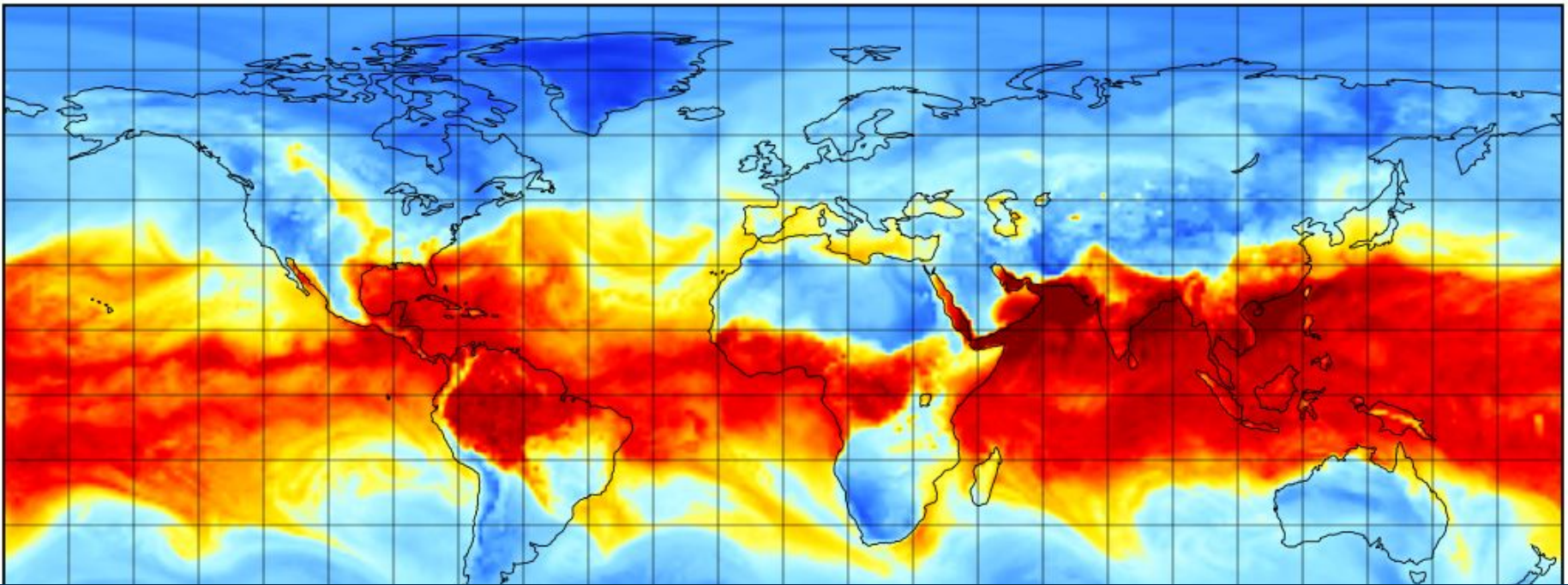




WATER IN THE ATMOSPHERE AND THE ROLE FOR CLIMATE

Part 1: Introduction into units and definitions

WS 25/26 | CHRISTIAN ROLF

ABOUT ME

Dr. Christian Rolf

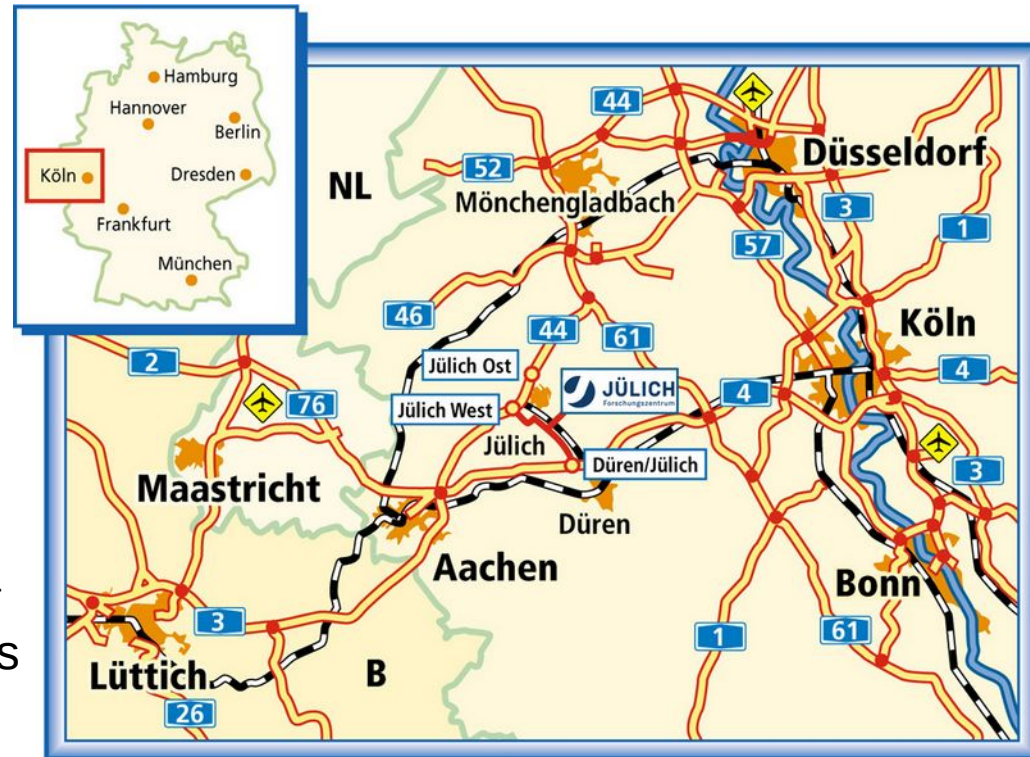
Physicist

Scientific interest

- Measurements of water vapour and cirrus clouds
- Air mass transport in the UTLS area
- Formation processes of cirrus clouds

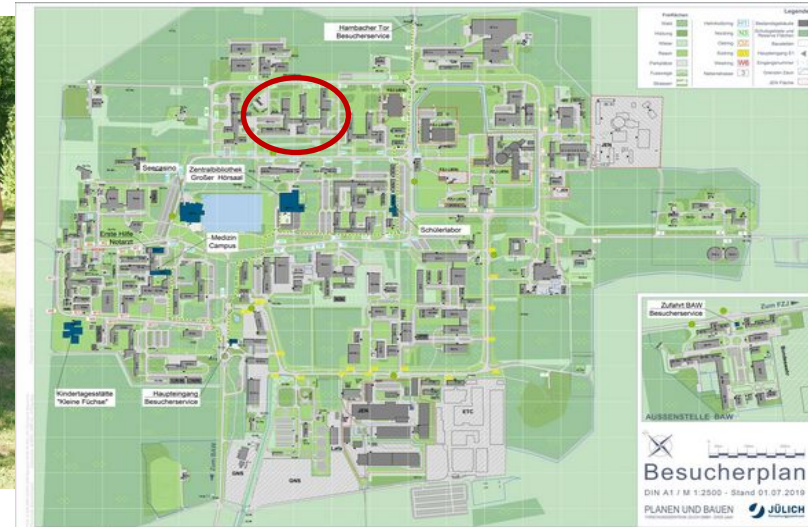
Contact

- Forschungszentrum Jülich GmbH, Institute of Climate and Energy Systems – Stratosphere (ICE-4), Wilhelm-Johnen-Straße, 52425 Jülich
- Phone: +49 2461 61-6933
- Email: c.rolf@fz-juelich.de
- Web: https://www.fz-juelich.de/profile/rolf_c



INSTITUTE OF CLIMATE AND ENERGY SYSTEMS (ICE-4) STRATOSPHERE

Investigating Atmospheric processes in the Stratosphere



ICE-4: ~ 60 Employees

Departments (5):

Atmospheric Modeling, Analysis of Climate Data records, Remote Sensing, Two In-situ Measurement groups (Water vapor/clouds and Ultra trace species)

MATERIAL / VORLESUNG

- **Skript** (Foliensammlung) 08.110.8010 Stratosphäre: Wasser in der Atmosphäre und die Bedeutung für das Klima:
<https://jogustine.uni-mainz.de>
als PDF Datei pro Kapitel.

(Lücken/Freiräume im Skript werden
durch Rechnungen in der Vorlesung ergänzt.)

- **Vorlesung:** Freitags vom 10:15-11:45 Uhr in Raum 05 121
und 14:15-15:45 Uhr in Raum 07 114 (Dachlabor)

Fr, 07. Nov. 2025

Fr, 14. Nov. 2025

Fr, 21. Nov. 2025 (online !)

Fr, 28. Nov. 2025

Fr, 05. Nov. 2025

Fr, 12. Dez. 2025

Fr, 19. Dez. 2025

Mögliche Exkursion nach Jülich ?

Dringende Bitte:

Bitte sagt rechtzeitig Bescheid, wenn
einer verhindert ist (dann würde ich die
Vorlesung online halten)

PROOF OF SUCCESSFUL PARTICIPATION

Successful completion of the lecture: Active participation

Starting with the second lecture, there will be a short test (max. 10 questions) at the beginning covering the content of the previous lecture.

At least 50% of all questions must be answered.

WATER IN THE ATMOSPHERE AND THE ROLE FOR CLIMATE

Water vapor plays a crucial role in our daily life due to cloud formation and weather. It is one of the strongest greenhouse gases in the atmosphere. Therefore its processes are relevant on short and long term.

Aim of the lecture:

The lecture will give a comprehensive overview of the role of water in the atmosphere for weather and climate. Beside basic principles and processes of the water cycle and their climate interactions, water vapor measurement techniques in different altitude ranges will be studied.

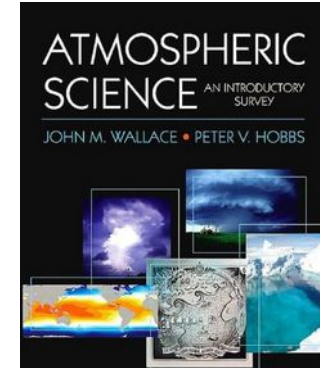
WATER IN THE ATMOSPHERE AND THE ROLE FOR CLIMATE

Topics:

1. Introduction into units and definitions
2. Water vapor distribution in the atmosphere
3. Cloud formation (water and ice clouds)
4. Water cycle
6. Water and climate feedback
7. Measurement of water in the atmosphere

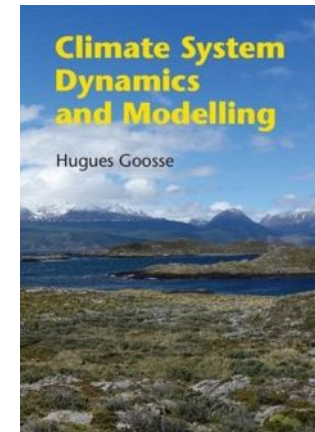
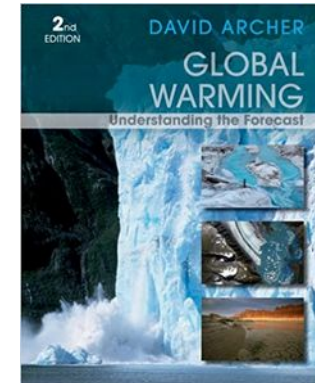
BOOKS

- 1) Atmospheric Science (2nd Edition)
An Introductory Survey
John Wallace & Peter Hobbs
2006, Academic Press
Hardcover ISBN: 9780127329512
- 2) Global Warming
By L. D. Danny Harvey
2000, Routledge,
ISBN 9780582381674



BOOKS

- 3) Global Warming:
Understanding the Forecast
By David Archer
2011, Wiley; 2. Edition
ISBN 978-0470943410
- 4) Climate System Dynamics and Modelling
by Hugues Goosse
2015, Cambridge University Press
ISBN 978-1-316-02869-8



TOPICS

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2. Water vapor distribution in the atmosphere
3. Cloud formation (water and ice clouds)
4. Water cycle
5. Water and climate feedback
6. Measurement of water in the atmosphere

SUBTOPICS (UNITS & DEFINITIONS)

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- **General things about water / Motivation**
- Phase diagram of water and phase changes
- Latent heat
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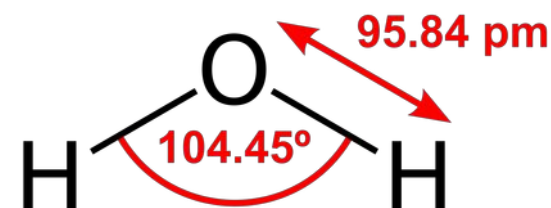
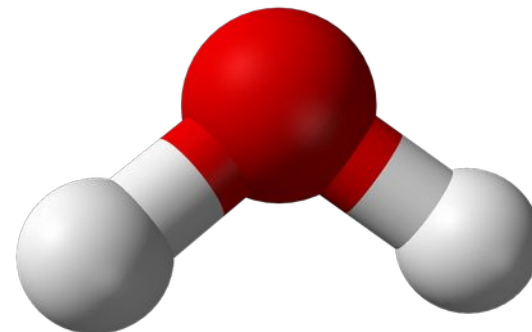
WATER

Liquid state: Water
Solid state: Ice
Gas state: Vapor
Molecular formula: H_2O

Molar mass: 18.01528 g/mol
Melting point: 0.00 °C (273.15 K)
Boiling point (1013hPa): 99.98 °C (373.13 K)

Density Liquid: 0.9998396 g/mL at 0 °C
0.99997 g/mL at 4 °C
0.9970474 g/mL at 25 °C
0.961893 g/mL at 95 °C
Density Solid: 0.9167 g/ml at 0 °C

specific gas constant: 461.5 J/(kg·K)
Heat of vaporization: 2.26 MJ/kg
Heat capacity at 300 K: 1.864 kJ/(kg·K)
Dipole moment: 1.8546 D
(1D = 1×10^{-21} C·m²/s)



WATER ON EARTH



- More than 2/3 of the Earth is covered by water.
 - ***blue planet*** and the ***watery planet***

The blue planet
NASA/MODIS

ORIGIN OF WATER ON EARTH



- There is plenty of water in the universe, produced from combined hydrogen and oxygen and released by supernovae.
- Nebulae clouds contain large amount of water.

Eagle nebulae, NASA, ESA and the
Hubble Heritage Team
(STScI/AURA)

WATER ON EARTH



NASA

- First hypothesis (nebular):
There was water on the Earth during its early stages (formation of zircons 4.3-4.4 By) and oceans were present 150-200 My after the formation of the Earth.
- Second hypothesis (meteorites):
Surface water came with bombing of early Earth by meteorites and comets in the early stages. This also explains the abundance of noble (siderophil) metals in the crust. 0,3% of Earth mass was added this way.

However, up to now not clear where the water exactly originate.

WATER VAPOR (H₂O) IN THE ATMOSPHERE

- Atmospheric humidity = Amount of Water vapor in the air:
- Relative portion by air volume:
0 – 5% → Tropics and Surface
↓
Poles or stratosphere
- Important greenhouse gas:
60% (+ 20 K) from natural
Greenhouse effect
- Hydrological cycle: Oceans, climate zones, vegetation, ...
- "Driver" for many processes in the atmosphere: clouds, precipitation, storms, cyclones, thunderstorms

Table 1.1 Fractional concentrations by volume of the major gaseous constituents of the Earth's atmosphere up to an altitude of 105 km, with respect to dry air

Constituent ^a	Molecular weight	Fractional concentration by volume
Nitrogen (N ₂)	28.013	78.08%
Oxygen (O ₂)	32.000	20.95%
Argon (Ar)	39.95	0.93%
Water vapor (H₂O)	18.02	0–5%
Carbon dioxide (CO₂)	44.01	380 ppm
Neon (Ne)	20.18	18 ppm
Helium (He)	4.00	5 ppm
Methane (CH₄)	16.04	1.75 ppm
Krypton (Kr)	83.80	1 ppm
Hydrogen (H ₂)	2.02	0.5 ppm
Nitrous oxide (N₂O)	56.03	0.3 ppm
Ozone (O₃)	48.00	0–0.1 ppm

^a So called *greenhouse gases* are indicated by bold-faced type. For more detailed information on minor constituents, see Table 5.1.

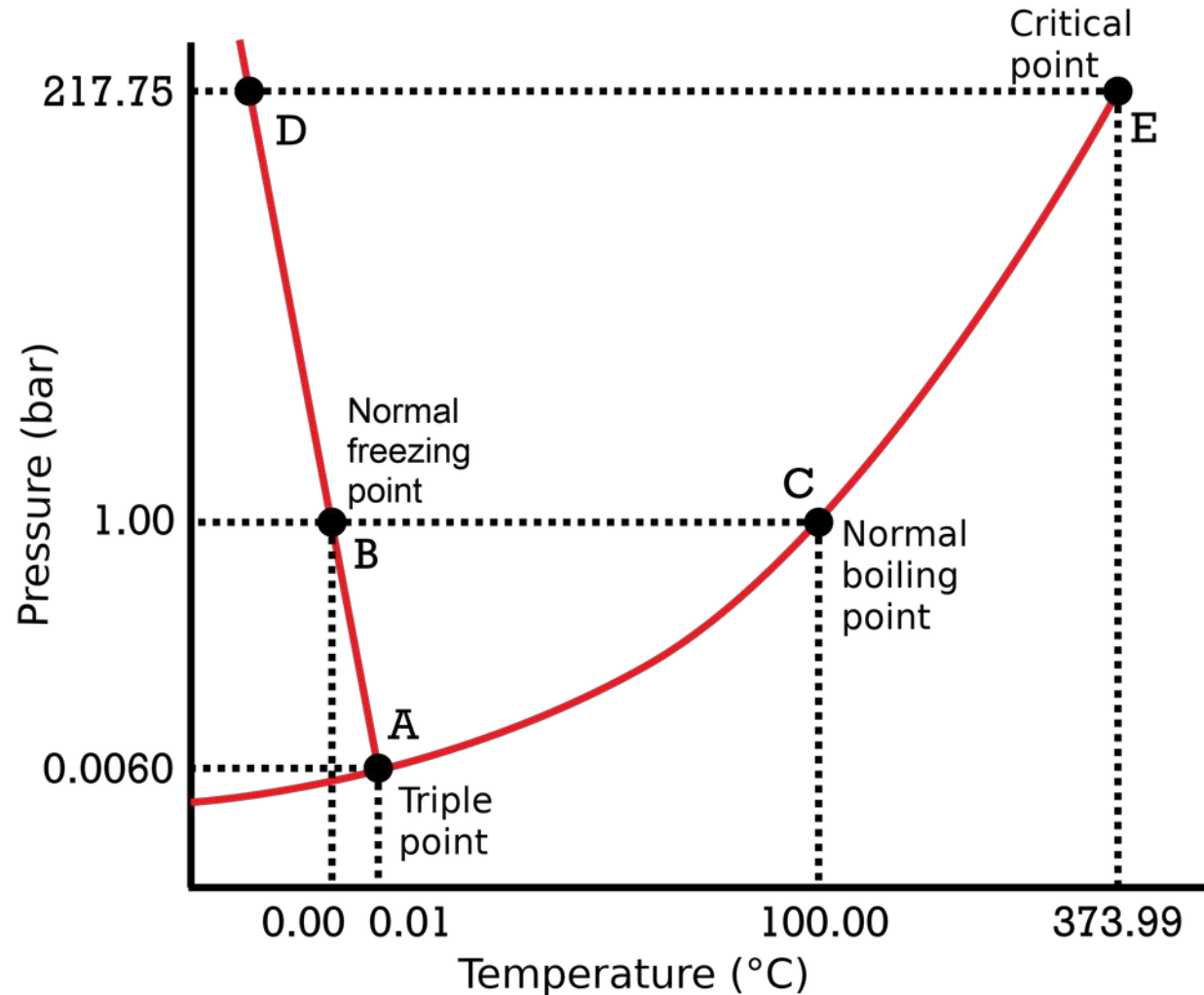
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PHASE DIAGRAM OF WATER

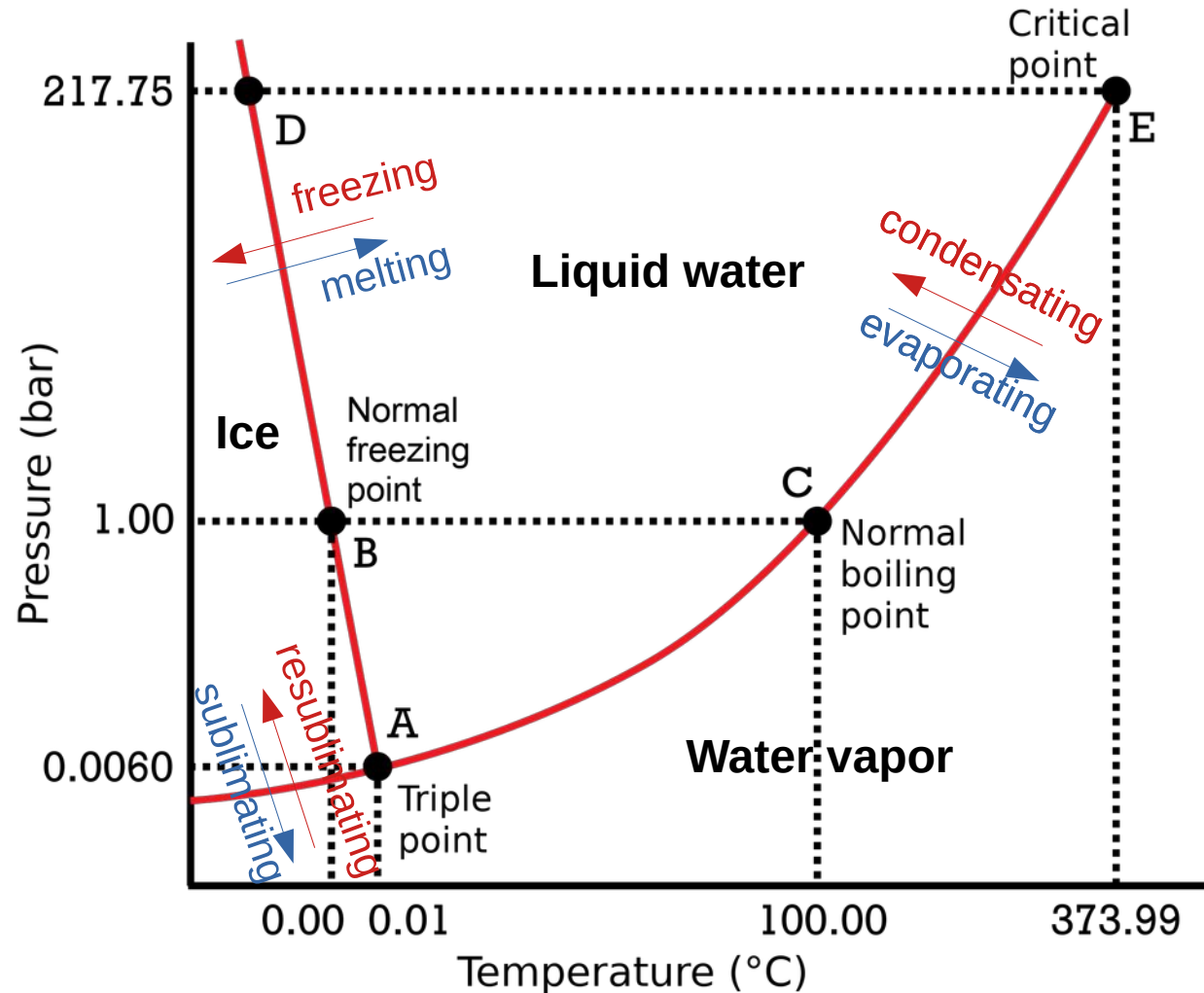
- Coexistence of two phases along a curve (equilibrium)
- **Phase changes:**
 - Cooling/Warming
 - Increase/decrease of pressure
 - Increase/decrease of water vapor



1 bar = 1000 hPa

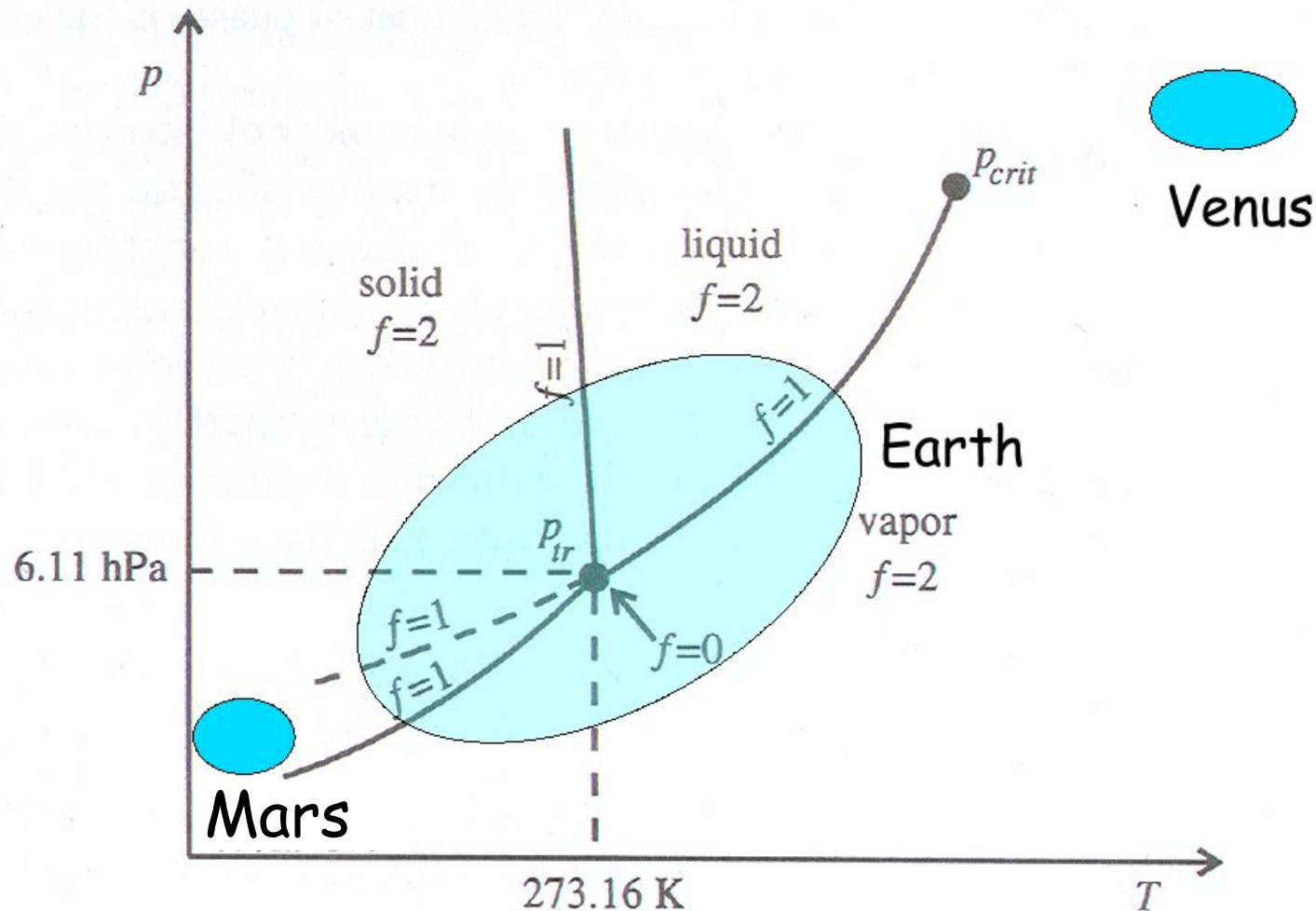
PHASE DIAGRAM OF WATER

← Release of heat
→ Extraction of heat



- Latent heat is the heat released or absorbed per unit mass when water changes phase.
- Latent heating is an efficient way of transferring energy globally and is an important energy source for Earth's weather and climate.

WATER ON EARTH (PHASE DIAGRAM)



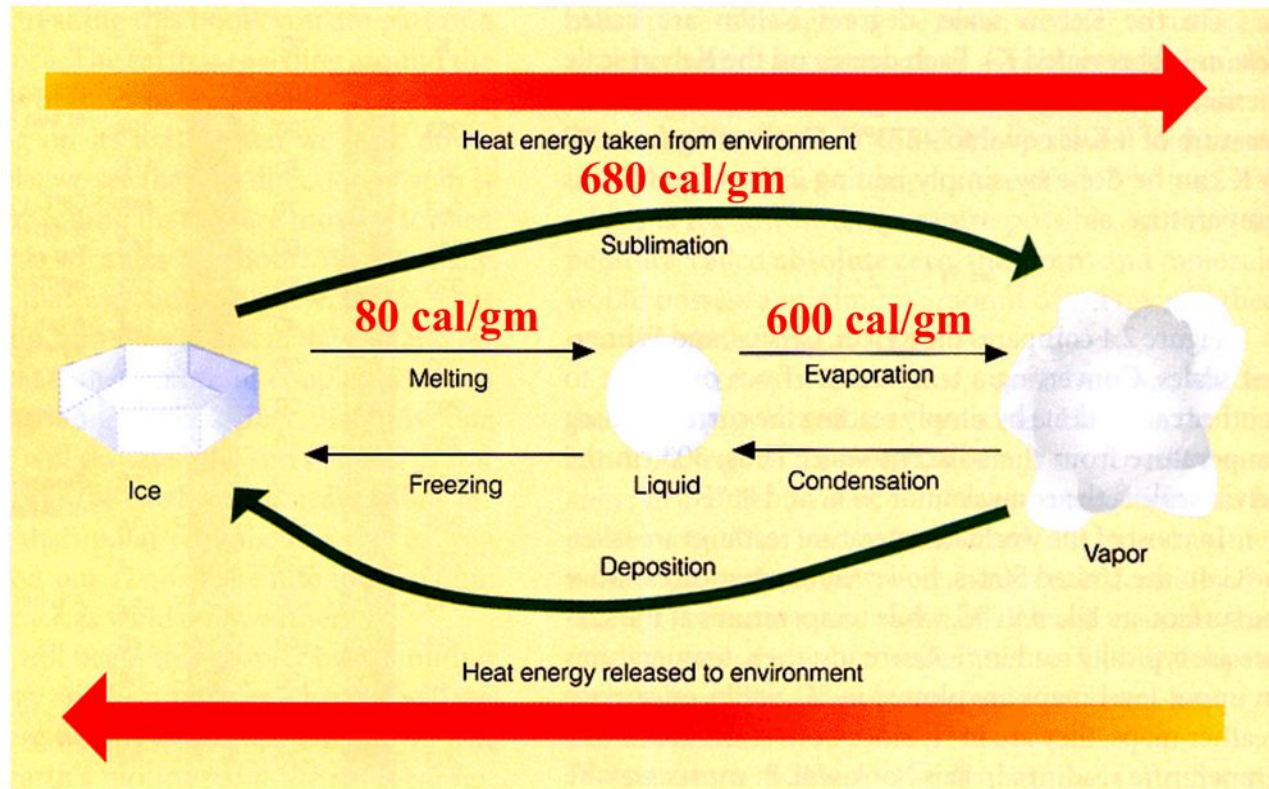
Earth conditions are such that water is present at the surface and in the atmosphere under its three phases.

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LATENT HEAT



(from Meteorology: Understanding the Atmosphere)

- The energy needed to evaporate 1 kg of water is about three times as large as the energy needed to heat it from 0°C to 100°C!

LATENT HEAT

- Heat absorbed (given away) by a isothermal or isobaric phase change

$$L = dQ = \text{constant}$$

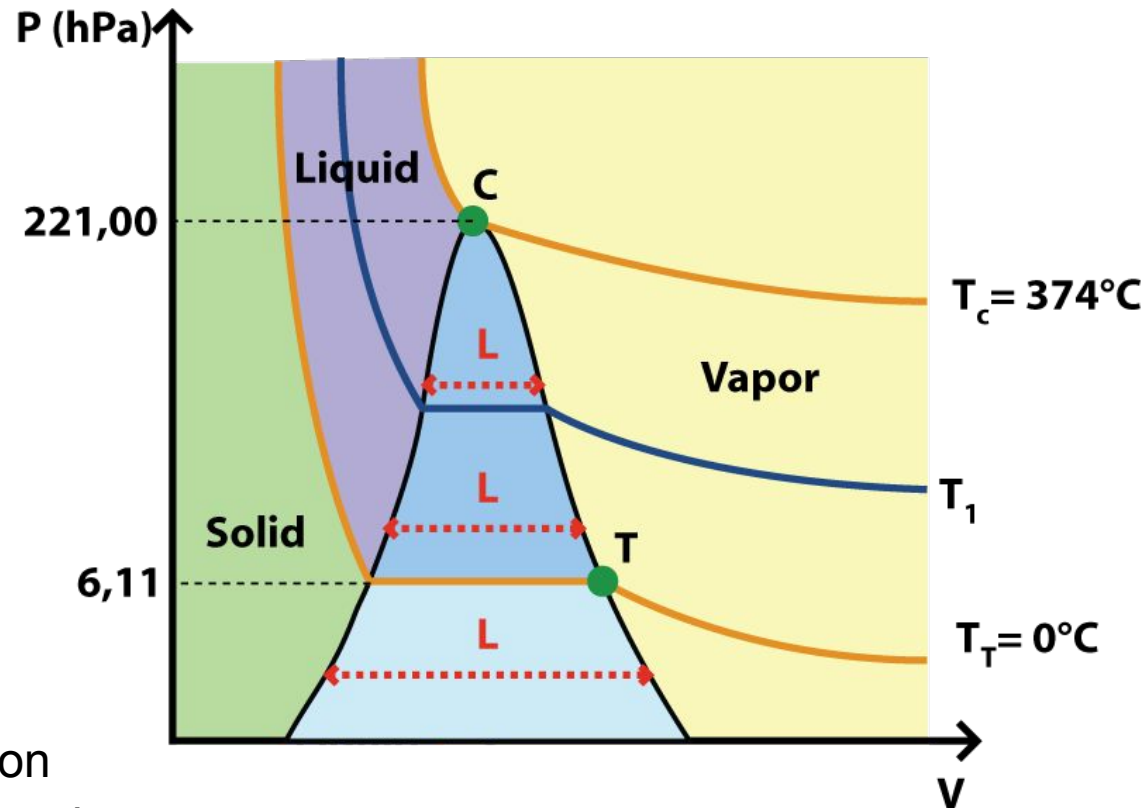
From the forming or breaking of molecular bonds that hold water molecules together in its different phases

- Latent heats are a weak function of temperature and given phase change:

$$l_w = 333.5 \text{ kJ/kg}, l_v = 2257 \text{ kJ/kg}, l_i = 2835 \text{ kJ/kg} \quad \text{for } T_T$$

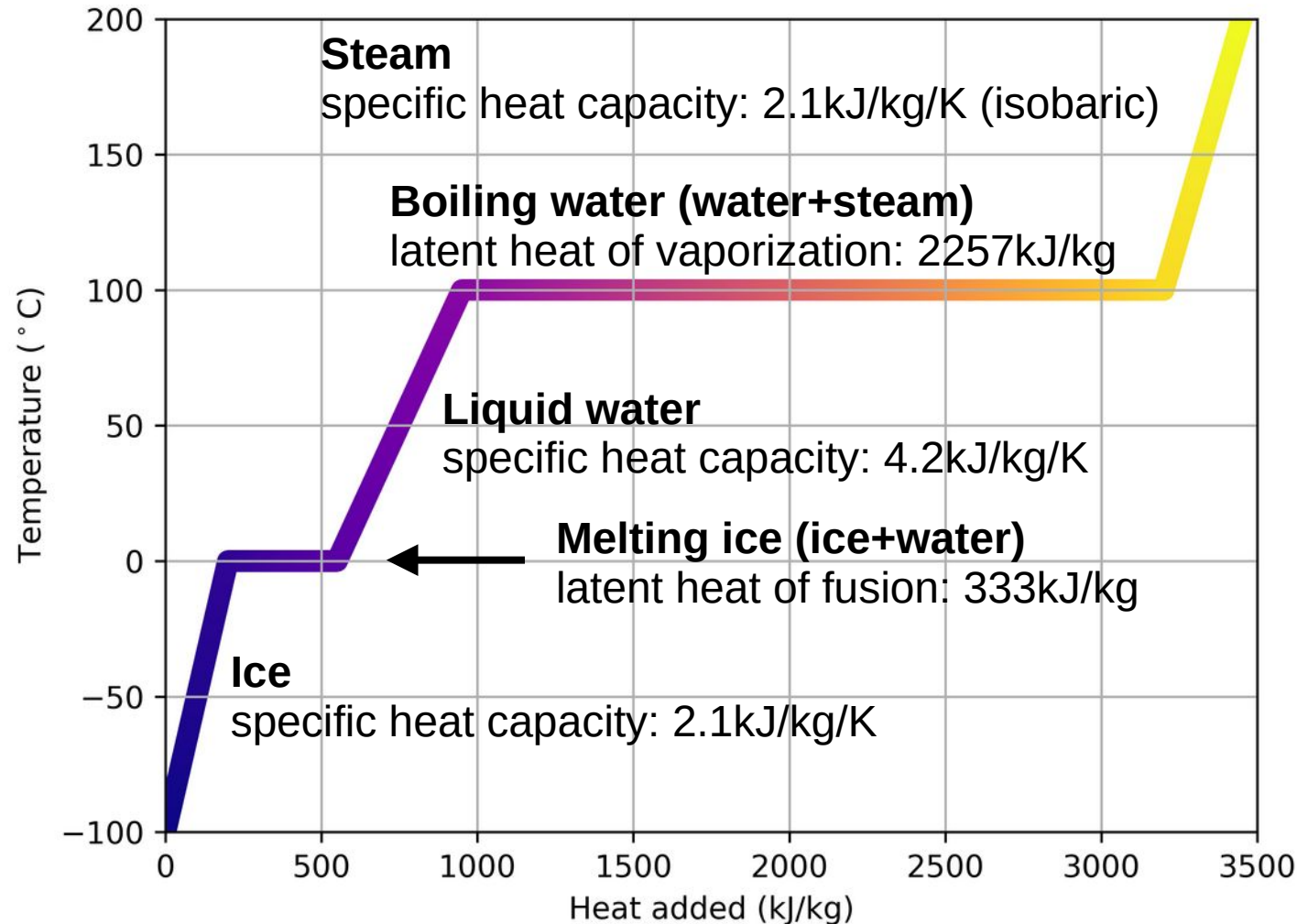
Specific latent heat (l) can be calculated with L and mass of the the body m :

$$l = \frac{dQ}{dm} = \frac{L}{dm}$$



LATENT HEAT & SENSIBLE HEAT OF WATER

How much energy is needed to heat water from -100 to 200 °C ?

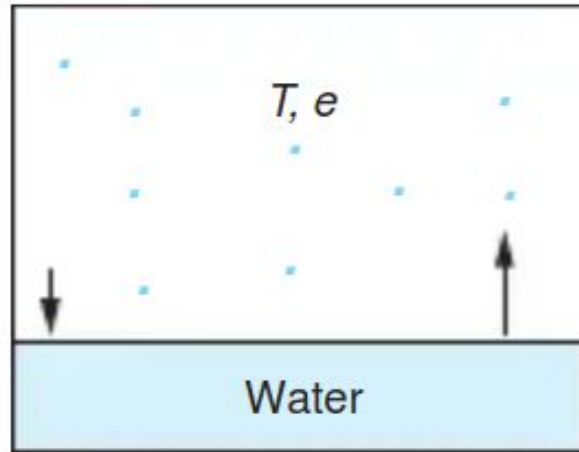


SUBTOPICS (UNITS & DEFINITIONS)

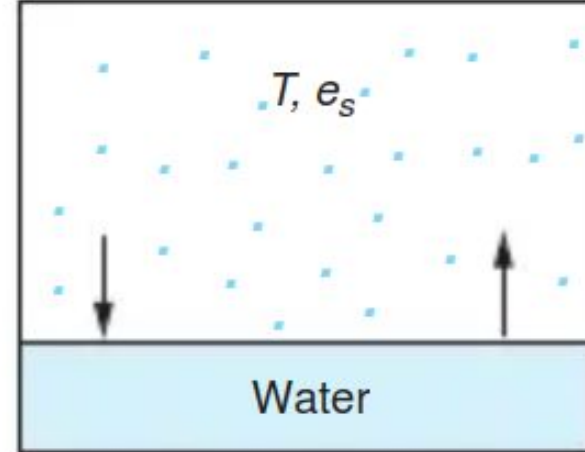
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SATURATION OF AIR



(a) Unsaturated



(b) Saturated

from Wallace and Hobbs

- $\uparrow$ **Evaporation:** The process whereby molecules break free of the liquid volume.
- $\downarrow$ **Condensation:** Water vapor molecules randomly collide with the water surface and bond with adjacent molecules.

SATURATION VAPOR PRESSURE (1)

For equilibrium conditions we assume:

$$T = T_v = T_i = T_w$$

Ideal gas law for water vapor pressure (e):

$$p_v = \rho_v R_v T_v \quad \longrightarrow \quad e = \rho_v R_v T$$

Difference between the equilibrium (saturation) vapor pressure and the regular vapor pressure

e = vapor pressure

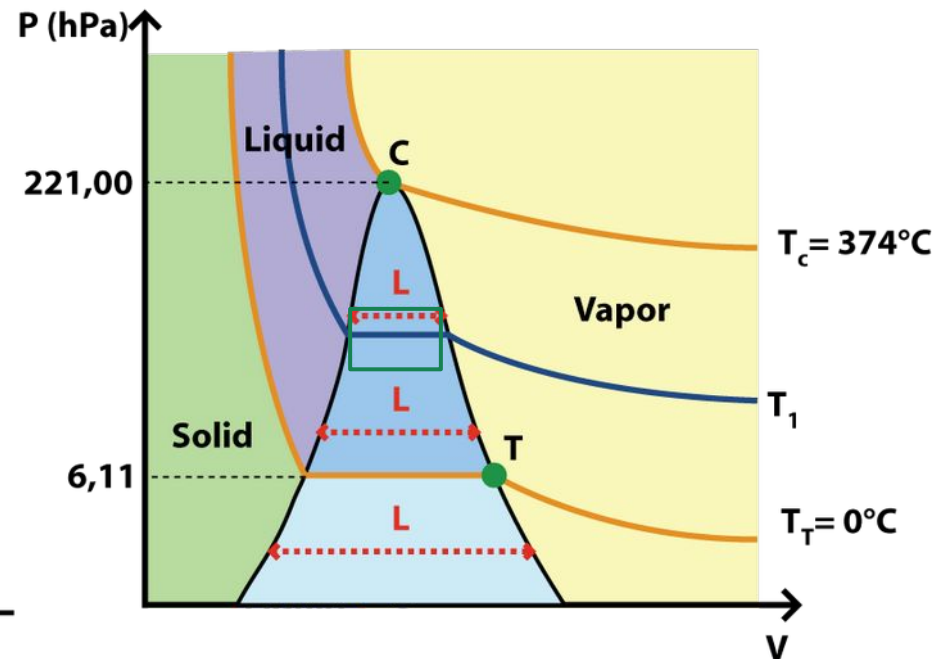
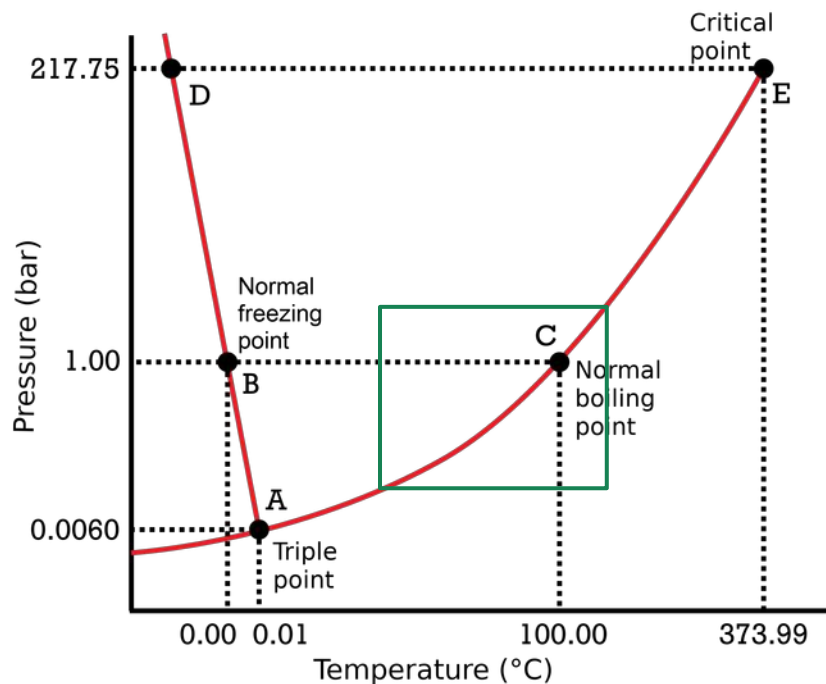
e_{sw} = saturation vapor pressure wrt . water

e_{si} = saturation vapor pressure wrt . ice

SATURATION VAPOR PRESSURE (2)

Basic idea for the saturation vapor pressure equation:

- Provide a mathematical relationship that describes any equilibrium state of water as function of temperature and pressure.
- Accounts for phase changes at each equilibrium state (each temperature)



SATURATION VAPOR PRESSURE (3)

SATURATION VAPOR PRESSURE (4)

SATURATION VAPOR PRESSURE (5)

SATURATION VAPOR PRESSURE (6)

- Saturation vapor pressure depends primarily on the air temperature.
- Saturation vapor pressure describes how much water vapor is needed to make the air saturated at any given temperature.
- Can only be numerically solved due to the temperature dependence of l , α .

Clausius-Clapeyron Equation

$$\frac{de_{s(w,i)}}{dT} = \frac{l_{v,i}}{T \cdot (\alpha_v - \alpha_{w,i})}$$

T : temperature

e_s : saturation vapor pressure

l : latent heat

α : specific volume of
vapor (v) $\wedge$ water (w) $\wedge$ ice (i)

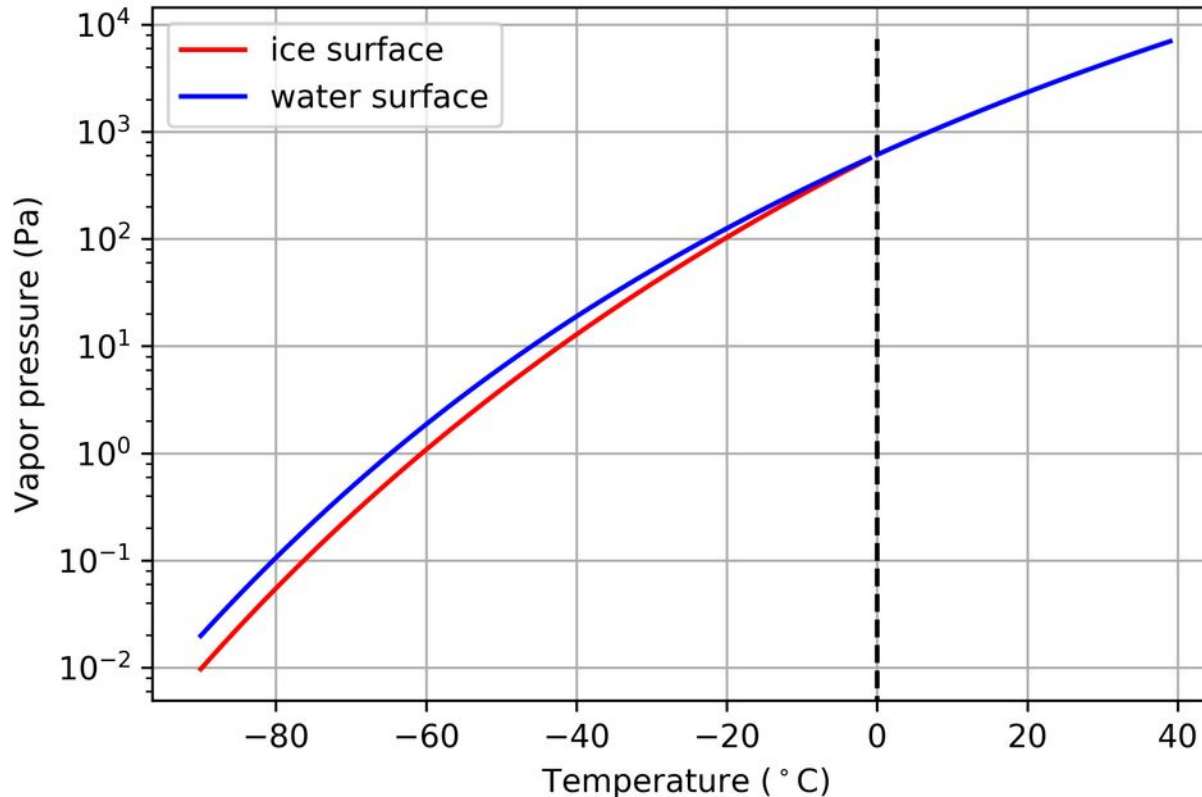
CLAUSIUS-CLAPERYRON EQ. (1)

CLAUSIUS-CLAPERYRON EQ. (2)

SATURATION VAPOR PRESSURE

- Saturation pressure increases exponentially with air temperature.

Clausius-Clapeyron Equation



$$\frac{de_{sw}}{dT} = \frac{l_v}{T \cdot (\alpha_v - \alpha_w)}$$

$$e_{sw} \approx 611 \cdot e^{\frac{L_v}{R_v} \cdot \left(\frac{1}{T_0} - \frac{1}{T} \right)}$$

R_v : specific gas constant for water vapour

$$R_v = 461.52 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$$

$$\frac{de_{si}}{dT} = \frac{l_i}{T \cdot (\alpha_v - \alpha_i)}$$

Murphy & Koop, 2005

$$\ln(e_{sw}) \approx 54.842763 - \frac{6763.22}{T} - 4.210 \ln(T) + 0.000367 \cdot T + \tanh(0.0415 \cdot (T - 218.8)) \cdot \left(53.878 - \frac{1331.22}{T} - 9.44523 \cdot \ln(T) + 0.014025 \cdot T \right)$$

for $123 < T < 332 \text{ K}$ (liquid)

BOILING POINT OF WATER

Clausius-Clapeyron Equation

$$\frac{de_{sw}}{dT} = \frac{l_v}{T \cdot (\alpha_v - \alpha_w)}$$

Typical atmospheric conditions at ground (1013hPa) near the boiling point:

$$T = 100^\circ \text{C} = 373 \text{ K} \quad \alpha_v = 1.673 \text{ m}^3/\text{kg}$$
$$l_v = 2.26 \cdot 10^3 \text{ kJ/kg} \quad \alpha_w = 1.04 \cdot 10^{-3} \text{ m}^3/\text{kg}$$

Change of boiling point temperature as a function of atmospheric pressure when air is saturated

$$\frac{de_{sw}}{dT} = ?$$

Boiling point at the Zugspitze (750hPa) ?

$$\frac{de_{sw}}{dT} = \frac{e_{sw} - e_{sw,ref}}{T - T_{ref}} = ?$$

$$T_{ref} = 100^\circ \text{C} = 373 \text{ K}$$

$$e_{sw,ref} = 1013 \text{ hPa}$$

$$e_{sw} = 750 \text{ hPa}$$

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WATER VAPOR IN DRY AIR

Moist air is considered as a mixture of dry and vapor both assumed ideal gas

**Ideal gas law
(dry air)**

$$p_d = \rho_d R_d T$$

Density

Temperature

Pressure

Gas constant for dry air 287 J/Kg/K

Water vapor

$$e = \rho_v R_v T = \rho_v \frac{R_d}{\epsilon} T$$

Vapor Pressure

Vapor density

Gas constant for vapor 461 J/Kg/K

$$\epsilon = \frac{R_d}{R_v} = 0.622$$

WATER VAPOR IN DRY AIR

Partial pressures add if both gases occupy same volume V .

N_x are the mol masses

$$p = p_d + e$$

$$p_d = p N_d$$

$$e = p N_v$$

$$\Rightarrow \frac{dp}{p} = \frac{dp_d}{p_d} = \frac{de}{e}$$

$$\left. \begin{array}{l} p_d V = m_d R_d T \\ e V = m_v R_v T \end{array} \right\} p V = T (m_d R_d + m_v R_v)$$

WATER VAPOR IN DRY AIR

Absolut humidity

$$\rho_v = \frac{m_v}{V}$$

Specific humidity

Mass of water
vapour per unit
moist air

$$q = \frac{m_v}{(m_d + m_v)} = \frac{\rho_v}{\rho} = \epsilon \frac{e}{p - (1 - \epsilon)e} \approx \epsilon \frac{e}{p}$$

Mixing ratio

Mass of
water
vapour per
unit dry air

$$r = \frac{m_v}{m_d} = \frac{\rho_v}{\rho_d} = \epsilon \frac{e}{p - e} \approx \epsilon \frac{e}{p}$$

**Relation between
q and r**

$$q = \frac{r}{1 + r}$$

$$r = \frac{q}{1 - q}$$

SUBTOPICS (UNITS & DEFINITIONS)

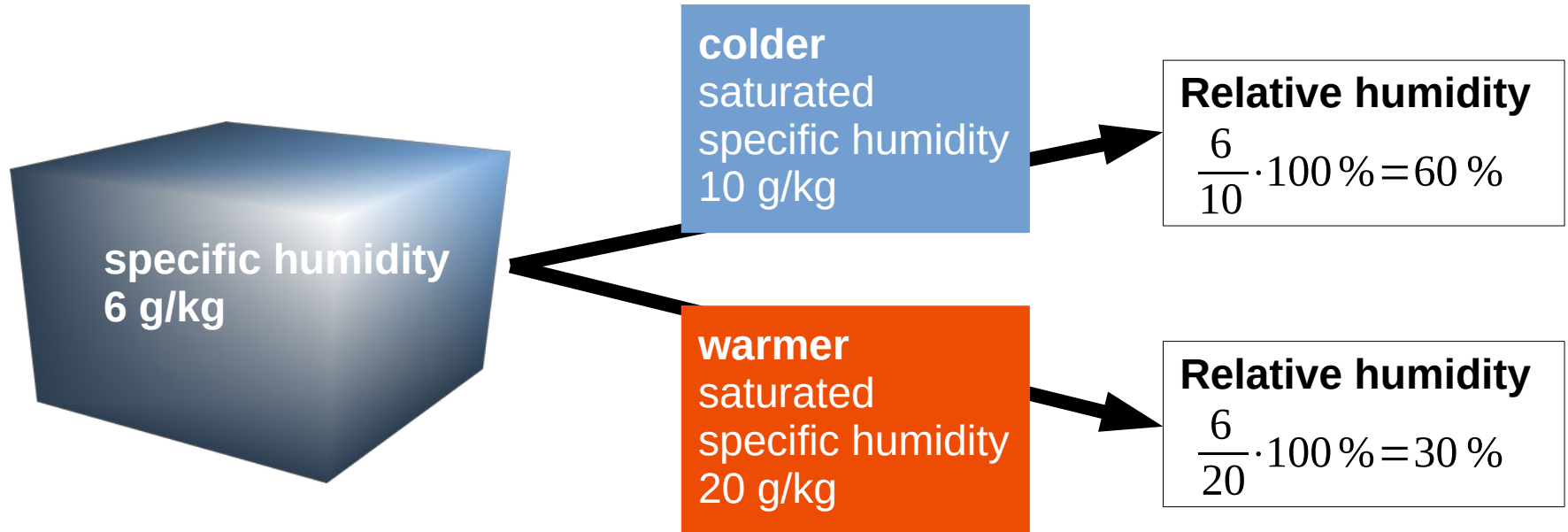
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UNITS OF WATER IN THE ATMOSPHERE

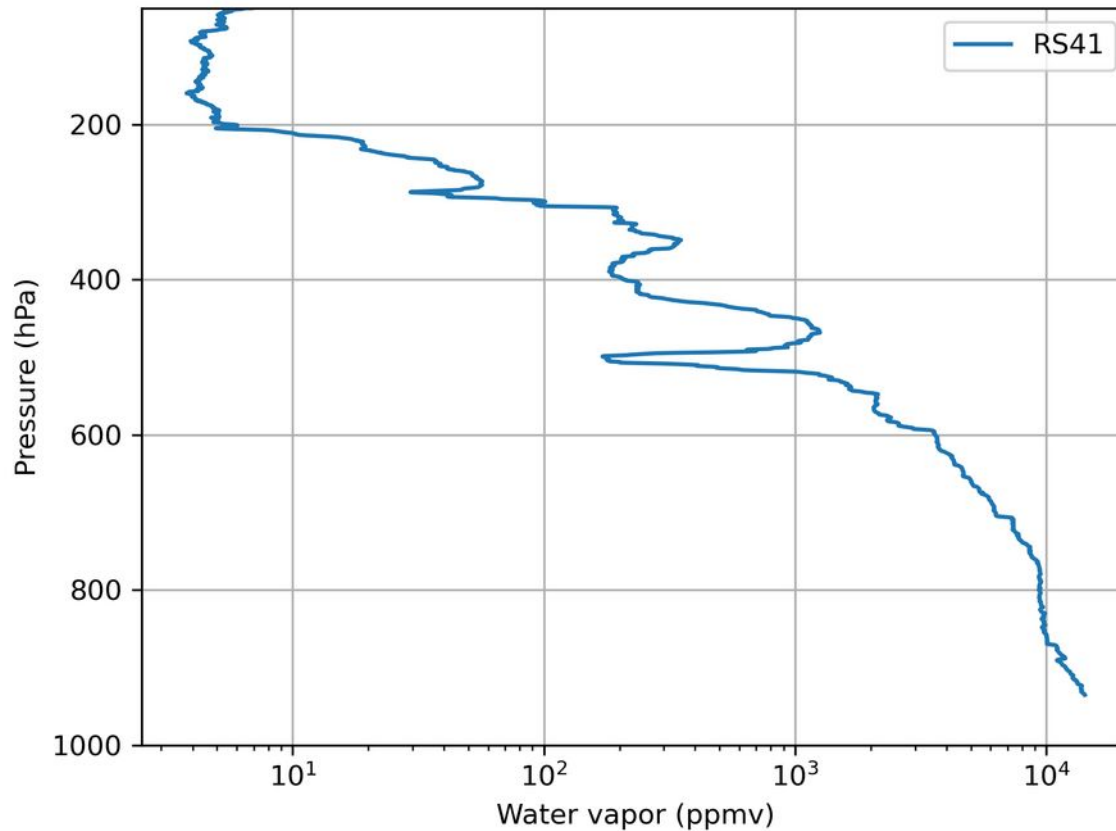
Quantity	Symbol	Units	Formular
Mass mixing ratio	r_m	ppmw or mg/kg	$\frac{\text{mass of water vapor}}{\text{mass of dry air}}$
Specific humidity	q	g/kg	$\frac{\text{mass of water vapor}}{\text{total mass of air}}$
Volume mixing ratio	r	ppmv or nmol/mol	$\frac{\text{volumne of water vapor}}{\text{volumne of dry air}}$
Absolute humidity	ρ	g/m ³	$\frac{\text{mass of water vapor}}{\text{volumne of air}}$
Vapor pressure of H ₂ O	e	hPa	
Relative humidity wrt. water	RH_w	%	$\frac{H_2O \text{ vapor pressure}}{\text{water saturation vapor pressure}} = \frac{\text{volumne mixing ratio}}{\text{water sat. mixing ratio}}$
Relative humidity wrt. ice	RH_{ice}	%	$\frac{H_2O \text{ vapor pressure}}{\text{ice saturation vapor pressure}} = \frac{\text{volumne mixing ratio}}{\text{ice sat. mixing ratio}}$
Dew point temperature	T_d	K	Temperature at which $RH_w = 100\%$
Frost point temperature	T_f	K	Temperature at which $RH_{ice} = 100\%$
Saturation mixing ratio wrt. water/ice	$r_{s(w,i)}$	ppmv	Volumen mixing ratio at which $RH_{w/i} = 100\%$

SPECIFIC VS. RELATIVE HUMIDITY



- Specific Humidity: How many grams of water vapor in one kilogram of air (in unit of gm/kg).
- Relative Humidity: The percentage of current moisture content to the saturated moisture amount (in unit of %).
- Clouds form when the relative humidity reaches 100%.

INTEGRATED WATER VAPOR



Important quantity for
the water cycle and
total moisture transport

An column **integrated water vapor** quantity

Precipitable water: P_{wat}

Units: kg m⁻² (mass) or mm (volume)

$$P_{\text{wat}} = \frac{1}{g} \int_0^{\infty} q(p) dp$$