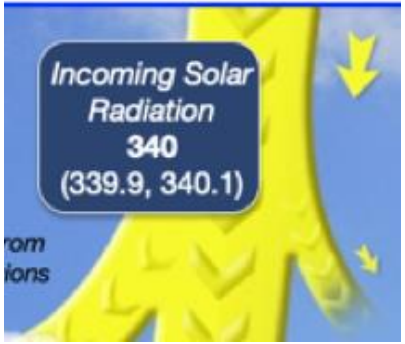
- Some important notions:
  - Lapse rate
  - Latent heat
- Radiative balance
- A joint debunking of climate-skeptic article

# Solar constant and radiative balance




- The solar luminosity (irradiance x surface) is $3.8\text{x}10^{26}$ 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, **$r = 150\text{x}10^6$ km**
- So the energy received by each $m^2$ on Earth is: $3.8\text{x}10^{26} / 4\pi r^2$

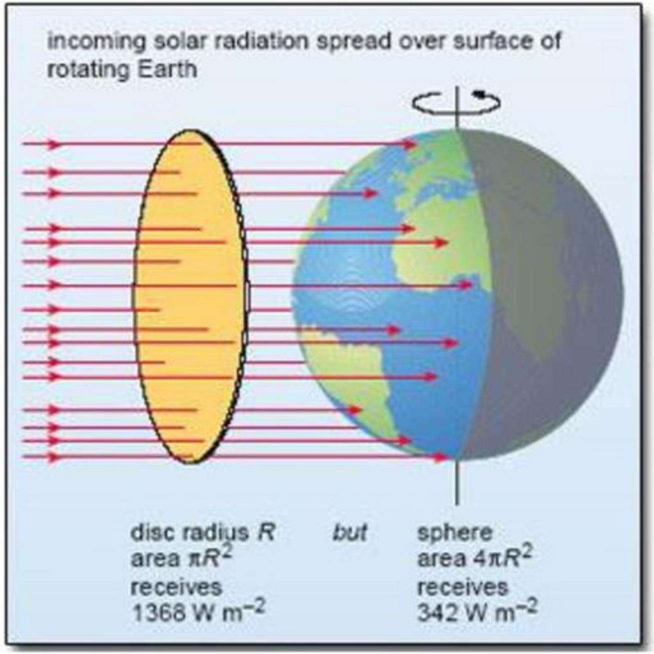
$$= 1370\ W\ m^{-2}$$ **Solar constant**



# Why incoming solar radiation ≠ 1370 W.m$^{-2}$ ?

# Solar constant and incoming solar radiation

Total Energy output of Sun $3.8\times10^{26}$ Watts




Earth receives 1370 W m$^{-2}$
$S_0$ Solar constant

- Why 340 W.m$^{-2}$ at the top of the atmosphere ?
- Ratio of 4 between the exposed area of a disc and of a rotating sphere

# Exercise: what would be the Earth surface temperature without the atmosphere ?

- **In Groups for 5 minutes:**
- Assume radiative equilibrium, i.e. the Earth does not gain nor lose energy
- Remember Stefan-Boltzmann law
- Assume that the albedo of the Earth is: $\alpha = 0.3$

- Solar constant: $F_s = 1370\ W\ m^{-2}$
- Boltzmann constant: $\sigma = 5.67*10^{-8}\ W/(m^2K^4)$

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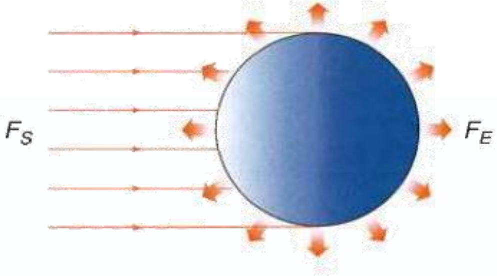
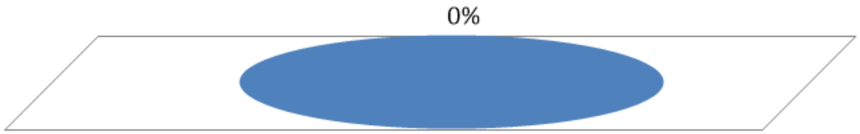






# Exercise: what would be the Earth surface temperature without the atmosphere ?

Solution:

At equilibrium, blackbody emission of Earth (Stefan- Boltzmann law) is equal to absorbed solar radiation by Earth (taking into account the Earth albedo) .

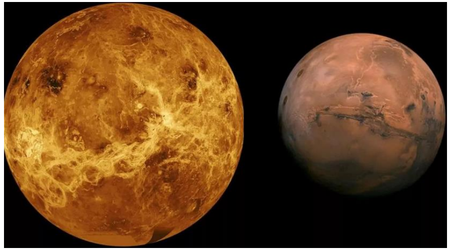
$$F_E = \sigma T_E^4 = \frac{(1-A)F_S}{4} = \frac{(1-0.3)1370}{4} \approx 240\ W\ m^{-2}$$

$$T_E = \sqrt[4]{\frac{F_E}{\sigma}} = \left(\frac{240}{5.67\ x\ 10^{-8}}\right)^{1/4} = 255\ K\ (-18\,°C)$$

- The average temperature before human perturbation was: $T_s = +14\,°C$
- Natural **greenhouse effect**: $T_s$ - $T_E = 32\ K$
-

# Exercise: same question for Mars and Venus

- **In Groups for 5 minutes:**
- Assume radiative equilibrium, i.e. Mars and Venus do not gain nor lose energy
- Remember Stefan-Boltzmann law
- Assume that the albedo of:
  - Venus is: $\alpha = 0.75$
  - Mars is: $\alpha = 0.25$



*Photos: NASA/JPL-Caltech/ESA*

- Solar luminosity: $S = 3.8*10^{26}\,W$
- Boltzmann constant: $\sigma = 5.67*10^{-8}\,W/(m^2K^4)$
- Distance Sun-Venus: $108*10^6$ km
- Distance Sun-Mars: $228*10^6$ km

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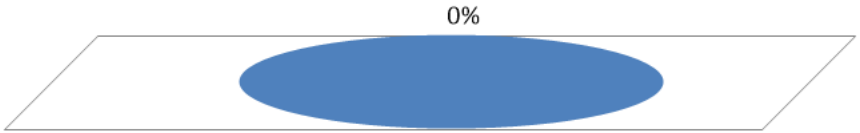
Answer first for Venus (in K)

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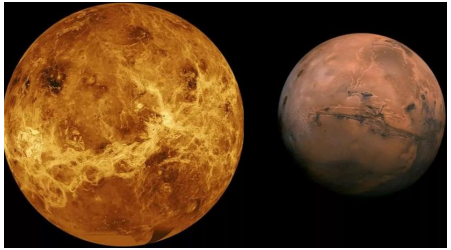

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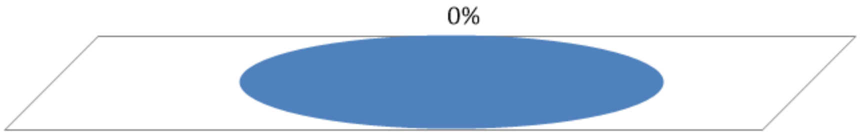


Answer then for Mars (in K)

:300

# Exercise: same question for Mars and Venus

Venus

$$S_V = \frac{3.8x1026}{4\pi(108.10^9)^2}$$

$$S_V = 2592\ W/m^2$$

$$F_V = \sigma T_V^4 = \frac{(1-A)F_S}{4} = \frac{(1\text{-}0.75)\ 2592}{4} \approx 162\ W\ m^{-2}$$

$$T_V = \sqrt[4]{\frac{F_V}{\sigma}} = \left(\frac{162}{5.67\ x\ 10^{-8}}\right)^{1/4} = 231\ K\ (-42\,°C)$$

Mars

$$S_M = \frac{3.8x1026}{4\pi(228.10^9)^2}$$

$$S_M = 582\ W/m^2$$

$$F_M = \sigma T_M^4 = \frac{(1-A)F_S}{4} = \frac{(1\text{-}0.25)\ 582}{4} \approx 109\ W\ m^{-2}$$

$$T_M = \sqrt[4]{\frac{F_M}{\sigma}} = \left(\frac{109}{5.67\ x\ 10^{-8}}\right)^{1/4} = 209\ K\ (-64\,°C)$$

- No big difference…
- Dominant effect of albedo : if α of Venus taken at 0.15 (≈Moon), $T_V$ would be 314 K (41°C)

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# Exercise: same question for Mars and Venus



- In reality:
  - $S_V$ = 462°C !
  - $S_M$ = - 55°C
- Why ?

| Constituent | Venus (% by volume) | Mars (% by volume) |
|---|---|---|
| Carbon Dioxide ($CO_2$) | ~96.5% | ~95.0% |
| Nitrogen ($N_2$) | ~3.5% | ~2.7% |
| Argon (Ar) | Trace (<0.01%) | ~1.6% |
| Oxygen ($O_2$) | Trace (negligible) | Trace (<0.15%) |
| Water Vapor ($H_2O$) | Trace (~0.002%) | Trace (~0.03%) |
| Carbon Monoxide (CO) | Trace (~0.0017%) | Trace (~0.07%) |
| Neon (Ne) | Trace (<0.001%) | Trace (<0.001%) |
| Sulfur Dioxide ($SO_2$) | ~150 ppm (~0.015%) | Trace (<1 ppm) |

Comments ?

# Exercise: same question for Mars and Venus

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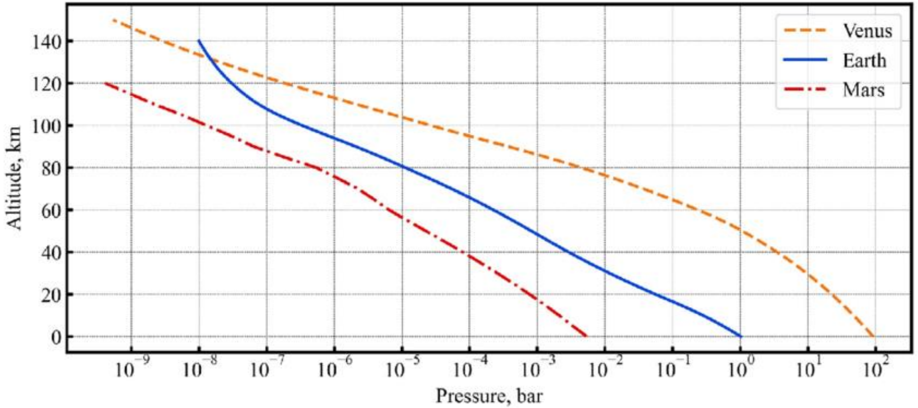
| Neon (Ne) | Trace (<0.001%) | Trace (<0.001%) |
| Sulfur Dioxide ($SO_2$) | ~150 ppm (~0.015%) | Trace (<1 ppm) |

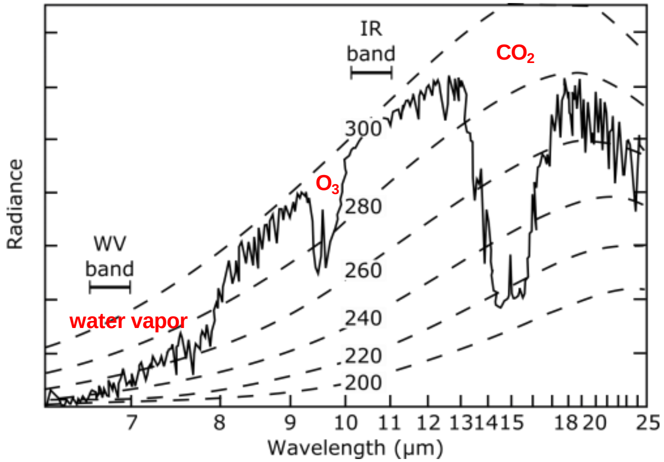
Atmospheric pressure profiles of Venus, Earth and Mars

*Source: Pradeepkumar Girija, Cornell University*

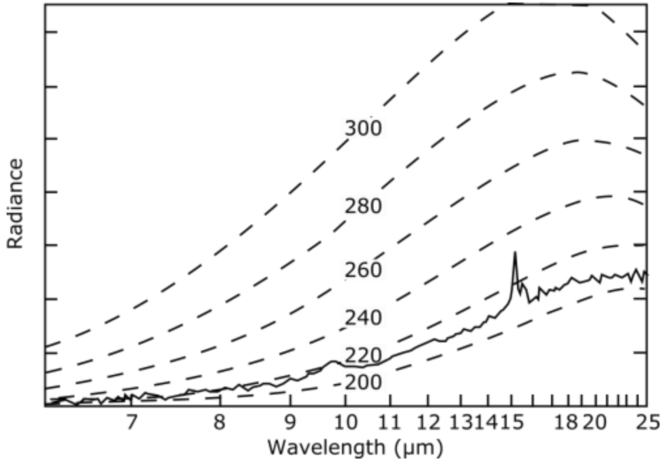



Surface pressure: Venus = 92 bar ; Mars = 6.5 mbar

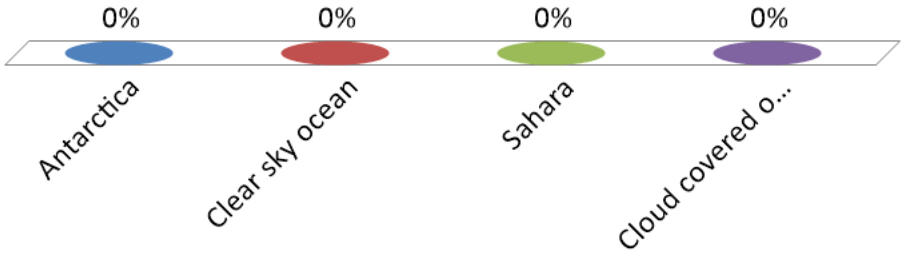
# Spectrum on top of the atmosphere: where ?



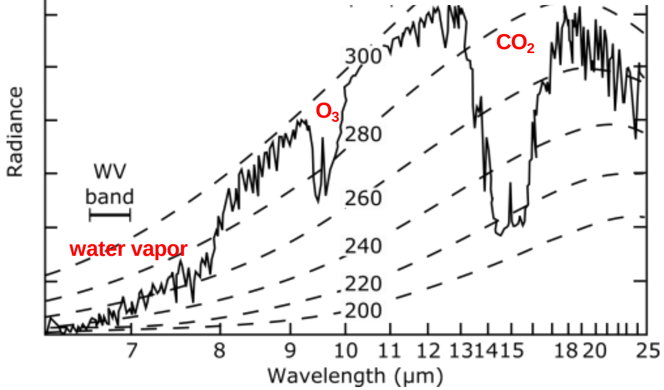

A. Antarctica
B. Clear sky ocean
C. Sahara
D. Cloud covered ocean

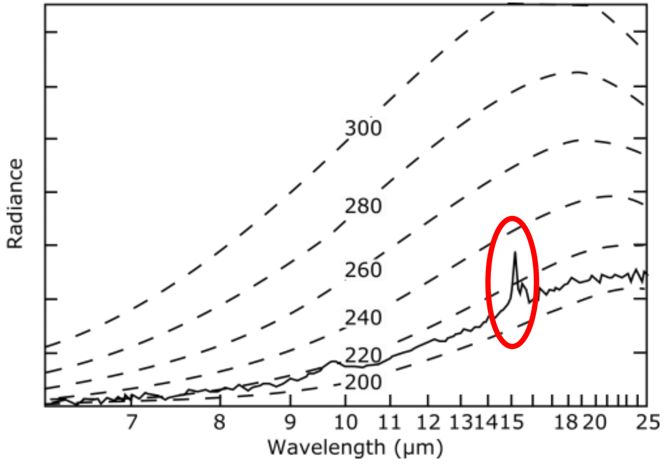



A. Antarctica (cold surface temperature)



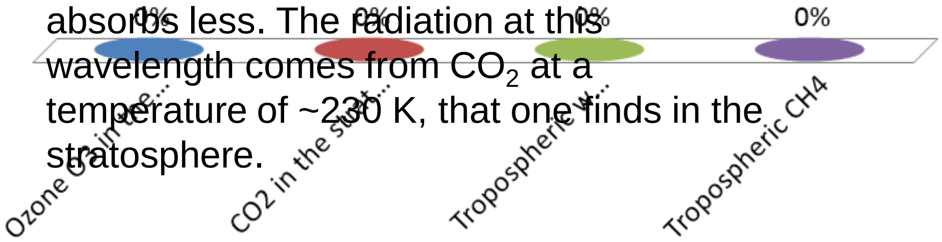
# Spectrum on top of the atmosphere: what is the peak at ~15 μm ?




A. Ozone $O_3$ in the stratosphere
B. $CO_2$ in the stratosphere
C. Tropospheric water vapor
D. Tropospheric $CH_4$

B. $CO_2$ in the stratosphere. It is located in the 15 μm spectral region where CO2 absorbs a lot. The peak is where tropospheric $CO_2$ absorbs less. The radiation at this wavelength comes from $CO_2$ at a temperature of ~230 K, that one finds in the stratosphere.



# Today's goals

- Some important notions:
  - Lapse rate
  - Latent heat
- Radiative balance
- A joint debunking of climate-skeptic article

# Understanding and debunking climate skeptic arguments

- Fred Singer, American physicist, deceased in 2020
- One of the most famous spokespersons among the climate skeptic-osphere.

- Statement in the Financial Times in 2003 : *“There is no convincing evidence that the global climate is actually warming.“*
- Proofs of funding received from ExxonMobil. By Philip Morris as well (campaign negating the risk of seconhand smoke)

- From time to time, we will address one of his statements published in a PBS interview, to challenge how you would answer them based on the course and on your own knowledge.

- Short reading (5 to 10 min), followed by Group discussion (5 min) and writing of bullet point arguments.

# Understanding and debugging climate skeptic arguments

Today, focus on:

- Water vapor
- Climate change
- Aerosols
- Spatial fingerprint of climate change
- Role of the sun

EPFL

# Extracts from F. Singer's interview at PBS, 2007



https://moodle.epfl.ch/pluginfile.php/3419430/mod_resource/content/1/Extract%20from%20Fred%20Singer.pdf

# What counter-arguments ?

Write short statements per category
(like *«clouds are included in models»*)

Categories:

- Water vapor
- Climate change
- Aerosols
- Spatial fingerprint of climate change
- Role of the sun

Other ?

# Water vapor

*you get more evaporation from the ocean. That's inevitable. Everyone agrees with that. Now, what is the effect of this additional water vapor in the atmosphere? Will it enhance the warming, as the models now calculate? Or will it create clouds, which will reflect solar radiation and reduce the warming? Or will it do something else? You see, the clouds are not captured by the models.*

# Water vapor



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No competition between water vapor change and cloud dynamics. It’s two different processes.

Clouds are included in climate models (still, uncertainties on the physics and response).

# Climate change

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# Climate change

*After all, we get climate changes by 100 degrees Fahrenheit in some places on the earth. So what difference does a 1-degree change make over 100 years?*

Usual confusion between weather and climate.

*“Weather is the dog on a leash”*

# Aerosols

*Also biomass burning, burning of forests, produces a lot of smoke and particulates in the atmosphere. Agriculture disturbs the land surface so that winds can then pick up dust. And dust in the atmosphere is another aerosol.*

*All of these particles in the atmosphere have some effect on climate. Some will cause a cooling. Some will cause a warming.*

# Aerosols

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*All of these particles in the atmosphere have some effect on climate. Some will cause a cooling. Some will cause a warming.*

False impression of compensation between warming and cooling effect
The overall cooling effect has been validated by satellite measurements

# Spatial fingerprint of climate change

*Since aerosols are mostly emitted in the northern hemisphere, where industrial activities are rampant, we would expect the northern hemisphere to be warming less quickly than the southern hemisphere. In fact, we would expect the northern hemisphere to be cooling. But the data show the opposite. Both the surface data and the satellite data agree that, in the last 20 years, the northern hemisphere has warmed more quickly than the southern hemisphere. So it contradicts the whole idea that aerosols make an important difference.*

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Northern Hemisphere =

- More lands (less thermal inertia)
- Higher concentration of short-lived greenhouse gases (anthropogenic sources)
- Arctic amplification (white sea ice replaced by black open ocean)
- More reduced ocean heat sink

*His argument would imply that – in the end – aerosols could have a dominant warming effect.*
*And thus that human activities warm the Earth' surface predominantly through aerosol emissions !*

# Role of the sun

*And inevitably during the next 100 years, you're going to have some warming, because the climate is constantly changing. Certainly it will change as the solar radiation becomes stronger or weaker. And we know solar radiation does fluctuate on an 11-year cycle and on longer cycles.*

# Role of the sun

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Solar radiation is measured and can be compared with temperature change.

Too small changes of irradiance on top of the atmosphere: 0.1% of 340 $W.m^{-2}$ = 0.3 $W.m^{-2}$