4. Air humidity

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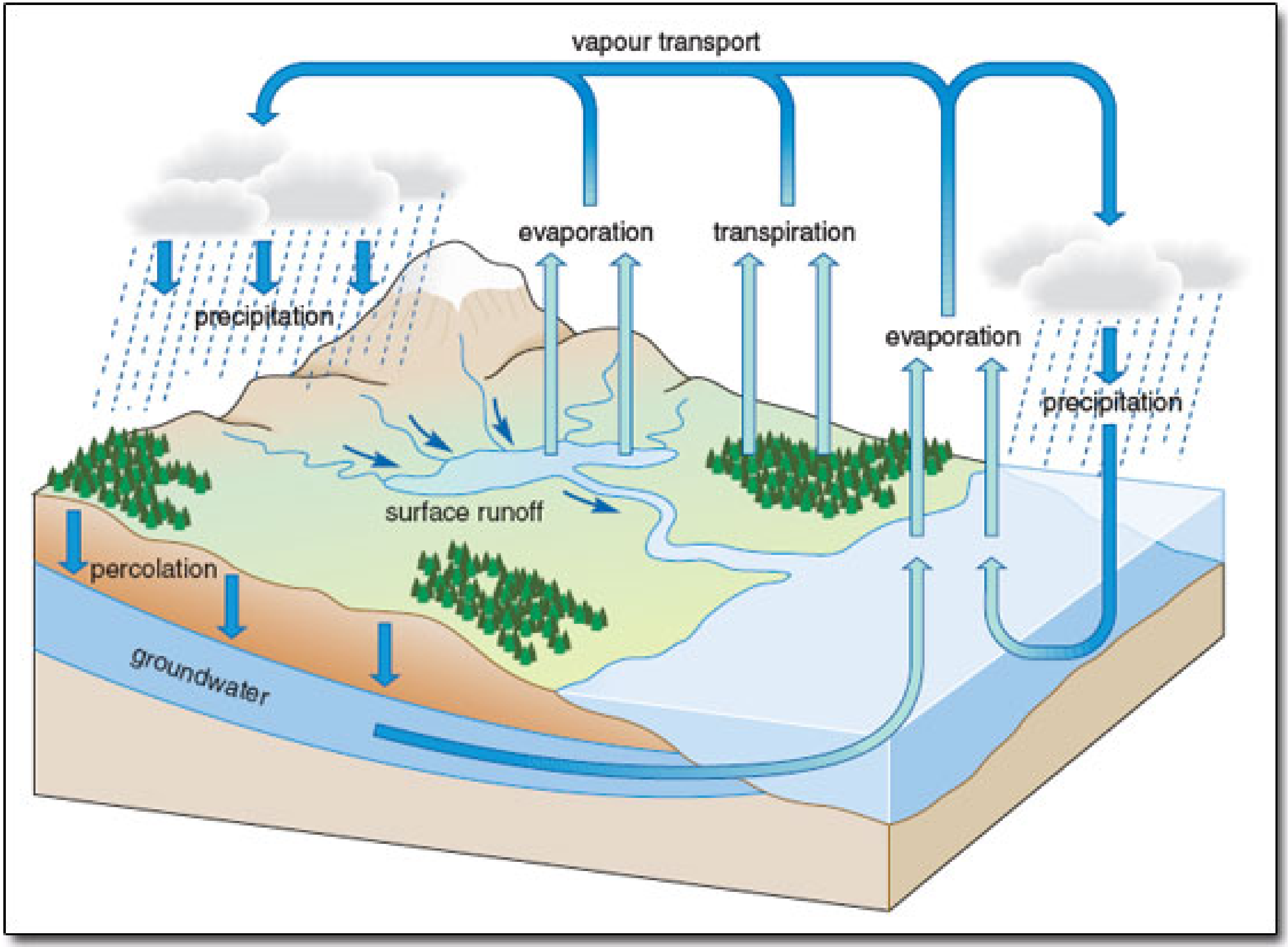
Experimental bioclimatology

What will we learn today?

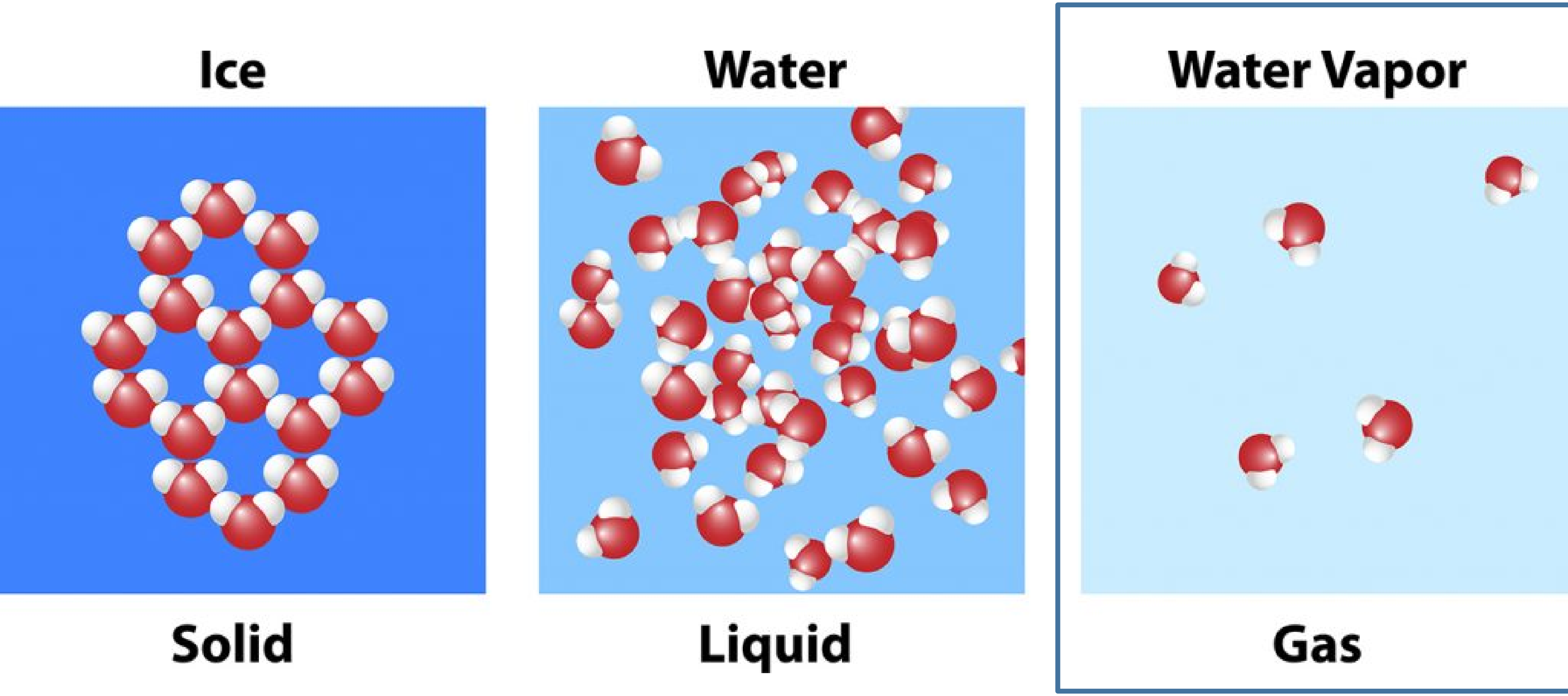
- How is water exchanged between ecosystems and the atmosphere?
- How can air humidity be quantified?
- How is air humidity measured?

Global water cycle



Source: https://demo.schoolweb.ch/pluginfile.php/350/mod_imscp/content/2/Items/x_sdk125_1_1_2.html

Water in three phases



Source: https://casenews.fiu.edu/2020/04/15/fiuhome-discover-why-water-matters/

Importance of water vapour

Clouds

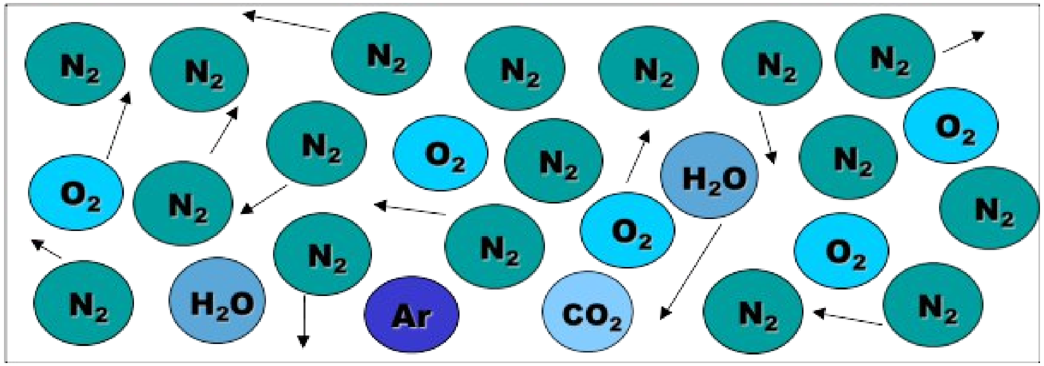
Precipitation

Fog

Dew

Rime/hoarfrost

Dalton's law - partial pressure



p = $\frac{m\,T}{M\,V}\,R$ (1) p_i = $\frac{mi\,T}{Mi\,V}\,R$ (2) => replacing $\frac{T}{V}\,R$ in (1) by (2) yields

$$\frac{pi}{p} = \frac{ni}{n}$$

$p_{air} = p_{N2} + p_{O2} + p_{Ar} + p_{CO2} + p_{H2O} + \ldots$

$p_{air} = \Sigma\, p_i$; i = N_2, O_2, CO_2, H_2O, Ar,...

Assumption: each gas has equal temperature and is equally distributed in a volume (ideal gas), but has different pressure => **partial pressure**

Partial pressure of water vapour

H_2O is assumed to be an **ideal gas** (randomly moving point particles, no interparticle interactions, only elastic collision)

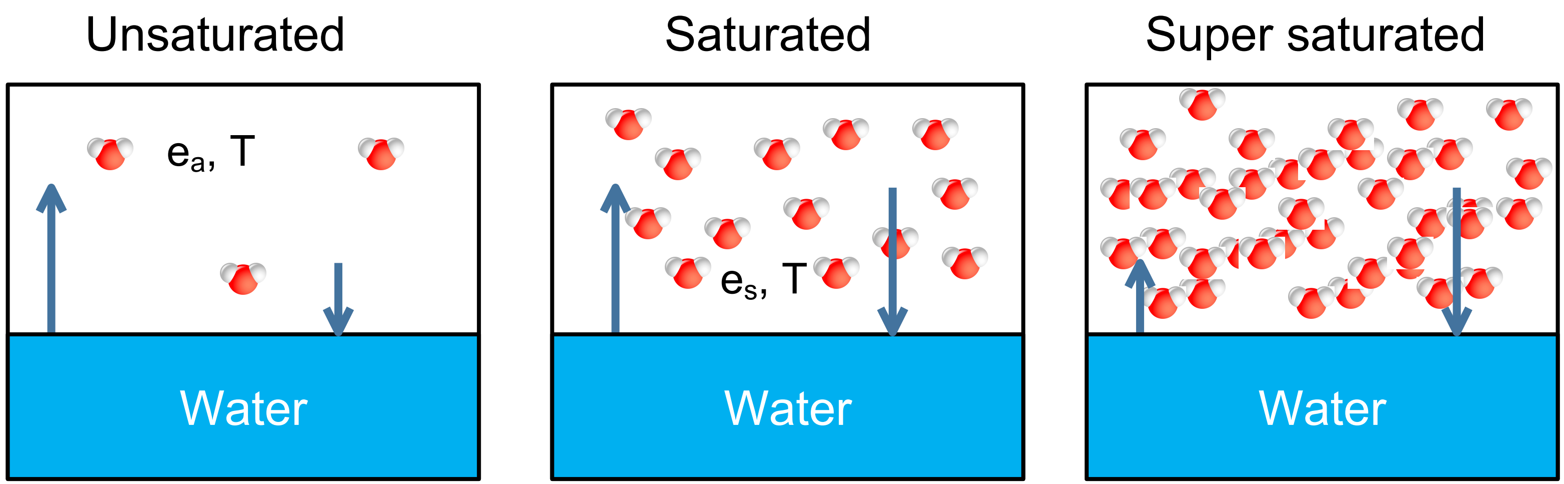
The **partial** or **actual vapour pressure of H_2O** is

$p_{H2O} = e_a = \rho_v R_v T$ [hPa]

ρ_v = density of water vapour [kg m^{-3}]
$R_v = R/M_v = 461.47$ [J K^{-1} kg^{-1}] - gas constant of water vapour
R = 8.314 J K^{-1} mol^{-1} - universal gas constant
$M_v = 18.016\ 10^{-3}$ kg mol^{-1} - molar mass of water vapour

- e_a ranges from 0 to 40 hPa
- the maximum value of e_a is defined as the **saturation vapour pressure**, e_s
- **e_s** is **temperature dependent** and increase with increasing temperature

Saturation

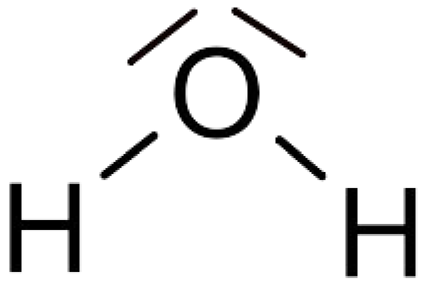


Molecules	Molecules	Molecules
out > in	out = in	out < in
$e_a < e_s$	$e_a = e_s$	$e_a > e_s$

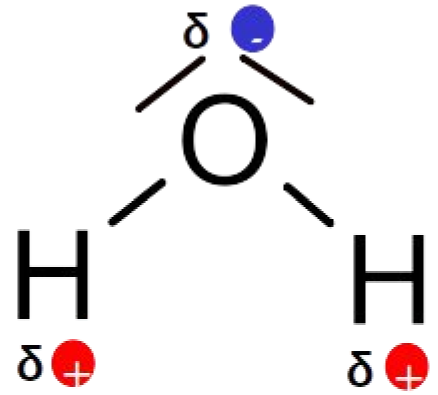
- water molecules exchange due to evaporation (liquid => gaseous) and condensation (gaseous => liquid)

Water molecules

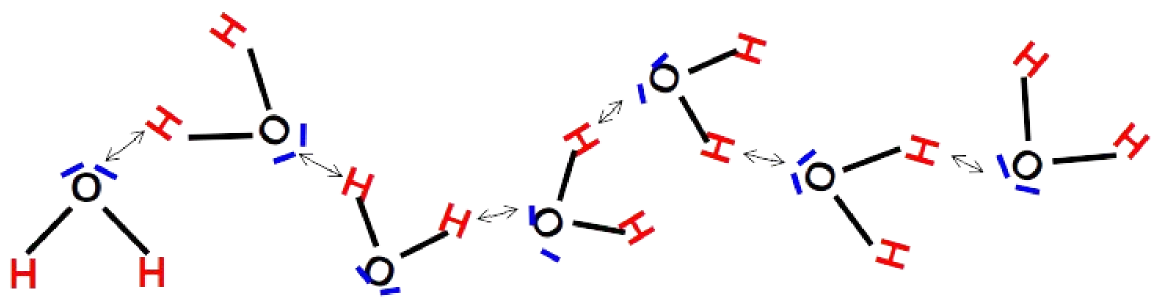
Water = H_2O



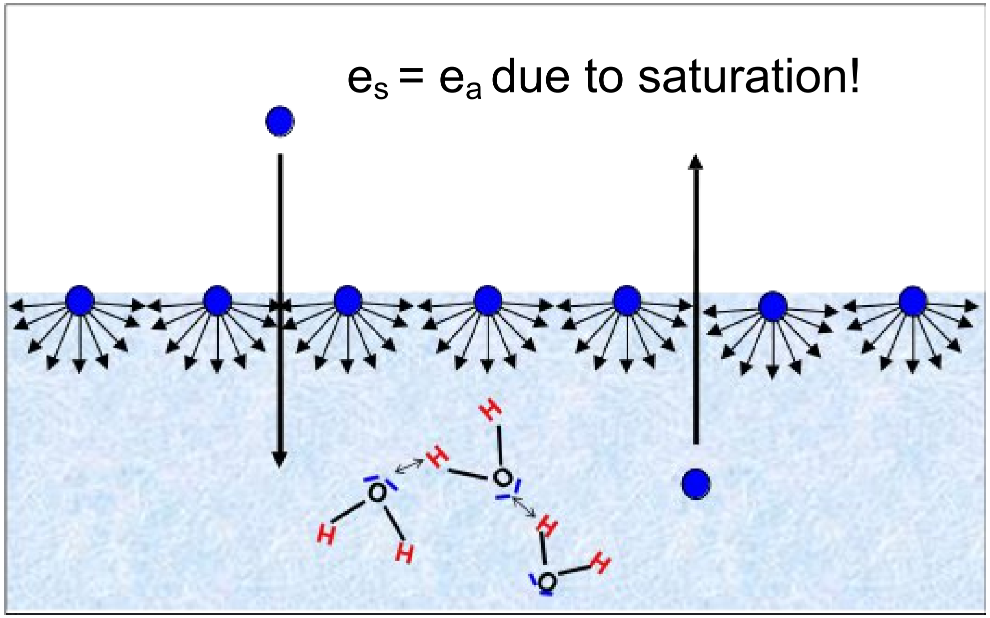
Water is a dipole
with two electron pairs



- In the liquid phase, water molecules attract each other due to hydrogen bonds



Phase change

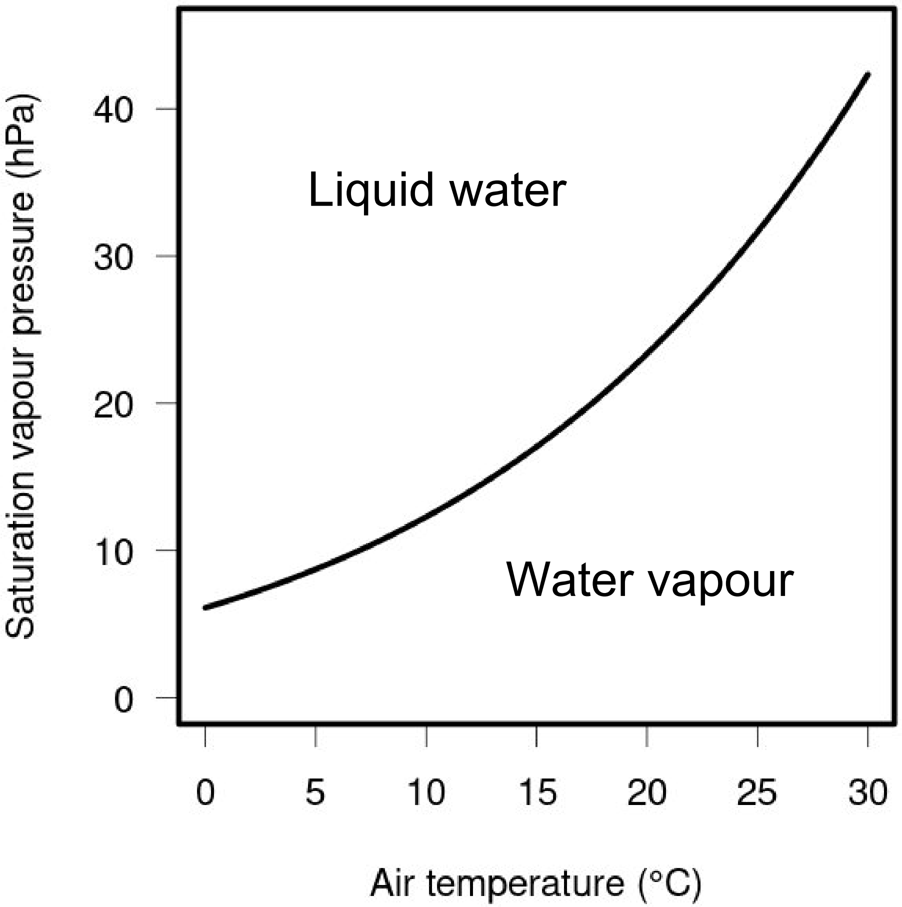


Surface tension

Cohesion force: binding force of molecules of same type

- For a change from liquid to gaseous water molecules need sufficient energy to overcome the cohesion force and surface tension.

Saturation vapour pressure curve



- e_s increase exponentially with temperature
- higher temperature -> faster molecular motion -> faster transition from liquid to gaseous phase
- warmer air has the potential to take up more water vapour

$$e_s = 6.1078 \text{ hPa } e^{\frac{17.08085\, Ta}{234.175°C + Ta}}$$

e_s = saturation vapour pressure [hPa]
T_a = air temperature [°C]

Water vapour measures

Actual vapour pressure, e_a [hPa]

Saturation vapour pressure, e_s [hPa]

Relative humidity, RH [%] = $\frac{e_a}{e_s} \cdot 100 \quad (0...100\ \%)\ 100\% \ \rightarrow$ air is saturated

Vapour pressure deficit, D [hPa] = e_s - e_a

Dewpoint temperature, T_d [°C] = the temperature to which air has to be cooled down to reach saturation ($e_a = e_s$) at a given actual vapour pressure

$$T_d = \frac{(ln(e_a) - ln(6.1078)) \cdot 234.175}{17.08085 - ln(e_a) + ln(6.1078)}$$

How much water vapour is in the air?

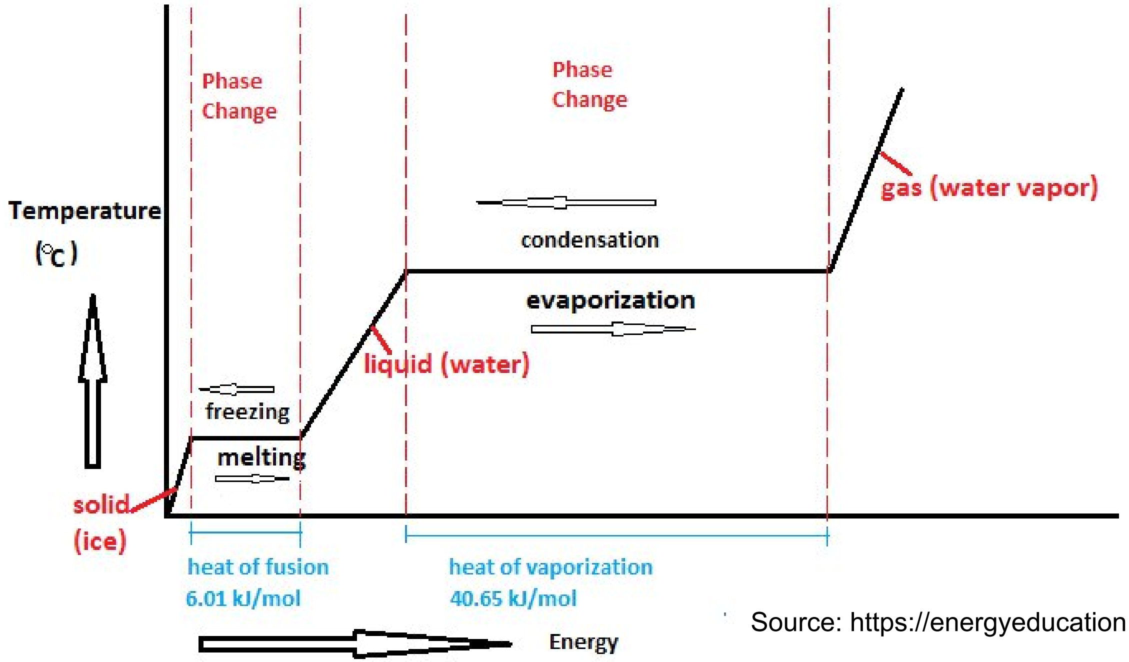
Absolute air humidity $\rho_v = e_a / (R_v \cdot T)$ [kg m^{-3}] is defined as the density of water vapour

Specific humidity $q = \frac{density\ of\ water\ vapour}{density\ of\ moist\ air} = 0.622 \cdot \frac{e_a}{p - 0.378\ e_a}$ [kg kg^{-1}]

Mixing ratio $m = \frac{density\ of\ water\ vapour}{density\ of\ dry\ air} = 0.622 \cdot \frac{e_a}{p - e_a}$ [kg kg^{-1}]

Mole fraction $\frac{number\ of\ water\ molecules\ in\ air}{total\ number\ of\ molecules}$ [mmol mol^{-1}]

Latent heat



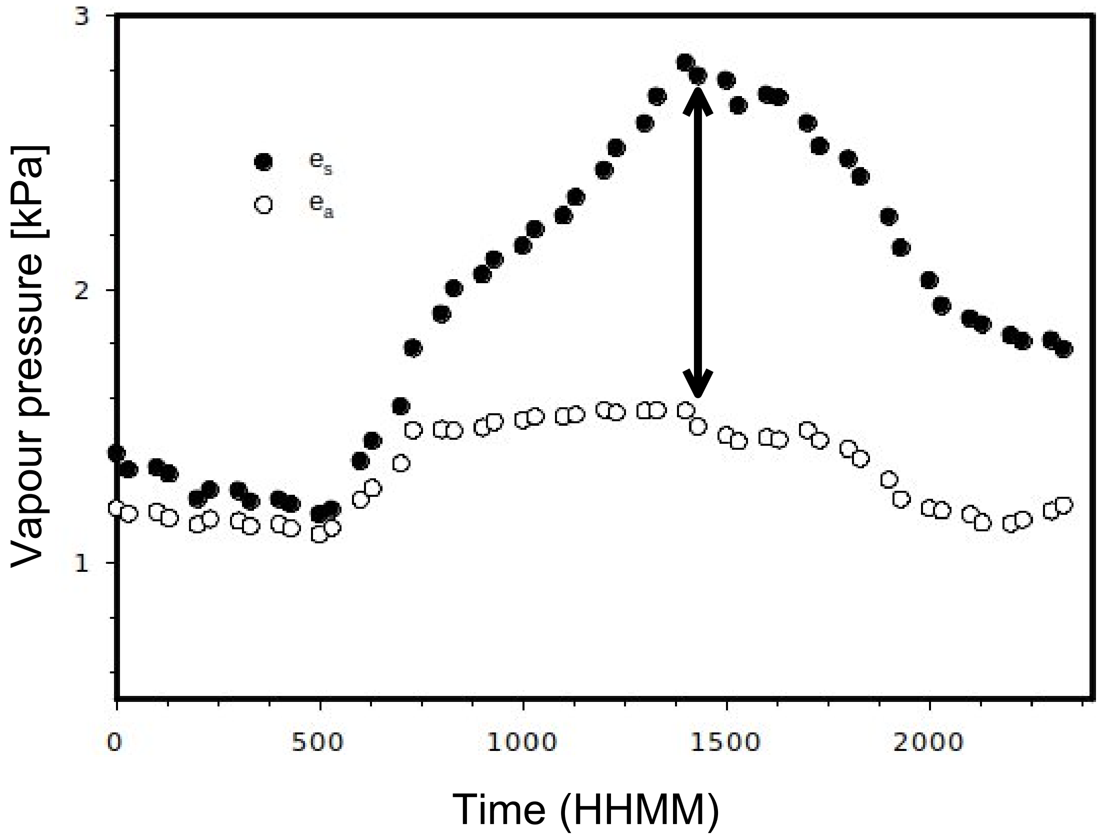
Source: https://energyeducation.ca/encyclopedia/Latent_heat

Equivalent temperature: is the temperature reached, when the whole water vapour in air condenses and the released heat leads to a temperature increase

$T_{eq} = T_a + L_v/C_p \cdot m \approx T_a + 2.5\ K \cdot m$!! m in g kg⁻¹

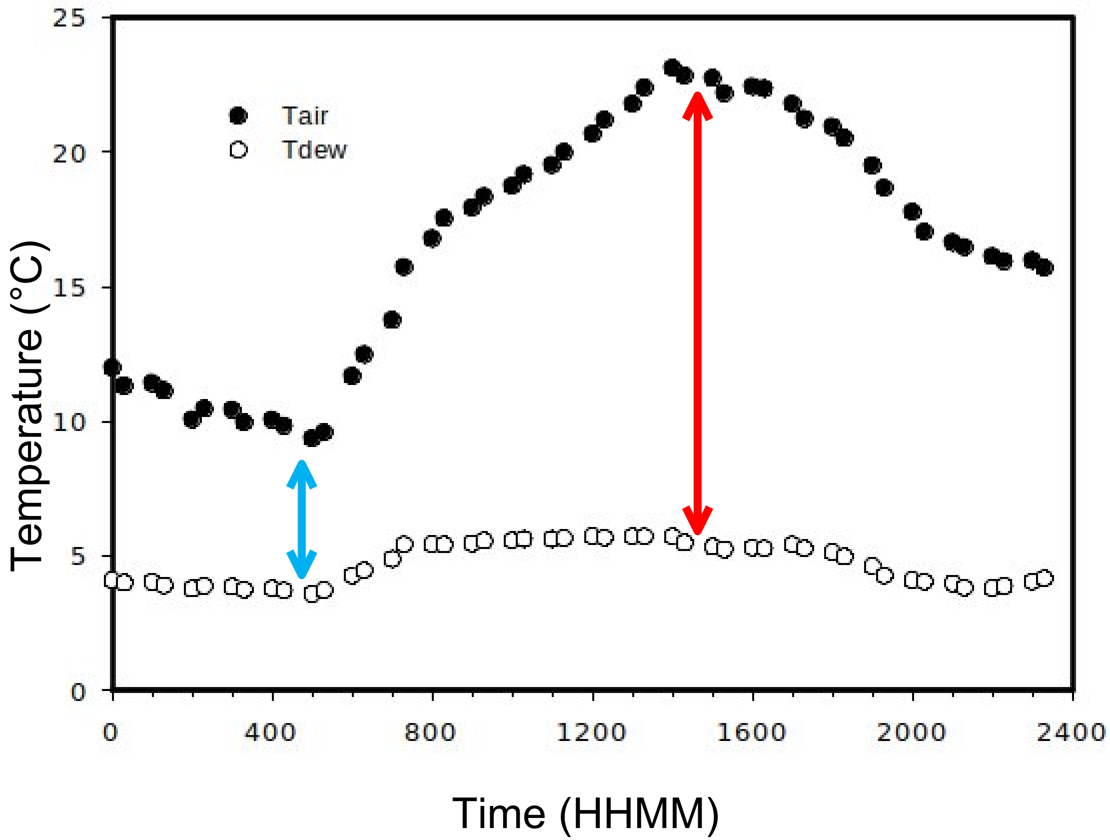
$L_v = 2.5 \cdot 10^6\ J\ kg^{-1}$ latent heat of vaporization
$C_p = 1004.6\ J\ kg^{-1}\ K^{-1}$ specific heat capacity of dry air
m = mixing ratio in g kg^{-1}
T_a = air temperature in K

Diel cycle e_a and e_s



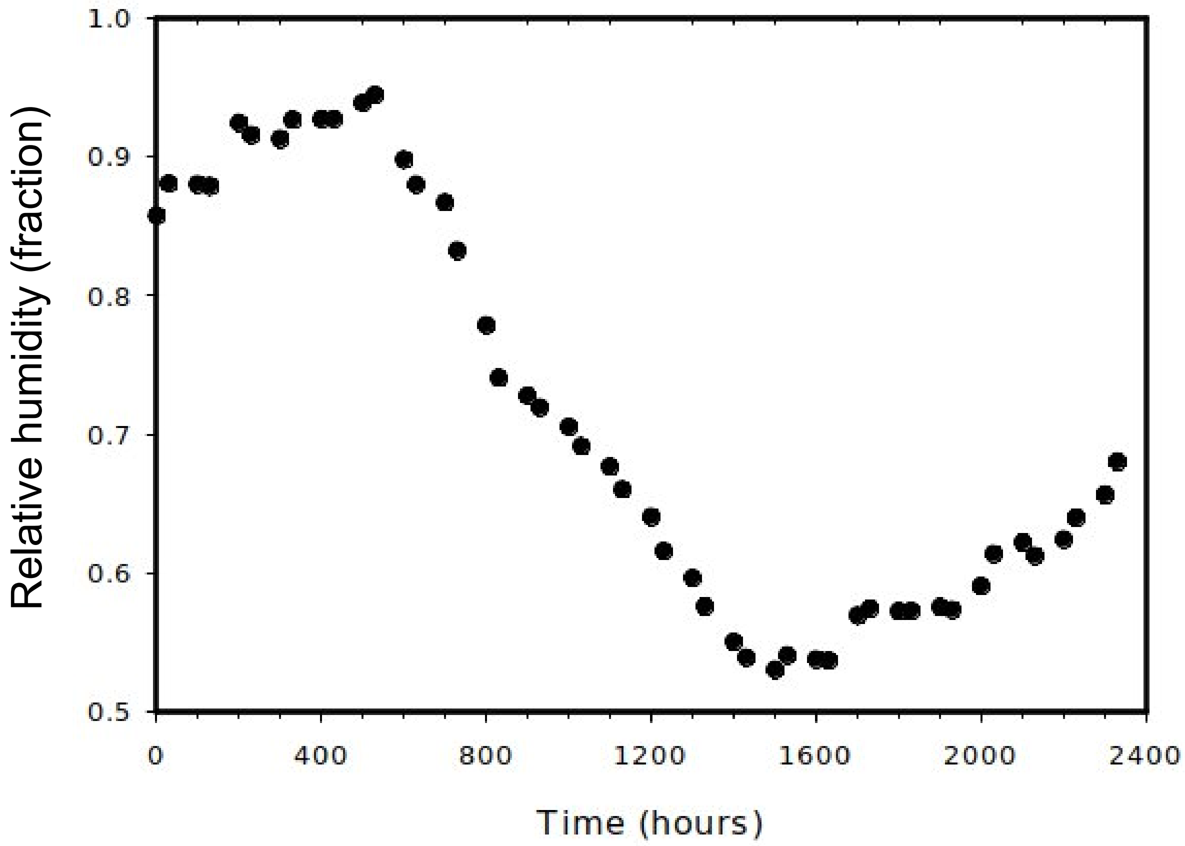
- e_a increase at sunrise due to evapotranspiration and decrease after sunset
- e_s increase at sunrise and decrease after sunset due to air temperature increase and decrease

Diel cycle of air and dew point temperature



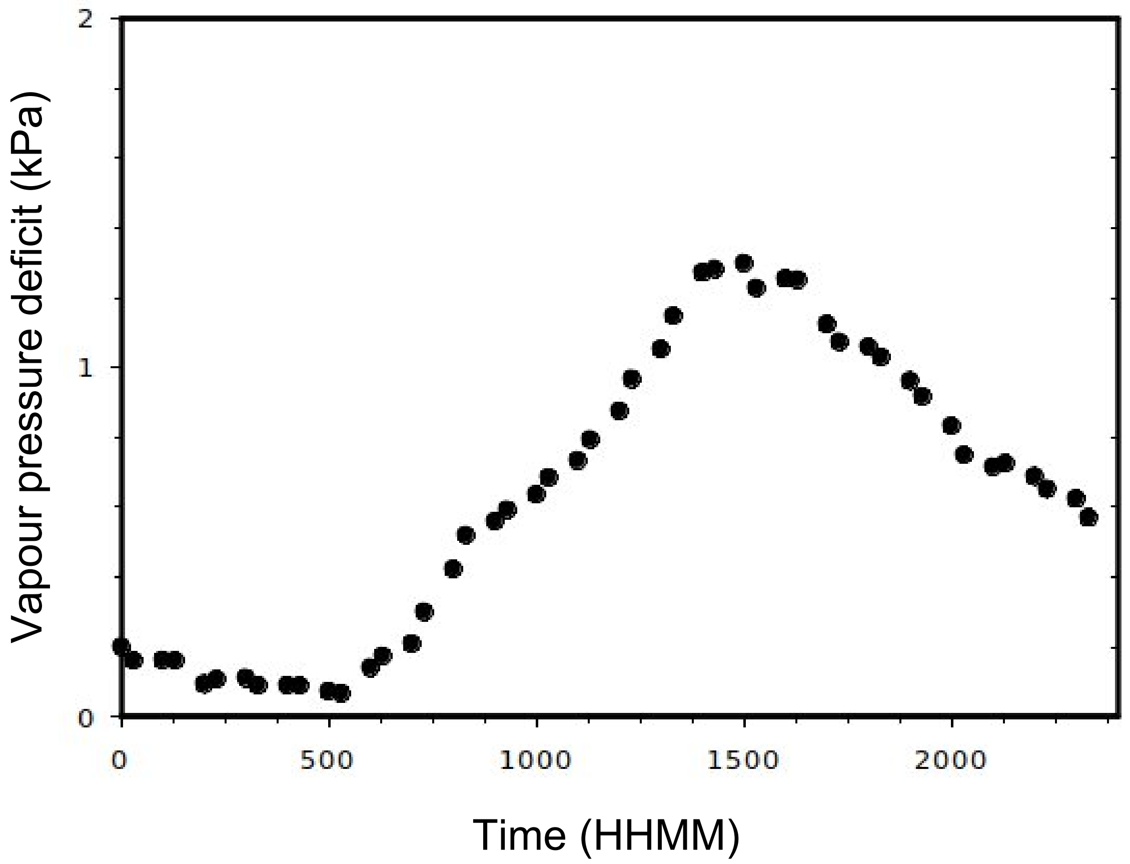
- T_{dew} relatively constant during the day
- difference between T_{dew} and T_{air} smallest during night and largest during day

Diel cycle of relative humidity



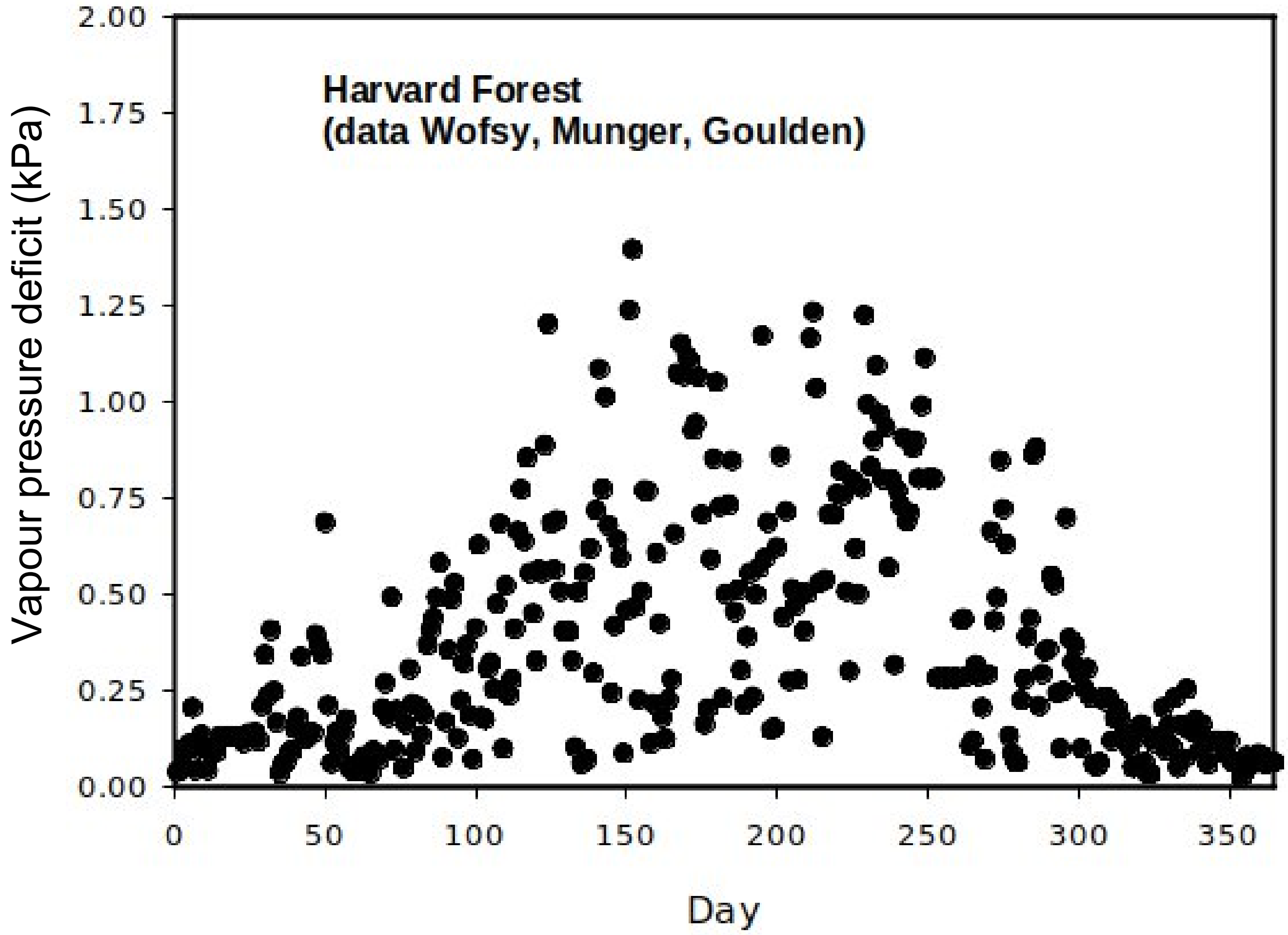
- decrease with sunrise and increase with sunset

Diel cycle of vapour pressure deficit



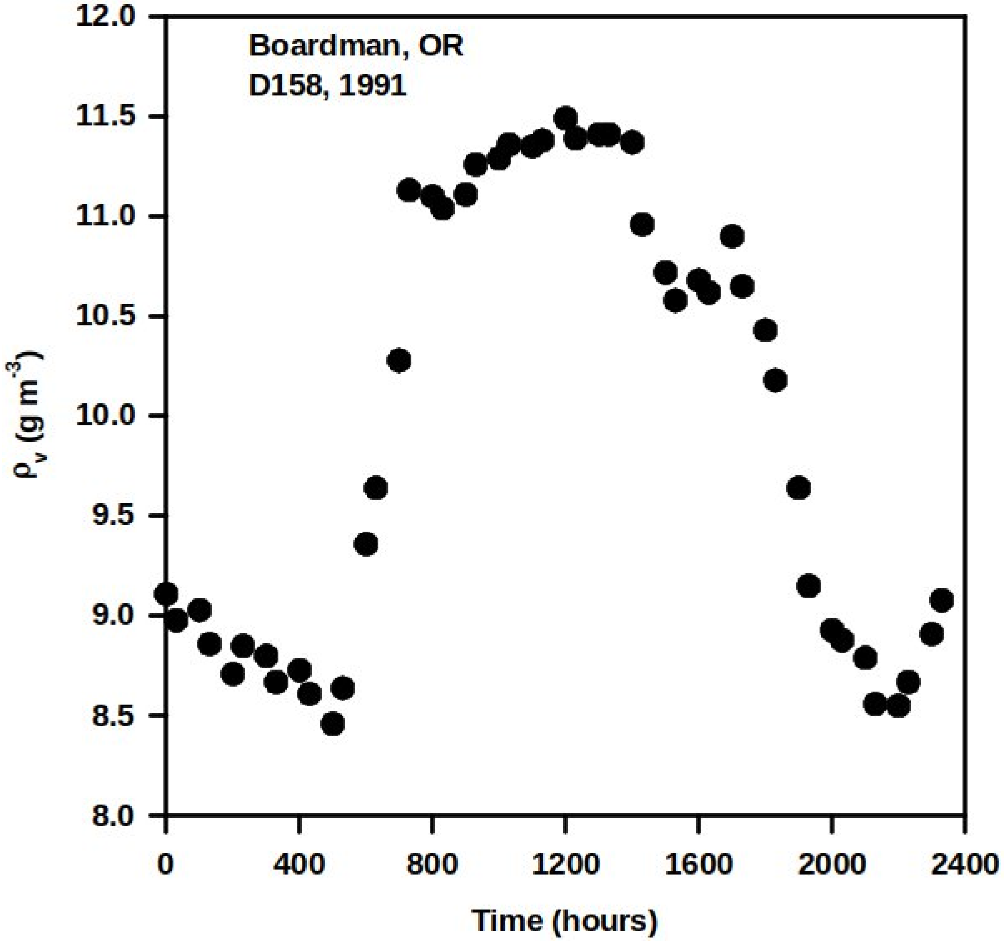
- increase after sunrise and decrease after sunset

Annual cycle of vapour pressure deficit



- varies with season and air temperature dependency of e_s

Diel cycle of absolute humidity



- highest during midday due to highest air temperature

Air humidity instruments

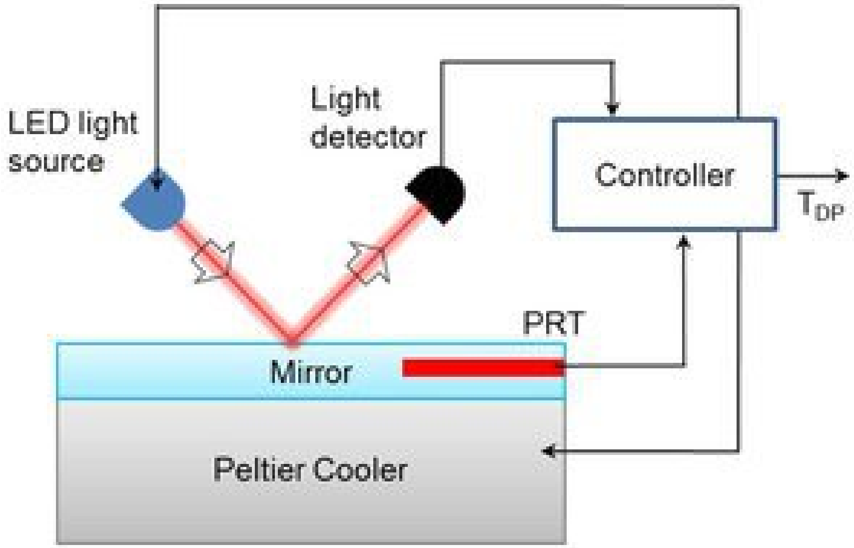
We can use material properties as a proxy for air humidity

1. Condensation
2. Hygroscopic measuring principles
3. Spectroscopic measuring principles
4. Capacitive measuring principle
5. Psychrometric humidity measurements

1. Condensation

Dew point mirror

- used to measure the **dew point temperature**
- a mirror is cooled down until **condensation** takes place
- this temperature represents the dew point temperature
- condensation detected with LED light source mirrored and detected with a light detector
- change in reflectance of the mirror is detected

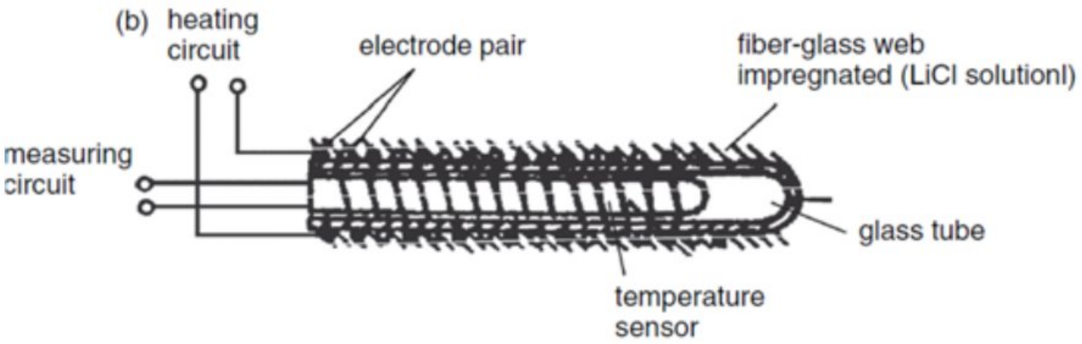


Source: Tao et al. (2016), Scientific reports, DOI: 10.1038/srep29672

1. Condensation

LiCL dew point hygrometer

- used to measure the **dew point temperature**
- LiCL strongly hygroscopic -> e_a over saturated salt solution < e_a over purified water at the same temperature
- e_a over saturated salt solution can be increased to purified water by increase in T -> water evaporates
- a current flows through saturated salt solution and not dry LiCL
- dew point temperature reached when evaporation and condensation are in equilibrium



Source: Yurish et al. (2019), Physical and Chemical Sensors: Design, Applications & Networks, ISBN 978-84-09-14512-6

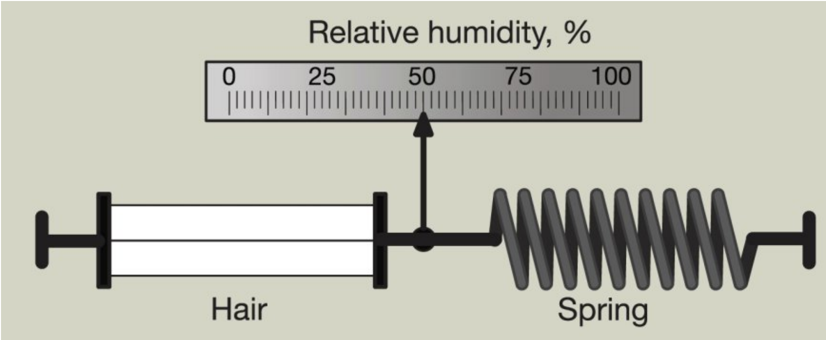
2. Hygroscopic measuring principle

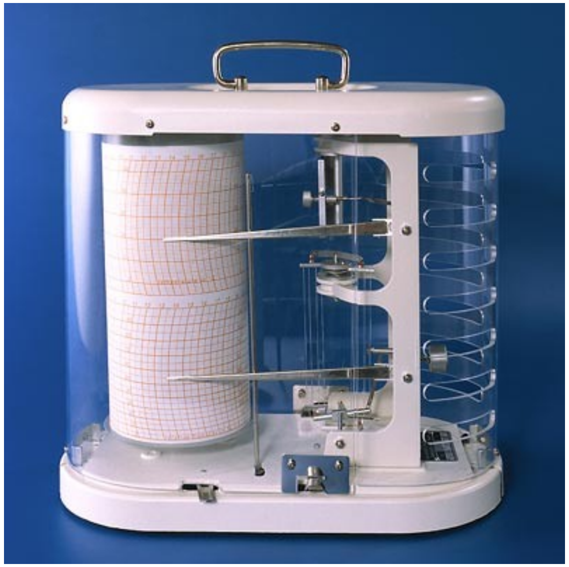
Hair hygrometer

- used to measure **relative humidity**
- human hair extends with increasing air humidity, the vapour pressure decrease
- hair has to be degreased and rolled to enable absorption of water
- many hairs (50) are grouped to increase the extension effect
- hair has to be cleaned often

to reduce side effect of water

absorption of other particles

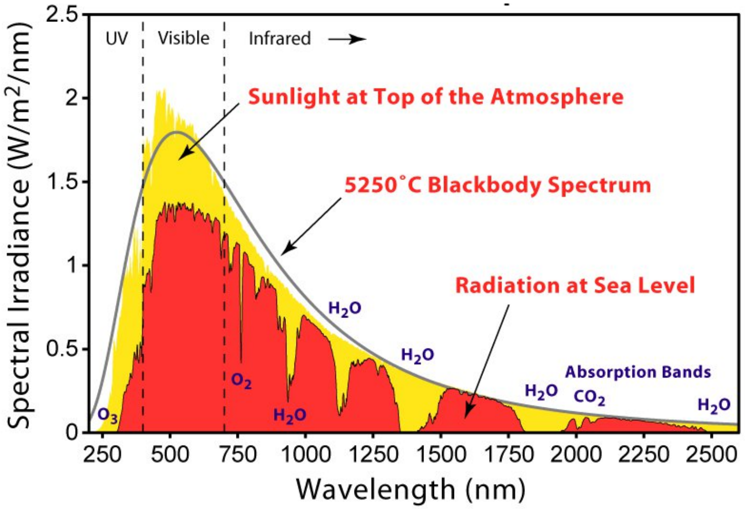


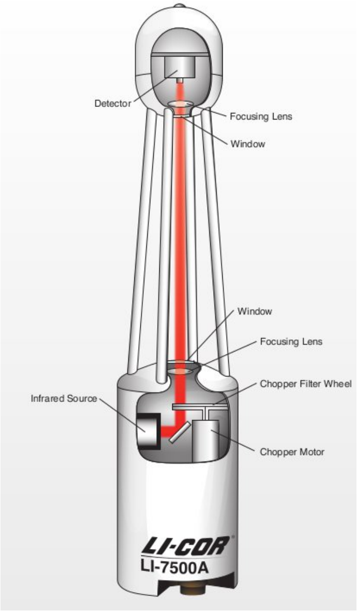


3. Spectroscopic measuring principle

Infrared gas analyser

- gases absorb IR light at certain wavelengths
- a IR gas analyser emits IR light of defined intensity through a air volume
- whilst passing the air volume, IR light is absorbed and the intensity is reduced
- the intensity reduction is proportional to the water vapour content
- instrument used for eddy covariance measurements

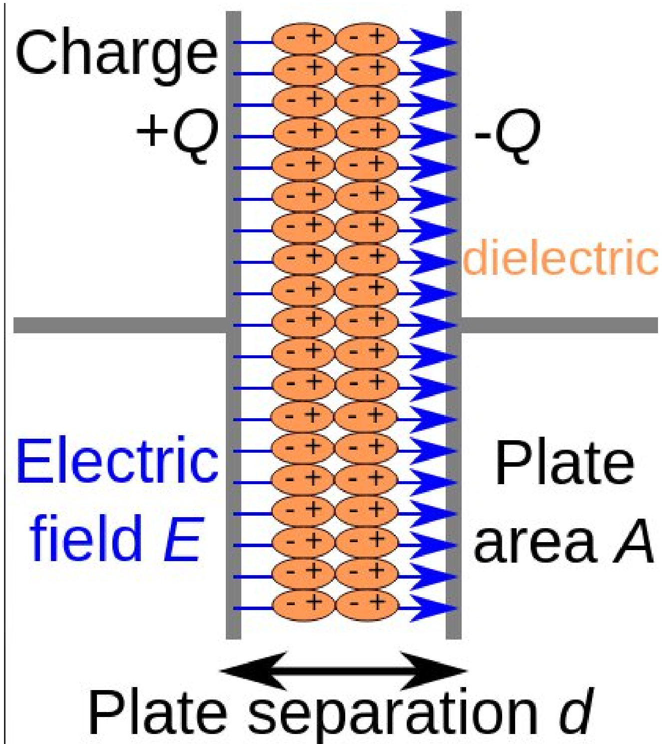


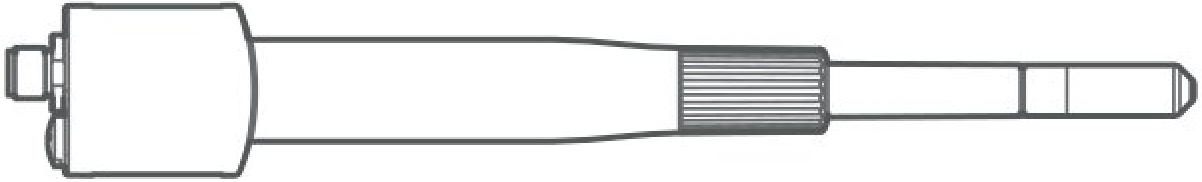


4. Capacitive measuring principle

Capacitive humidity sensor

- **relative humidity** measured
- consist of a capacitor with a hygroscopic polymer (dielectric) in between the capacitor plates
- an increase in air humidity leads to an increase in capacity
- high long-term stability
- fast response time





Source: https://en.wikipedia.org/wiki/Capacitor

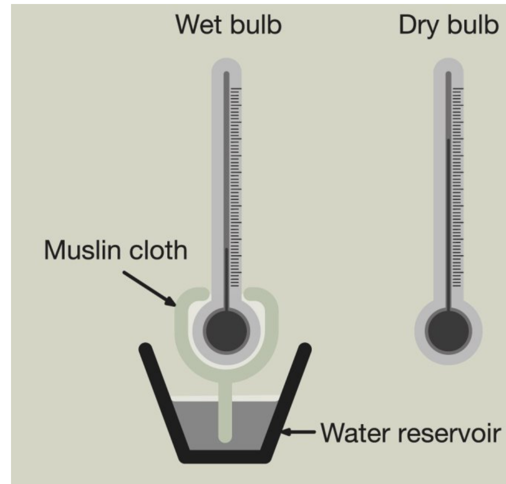
5. Psychrometric humidity measurements

- one wet and one dry bulb thermometer (mercury)
- during evaporation energy required -> evaporative cooling
- at RH = 100% -> $e_a = e_s$ and $T_{dry} = T_{wet}$
- at RH < 100% -> $e_a < e_s$ and $T_{dry} > T_{wet}$
- from the temperature difference between T_{dry} and T_{wet} we derive actual vapour pressure of dry air using the Psychrometer formula

$$e_{a,dry} = e_{s,wet} - A\,(T_{dry} - T_{wet})$$

$$A = \frac{p\, c_p}{0.622\, L} \approx 0.666$$

- psychrometer charts are available



Source: https://community.weatherflow.com/t/assmann-psychrometer/1541

This week's excercises

Calculate and visualize
1. actual vapor pressure,
2. saturation vapor pressure,
3. dewpoint temperature,
4. absolute humidity,
5. specific humidity,
6. mixing ratio,
7. vapor pressure deficit, and
8. equivalent temperature.

-> How and when do actual and saturation vapour pressure differ?
-> Compare air and dew point temperature, how do they differ and how are they related to relative humidity?
-> When is absolute humidity largest and why?
-> Compare mixing ratio and specific humidity, how and why do they differ?
-> When is the vapour pressure deficit and equivalent temperature largest?


Questions?