The volatile component of rocky planets
(hydrospheres and atmospheres)

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Hydrospheres of rocky planets

- Mercury
  - No hydrosphere
  - Not clear if it has ever accreted water given its vicinity to the Sun
- Venus
  - Currently does not have a hydrosphere
  - Water was possibly present in the early stages of its history, but lost via a Runaway Greenhouse mechanism

The Earth's Hydrosphere

The Earth is the only planet of the Solar System with <u>surface liquid oceans</u>

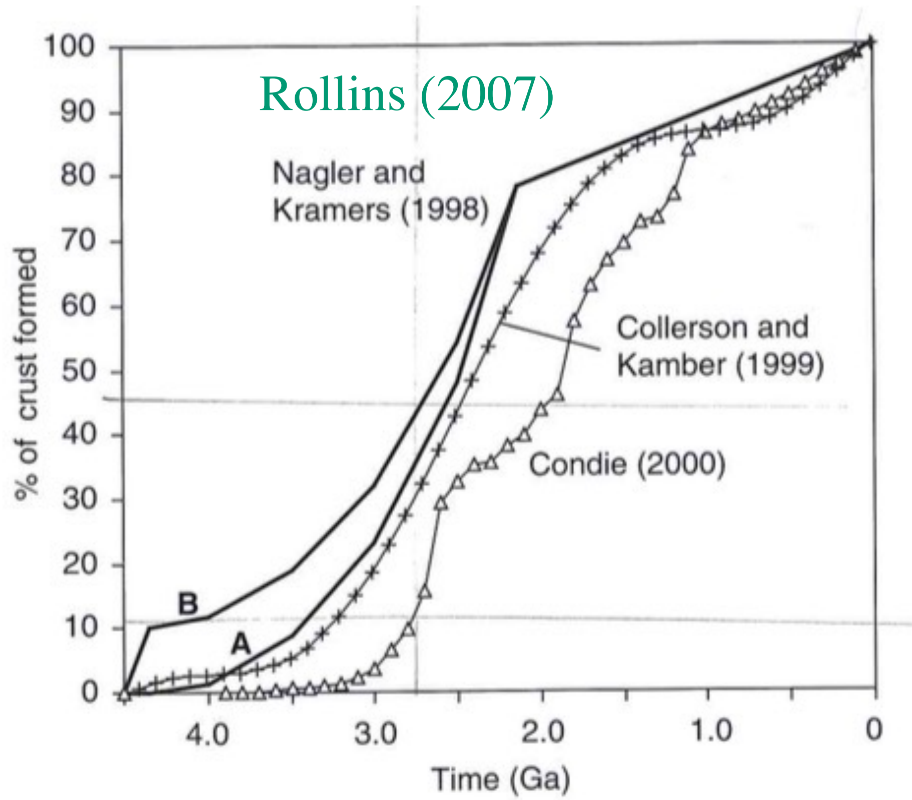
Current ocean coverage: ~70%

Typical ocean depth: 3 km

Current continent coverage: ~30%

The fraction of continents has increased over geological time due to the emergence of continents as a result of tectonic activity

<u>*Water is present in three different phases: liquid, vapour and ice*</u>



Earth water reservoirs

Rollins (2007)

TABLE 5.2 Estimates of the fraction of water and mass of water in the different mantle reservoirs. Also shown are estimates of water balance in the modern mantle.

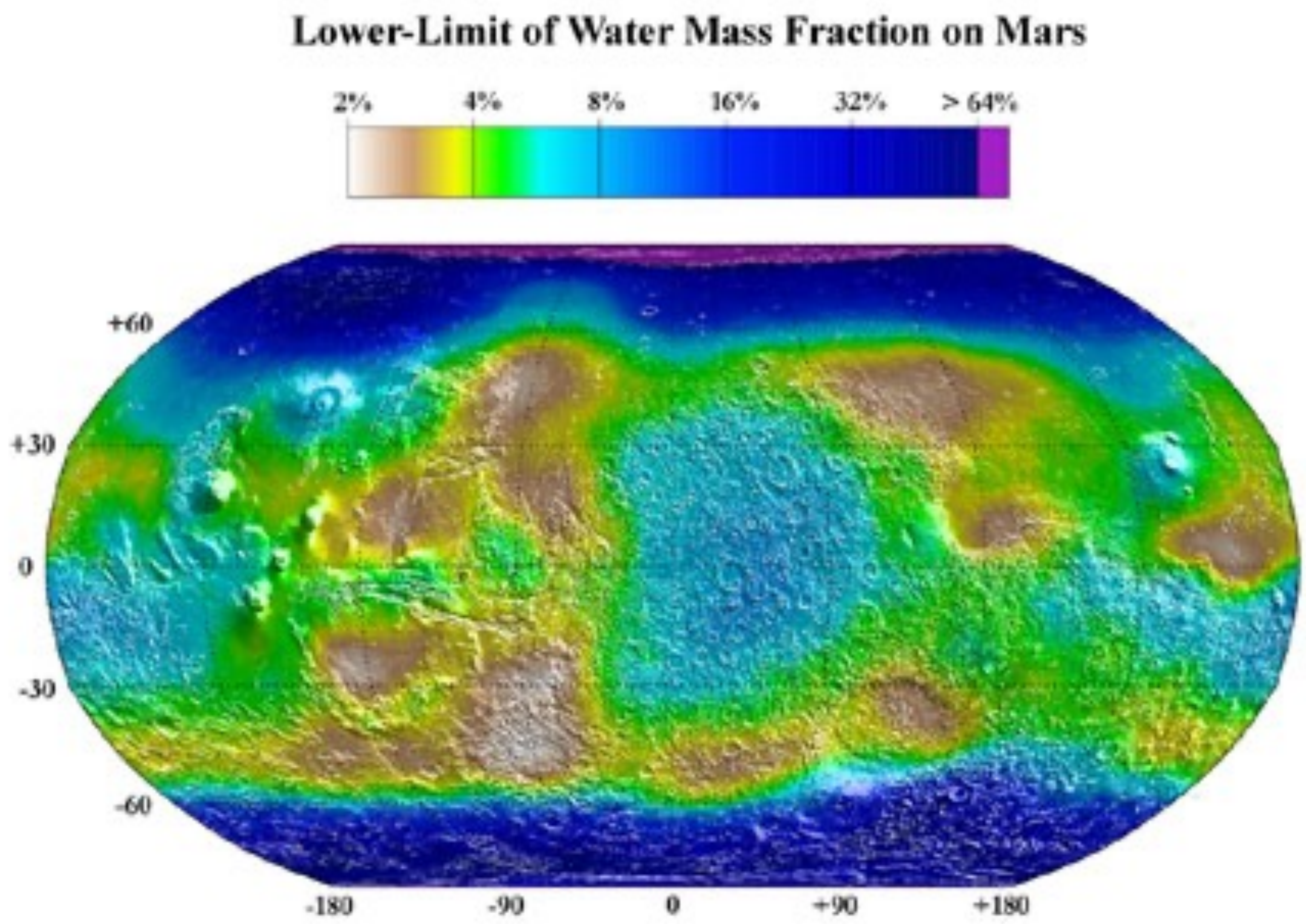
Reservoir		Mass of water	Reference
Water budget			
Surface water		1.4×10^{21} kg	Lecuyer et al. (1998)
Sedimentary rocks		0.23×10^{21} kg	Lecuyer et al. (1998)
Upper mantle		$0.2–0.3 \times 10^{21}$ kg	Data from Saal et al. (2002)
Mantle transition zone		$2.6–5.2 \times 10^{21}$ kg	Ohtani (2005)
Lower mantle		$3.4–4.5 \times 10^{21}$ kg	Ohtani (2005)
Total Mantle		**$7.0–11.0 \times 10^{21}$ kg**	
Water balance			
Total water returned to mantle (subduction)	1.83×10^{12} kg/yr		Jarrard (2003)
Total outgassing (arc + ridge)	2.0×10^{11} kg/yr		Peacock (1990)

Water in the outer reservoirs (1.4×10^{21} kg) make ~ 2×10^{-4} of Earth mass

The mass fraction of water has an optimal value that avoids the extremes of an ocean planet and a dry planet

Mars water content

Water-equivalent hydrogen content of sub-surface water-bearing soils derived from the *Mars Odyssey* neutron spectrometer



Mars volatile reservoirs

Water (H_2O) Reservoir	*Equivalent Global Ocean Depth*
Atmosphere	10^{-5} m
Polar caps and layered terrains	5–30 m
Ice, adsorbed water, and/or hydrated salts stored in the regolith	0.1–100 m
Deep aquifers	Unknown
Carbon Dioxide (CO_2) Reservoir	*Equivalent Surface Pressure*
Atmosphere	~6 mbar
Carbonate in weathered dust	~200 mbar per 100 m global average layer of weathered dust
Adsorbed in regolith	<200 mbar
Carbonate sedimentary rock	~0 (at surface)

Radar evidence of subglacial liquid water on Mars
(Orosei 2018)

Rocky planet atmospheres

- Atmospheres have a strong influence on the climate and, as we shall see, are essential for planetary habitability

- Processes that shape the atmospheres of a rocky planet:
  - gravitational capture of gas from the protoplanetary disk

    important for massive planets during the epoch of planet formation
  - emission of gas from the surface

    evaporation, sublimation, loss from the interior, and de-absorption
  - loss of the atmosphere to space

Primary atmosphere:

generated at the epoch of planetary formation

Secondary atmosphere:

created after the loss of the primary atmosphere

Vertical structure of planetary atmospheres

In a planet with a solid surface the atmospheric pressure, p, decreases with increasing height from the surface, z

If the atmosphere is in *hydrostatic equilibrium* the pressure decreases with an exponential law

$$p(z) = p_s \exp(-z/H)$$

where H is the scale height of the atmosphere.

Let us express H in terms of atmospheric parameters

Atmospheric scale height

- Derivation of *H*
  - If the atmosphere is much thinner than the planet radius, the surface gravity acceleration, g, can be considered constant
  - From the condition of <u>hydrostatic equilibrium</u> we obtain a relationship between the pressure, p, and the mean density, ρ

$$dp = -g\, \rho\, dz$$

In an *ideal* case of uniform temperature, T, from the law of perfect gases, $p = \rho\, kT/\mu$, we obtain

$$p(z) = p_s \exp(-z/H)$$

$$H = kT/\mu g$$

where $p_s=p(0)$ is the surface pressure and μ the *mean molecular weight*, which depends on the atmospheric chemical composition

Atmospheric scale height

– In the real case the atmospheric temperature is not uniform:

$$T = T(z)$$

We can still derive a simple relationship between surface pressure and height (for a constant molecular weight):

$$p(z) = p_s \exp(-z/H_z)$$

$$H_z = k\, T_h(z) / \mu g$$

where $T_h(z)$ è is the *harmonic mean* of the temperature between the surface and the geometric height z

Since the temperature is in absolute scale (kelvin degrees), the percent variations of $T_h(z)$ can be relatively small over a significant part of the atmosphere

Therefore, to first approximation, the pressure follows an exponential decay even considering the vertical temperature gradient

Atmospheres of rocky planets

Allen (2000)

Planet	Surface pressure p [bar]	Scale height H [km]	Surface gravitational acceleration g [m/s^2]
Mercury	…	...	3.7
Venus	90	15	8.9
Earth	1	8	9.8
Mars	~0.007	11	3.7

Differences in μ (chemical composition), p and H, and different evolutionary paths, make hard to predict the properties of rocky exoplanet atmospheres

Chemical composition of rocky planet atmospheres

Gas	Venus [2]	Earth [2]	Mars [2]
N_2	0.035	0.78084	0.027
O_2		0.20948	1.3×10^{-3}
CO_2	0.965	3.33×10^{-4}	0.953
CO	3×10^{-7}	2×10^{-7}	2.7×10^{-3}
CH_4		2.0×10^{-6}	
NH_3		4×10^{-9}	
H_2O	2×10^{-5}	$\sim 10^{-6}$	3×10^{-4}
H_2		5×10^{-7}	
He	1.2×10^{-5}	5.24×10^{-6}	
Ar	7×10^{-5}	9.34×10^{-3}	0.016
Ne	1×10^{-5}	1.818×10^{-5}	2.5×10^{-6}
Kr	3×10^{-9}	1.14×10^{-6}	3×10^{-7}
Xe		8.7×10^{-8}	8×10^{-8}
H_2S	3×10^{-6}	2×10^{-8}	
SO_2	1.5×10^{-4}	1×10^{-9}	

Allen (2000)

Physical regimes of the atmosphere at low and high *z*

- Mixing and diffusion

  Bakulin , Kononovic & Moroz 1984

  – Low *z*
    - *convection* and *turbulence* dominate
    - the gas is well mixed
      - the chemical composition and mean molecular weight do not change significantly with height

  – High *z*
    - *diffusion* dominates because this process scales inversely with the density (concentration by number), which decreases with *z*
      - the mean molecular weight decreases with increasing z
      - H and He become the main constituents

Physical regimes of the atmosphere at low and high z

- Mean free path of molecules, ℓ

  Bertotti & Farinella 1990

  – Low z

    $\ell < H$

    - molecules can attain *local thermal equilibrium* through collisions
    - the atmosphere is confined and can be described as a fluid

  – High z

    $\ell > H$

    - there is no gravitational confinement of the gas
    - the fastest molecules can excape to the interplanetary medium
    - interplanetary molecules can be captured

Physical regimes of the atmosphere at low and high z

- Optical depth in the infrared band, τ_{IR}

  Bakulin , Kononovic & Moroz 1984

  – Low z

    $\tau_{IR} >> 1$

    - in thick atmospheres the lowest layers, with highest density, are optically thick to thermal radiation
      - thermal radiation is mostly due to surface heating by stellar radiation
      - also geothermal heating could be present

  – High z

    $\tau_{IR} \sim 0$

    - the highest atmospheric layers are transparent to thermal radiation; the thermal radiation from underlying layers can escape to space

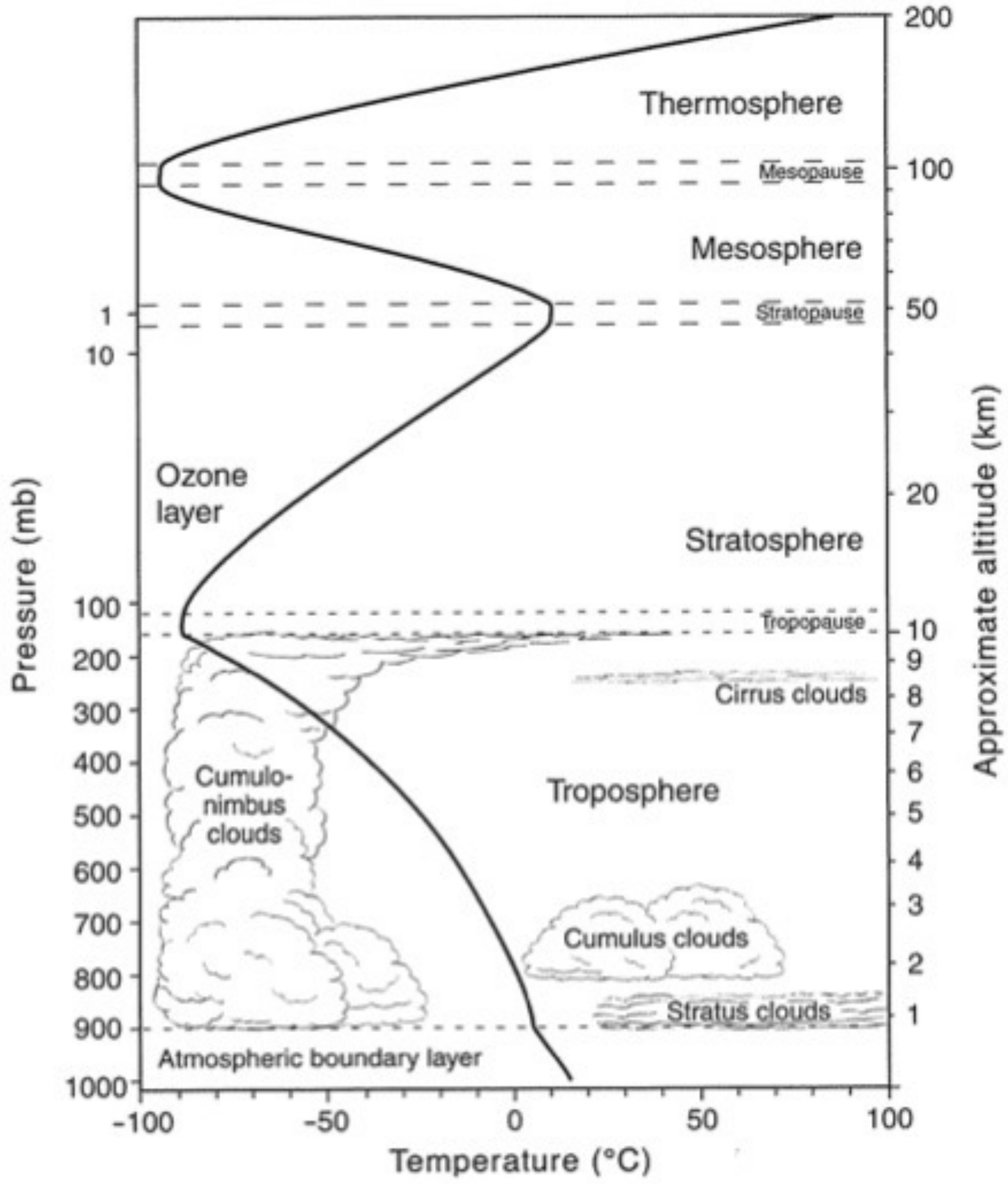
Vertical structure of the atmosphere

- For a given planet the transitions between the above mentioned different regimes may take place at different heights, depending on the type of process under consideration
  - mixing/diffusion, molecular mean free path and infrared optical depth

- The lowest atmospheric layer where convection dominates and $\tau_{IR} > 1$ is called *troposphere*
  - It is characterized by a negative gradient of the temperature

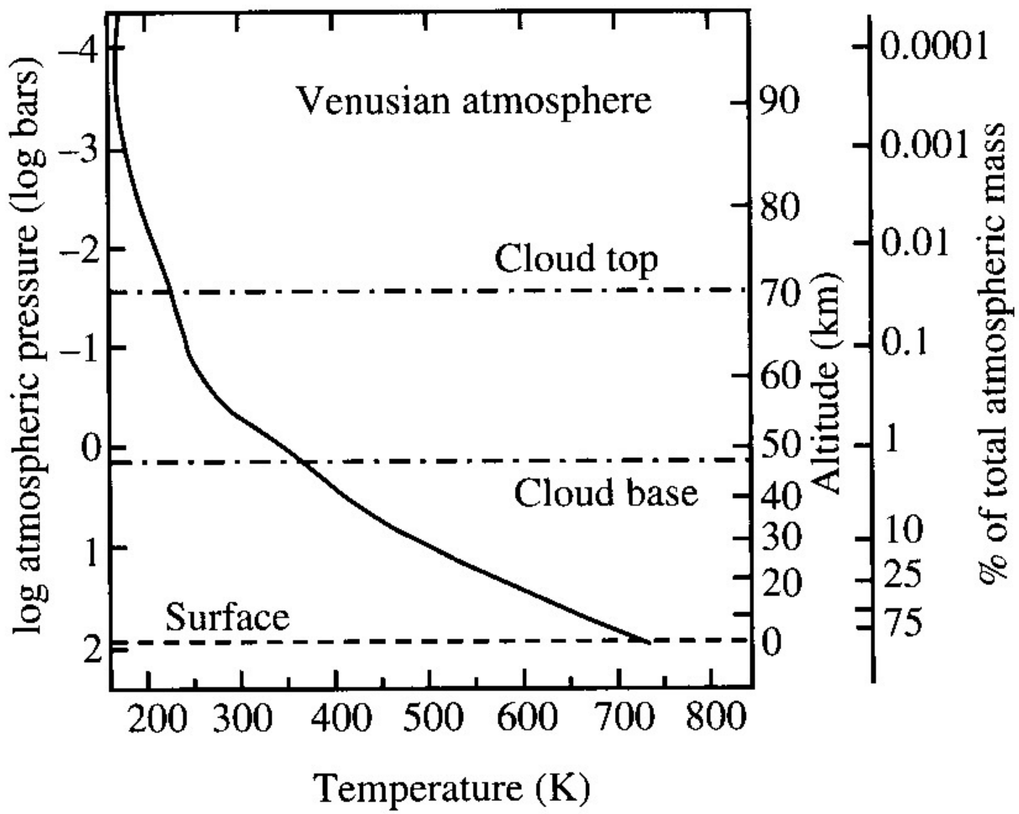
Vertical temperature distribution in Earth's atmosphere

- Negative gradient in the troposphere
  - The solar radiation penetrates the atmosphere and heats the surface
  - The lower atmospheric layers are opaque to thermal radiation emitted by the surface
  - The infrared flux is directed upwards, creating the observed negative gradient
- Complex temperature profile in the highest layers
  - Not considered in this course
  - The pressure and temperature must gradually merge with the values of the interplanetary medium



Vertical temperature distribution in Venus atmosphere

- Negative temperature gradient in the lower layers, as in the case of the Earth
- At the surface, p and T are significantly higher than in the case of the Earth
- At a height of ~50-60 km, p and T are roughly similar to the values found at the surface of the Earth



Containment of the atmosphere

- The escape velocity from the planet plays a key role in the containment of the atmosphere

  $v_{esc} \propto (M/R)^{1/2}$

  M, R: planet mass and radius

- Condition for the containment of the atmosphere

  $\langle v_{thermal} \rangle \ll v_{esc}$

  The mean thermal velocity of atmospheric atoms or molecules must be significantly lower than the escape velocity

  $\langle v_{thermal} \rangle \propto (T/\mu)^{1/2}$

  Where μ is the atomic or molecular mass

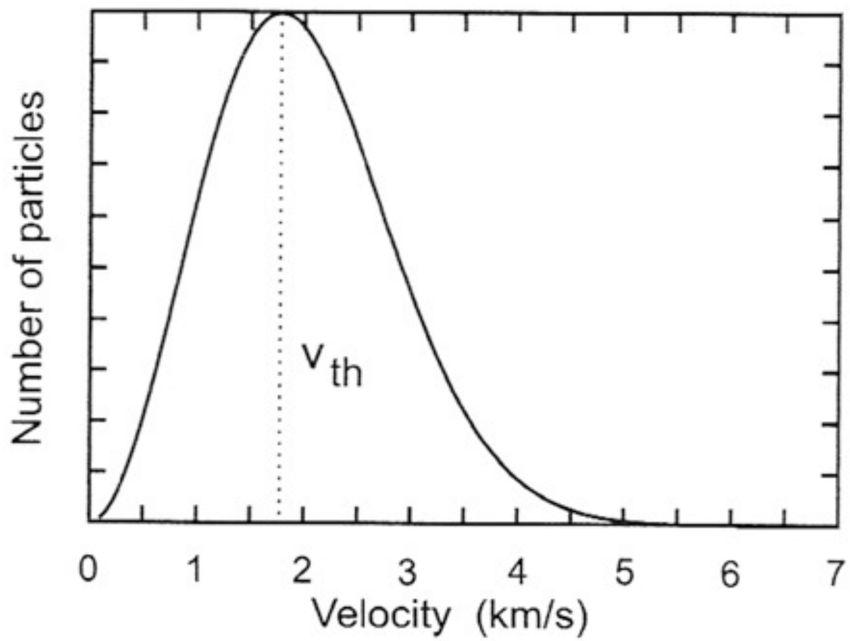
  For a given temperature, atoms and molecules with low μ will be lost more easily

Planet	Equatorial escape velocity (km s^{-1})	
Mercury	4.3	
Venus	10.4	
Earth	11.2	
Mars	5.0	
Jupiter	59.5	
Saturn	35.5	
Uranus	21.3	
Neptun	23.7	
Moon	2.4	

Allen (2000)

Loss of atmospheric layers

- "Jean escape" mechanism
  - Loss of atmospheric molecules with velocities in the high-velocity tail of the Maxwellian distribution
  - Takes place in the external layers, where the mean free path becomes larger than the atmospheric scale height, i.e., $\ell > H$
  - Figure: Maxwellian distribution for H_2 molecoles at T=390K

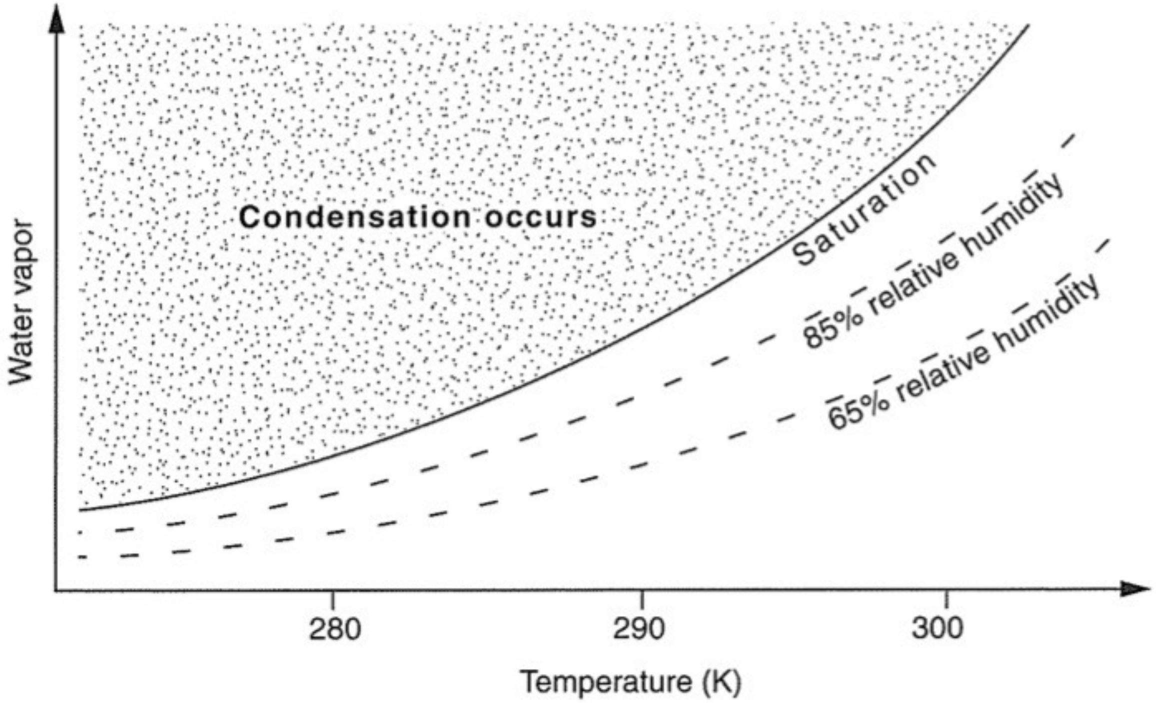


Water vapour in the atmosphere

- Water vapour plays a key role in planetary atmospheres
  - Is a very effective greenhouse gas and therefore affects the atmospheric radiative transfer and vertical energy transport
  - Provides a way of storing/releasing energy in the form of "latent heat" during the transitions between liquid and vapour phases
  - Affects the efficiency of the meridional energy transport

- The atmospheric water vapour content depends on the presence of
  - Surface reservoirs, sources or sinks of liquid water
  - Atmospheric temperature
  - Biological feedbacks (e.g. vegetation)
  - Mechanisms of containment of atmospheric water vapour

Water vapour and temperature

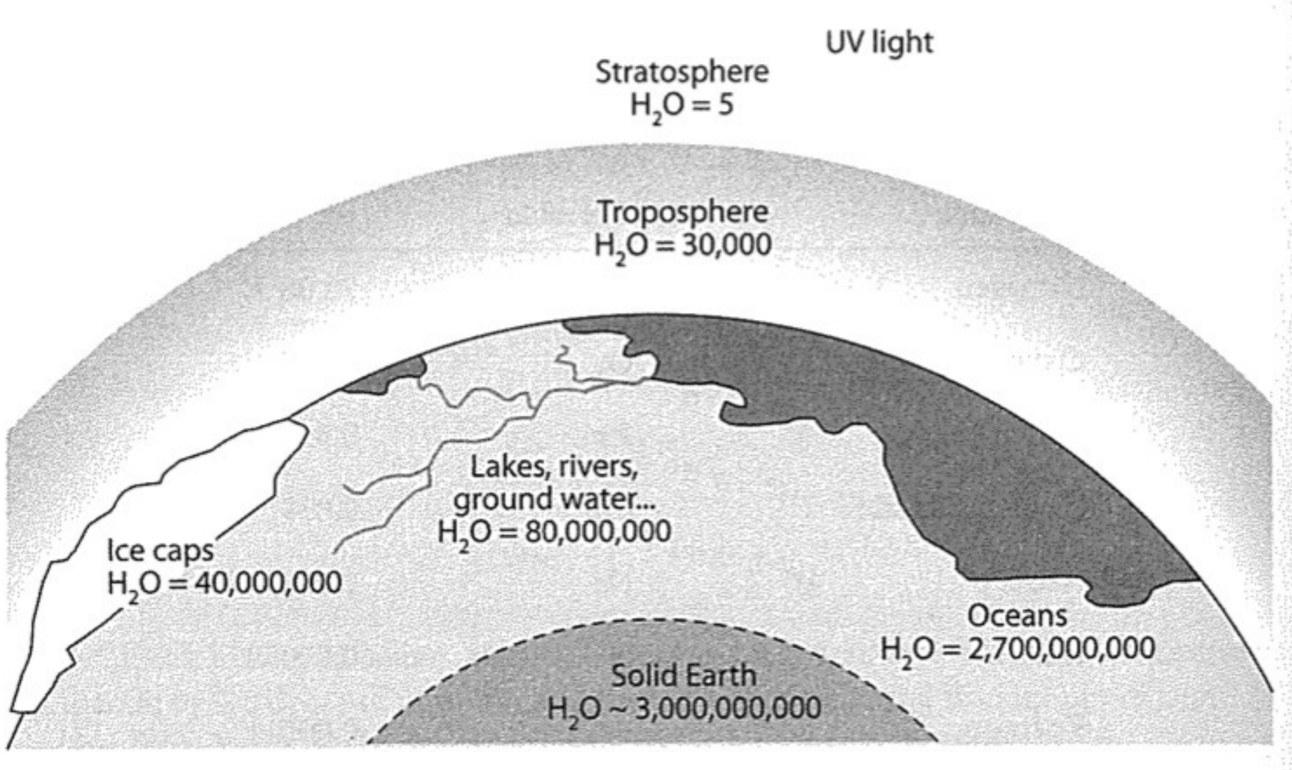


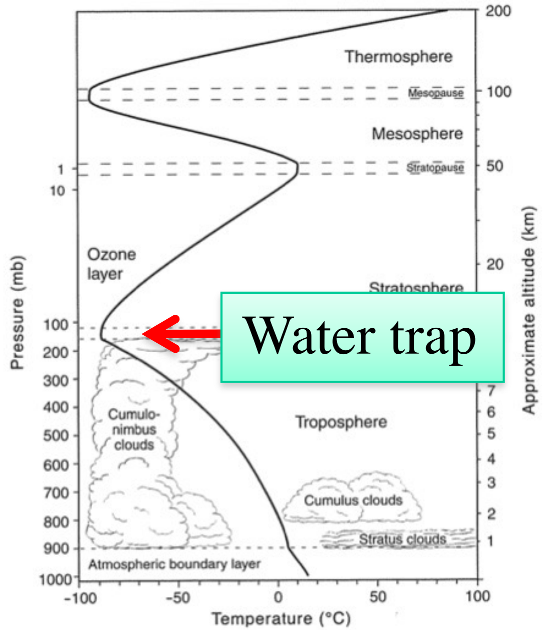
Clausius-Clapeyron equation (simplified form)

$$p_{sat}(T) = p_{sat}(T_0)e^{-\frac{L}{R_A}\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

R: gas constant; *L*: latent heat constant

Mechanisms of containment of atmospheric water vapour
The water trap on Earth





Thanks to the negative temperature gradient in the troposphere, all water precipitates in the higher tropospheric layers (due to Clausius-Clapeyron), and none migrates to the upper atmosphere

In absence of the water trap, water vapour could be photodissociated in the highest layers and the hydrogen would be lost to space