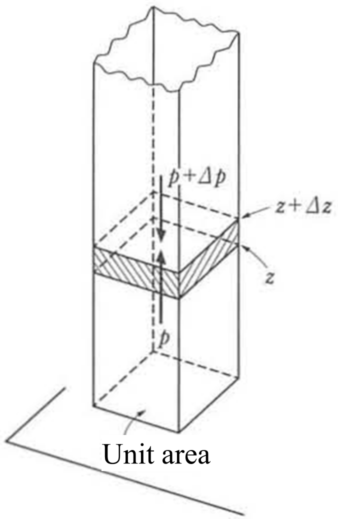
3. Atmospheric vertical structure

Heating	Radiation	Conduction	Convection
Heat transfer	Electromagnetic waves	Molecular motions	Fluid motions
Condition	Including vacuum	Continuum	Gravity
Governing law	Planck's law (Stefan-Boltzmann, Wien)	Molecular diffusion	Laminar advection Turbulent (eddy) diffusion
Temperature profile	dependent on optical depth (exponential)	exponential	isentropic (upward decreasing)
Constituents	–	Gravity separation	Homogenizing

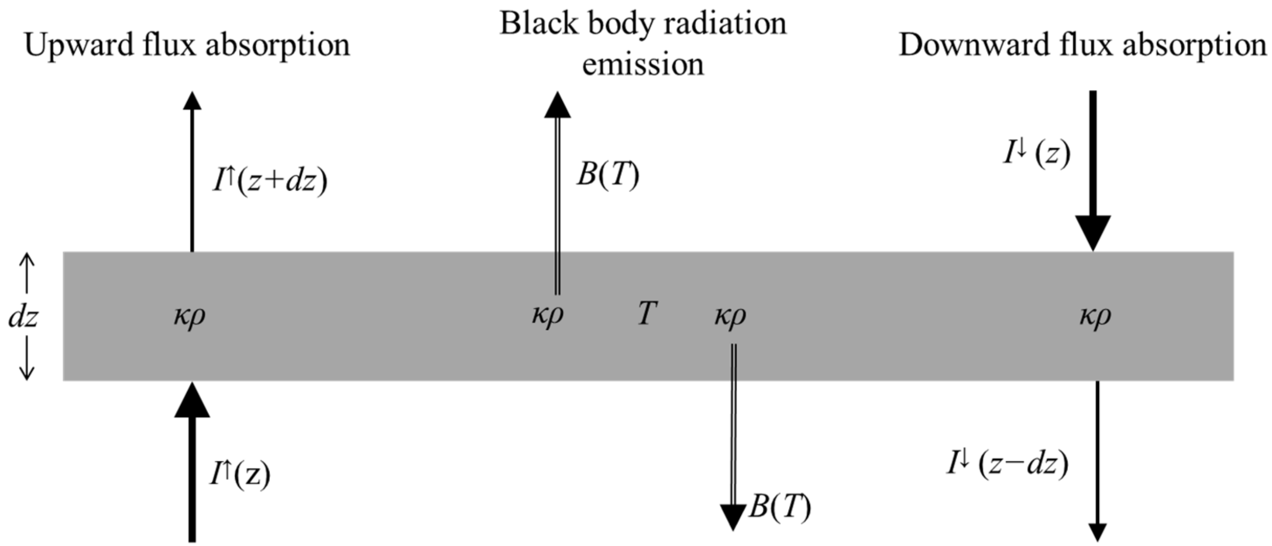
Hydrostatic equilibrium

←もっと説明→

"Two-Stream" Approximation for "gray" atmosphere



$$\Delta p = -g\rho\Delta z$$



Vertical distribution of pressure

- Hydrostatic equation:

$$\frac{dp}{dz} = -g\rho$$

- Rewriting ρ by the ideal gas equation (Boyle-Charles law): $p = R\rho T$

$$\frac{dp}{dz} = -\frac{g}{RT}p \quad \rightarrow \quad \frac{1}{p}\frac{dp}{dz} = -\frac{g}{RT} \equiv -\frac{1}{H}, \qquad H \approx \frac{287\ [\mathrm{J\ K^{-1}kg^{-1}}] \cdot 250\ [K]}{9.8\ [\mathrm{ms^{-2}}]} \approx 7[\mathrm{km}]$$

- Differentiation of logarithmic function:

$$\frac{1}{y}\frac{dy}{dx} = \frac{d\log_e y}{dx} = \frac{d\ln y}{dx} \quad \rightarrow \quad \frac{d\ln p}{dz} = -\frac{1}{H}$$

- Integration:

$$\ln p = -\frac{1}{H}z + \mathrm{const.}$$

- Exponential function:

$$p = e^{-\frac{1}{H}z+\mathrm{const.}} = e^{\mathrm{const.}} \cdot e^{-\frac{1}{H}z} \equiv \mathrm{const.}' \cdot e^{-\frac{z}{H}}$$

- Bottom boundary condition:

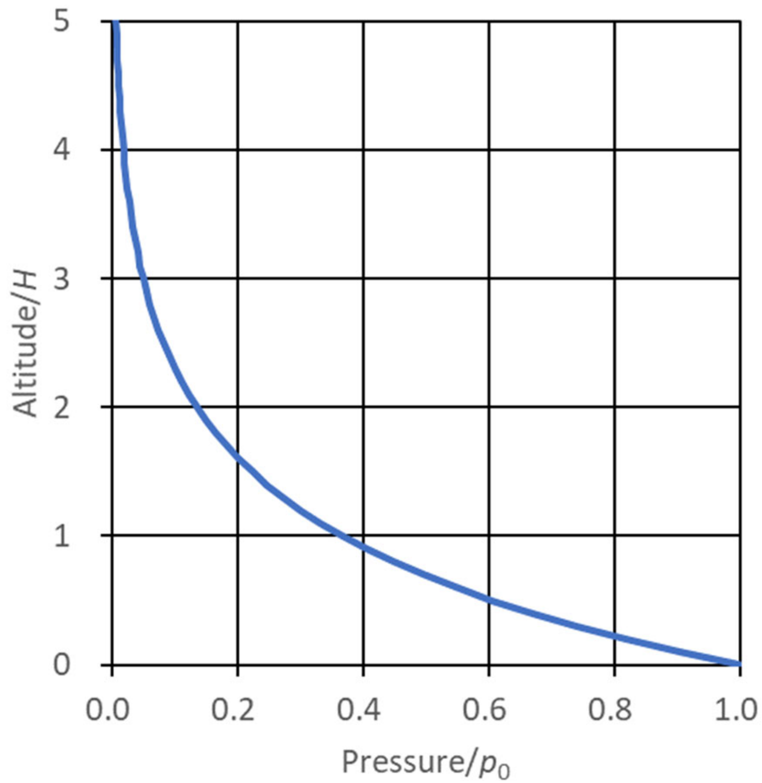
$$p = p_0 \quad \text{at} \quad z = 0 \quad \rightarrow \quad \mathrm{const.}' = p_0$$

- Solution:

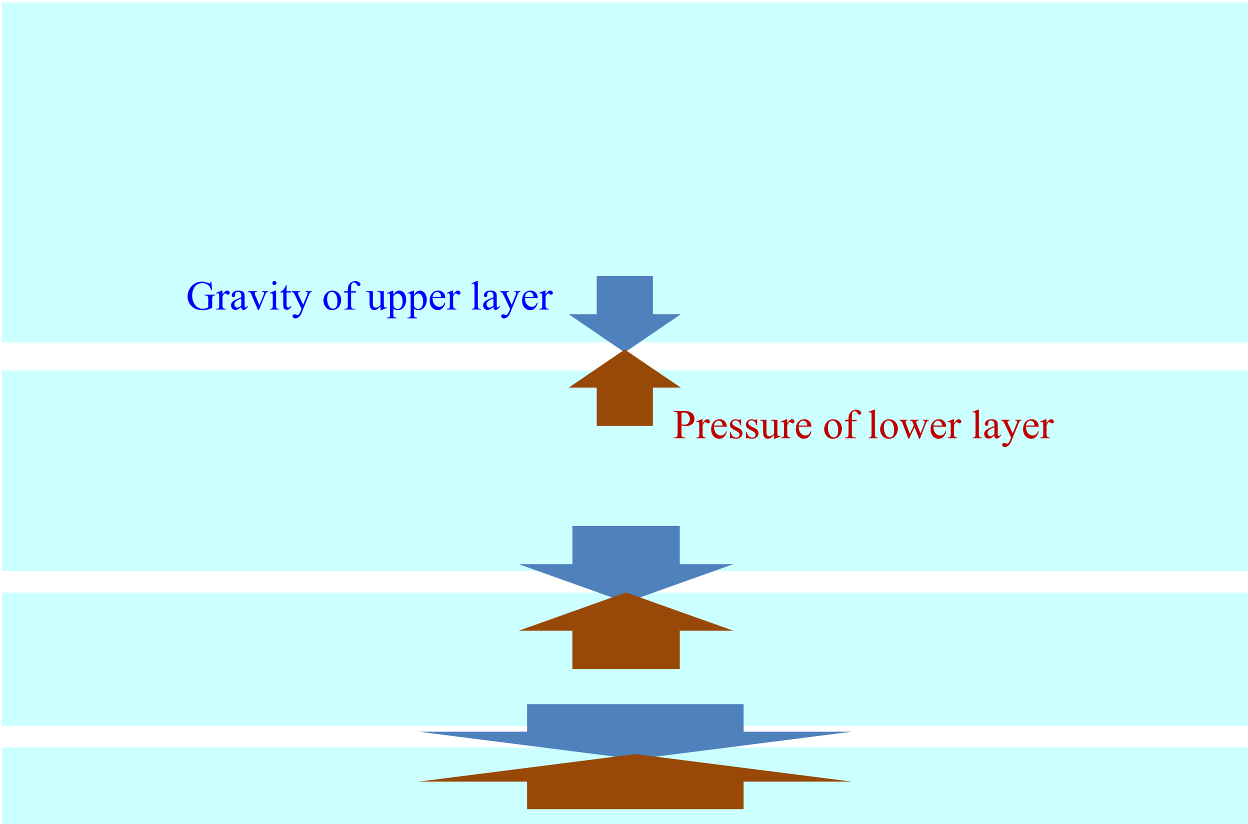
$$p = p_0 \cdot e^{-\frac{z}{H}}$$

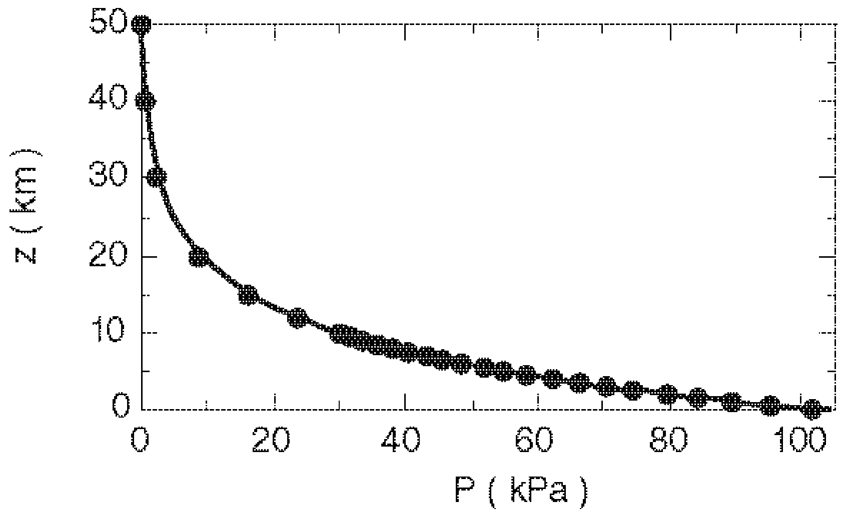
- Meaning of the "scale height" H:

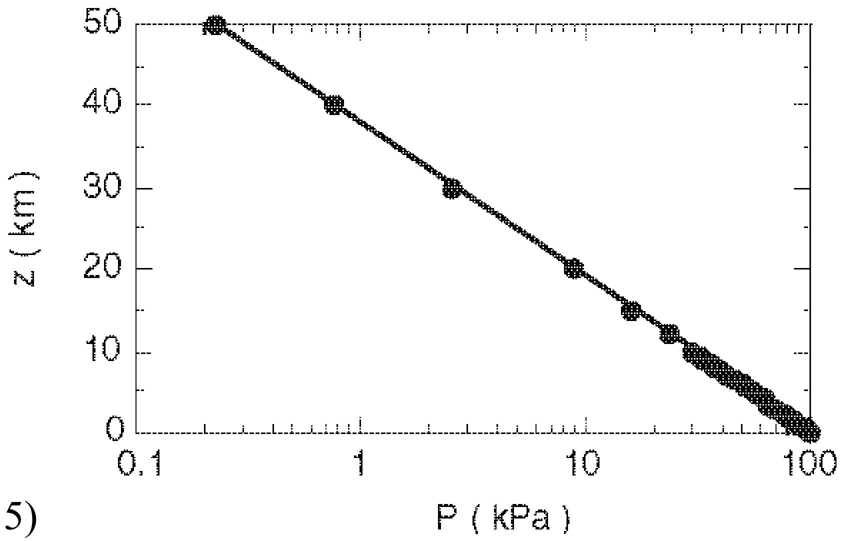
$$p = \frac{p_0}{e}, \frac{p_0}{e^2}, \cdots, \frac{p_0}{e^n}, \cdots \qquad \text{at} \quad z = H, 2H, \cdots, nH, \cdots$$



Pressure upward exponential decrease (Hydrostatic equilibrium)

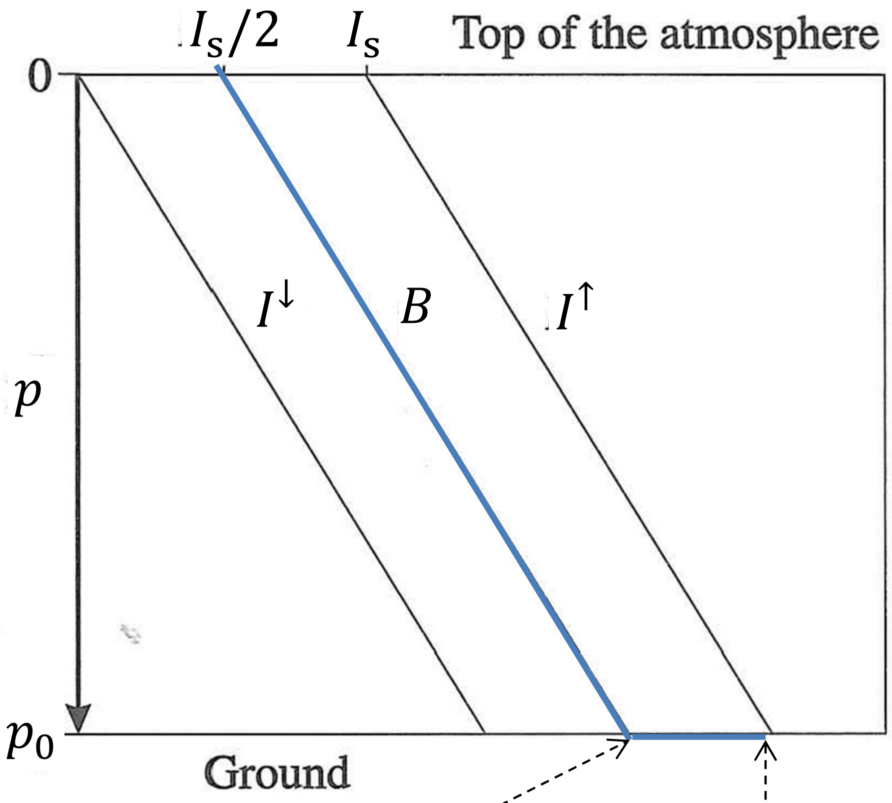






(Stull, 2015)

$$B(p) = \frac{I_s}{2}\left(\frac{\kappa}{g}p + 1\right) \longrightarrow T(p) = \left(\frac{B}{\sigma}\right)^{1/4} = \left[\frac{I_s}{2\sigma}\left(\frac{\kappa}{g}p + 1\right)\right]^{1/4}$$

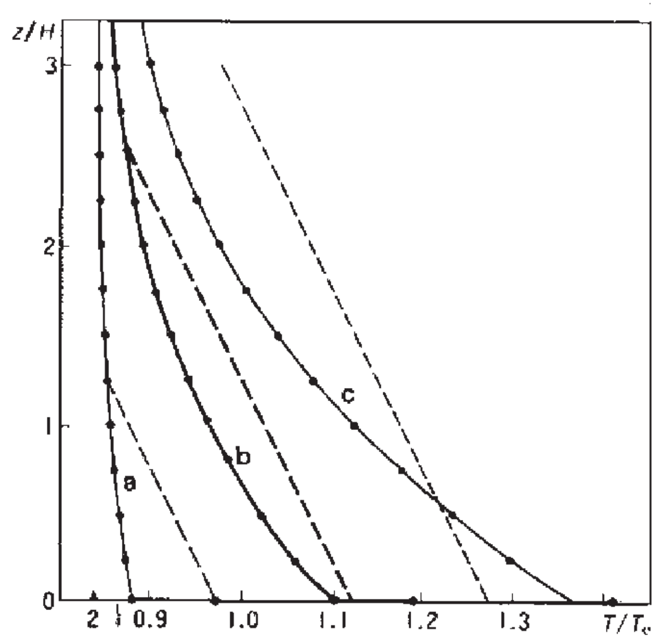


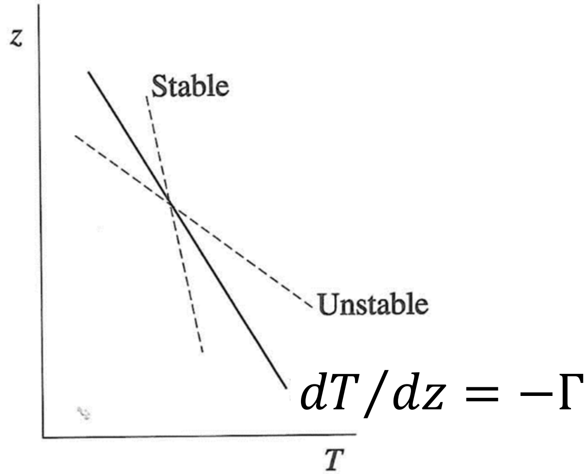
Atmos. Temp. at the bottom

$$\left[\frac{I_s}{2\sigma}\left(\frac{\kappa}{g}p_0 + 1\right)\right]^{1/4} = \left(\frac{B(p_0)}{\sigma}\right)^{1/4}$$

Ground temperature

$$T = \left(\frac{I^{\uparrow}(p_0)}{\sigma}\right)^{1/4} = \left(\frac{B(p_0) + I_s/2}{\sigma}\right)^{1/4}$$





1-dimensional climate: Radiative-convective equilibrium

- Radiative equilibrium

  $Q = \partial/\partial z\, [S + I^{\uparrow} - I^{\downarrow}] = 0$

  (S$\sim$0 for $z \neq 0$, ozone layer)

  $\Rightarrow \partial/\partial p\, [\sigma T^4] \sim S/p_1$

  $\Rightarrow -\partial T/\partial z$ increases downward

- Convective equilibrium (adjustment)

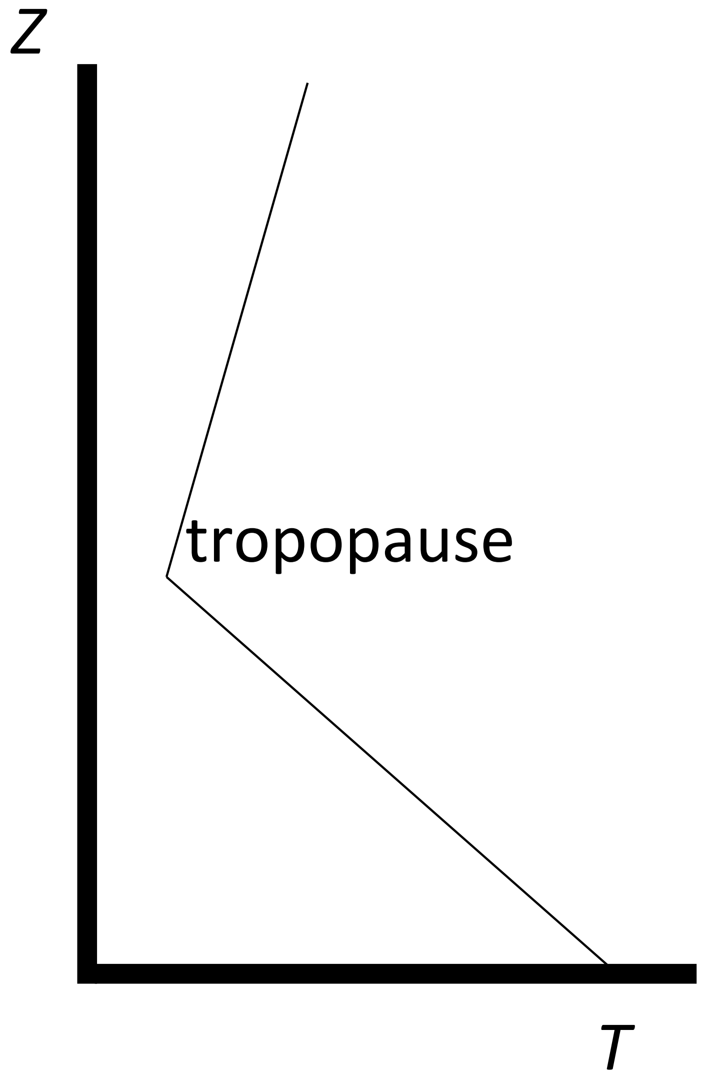
  $\partial \Theta/\partial z = 0$

  $\Rightarrow$ (dry) adiabatic lapse rate:

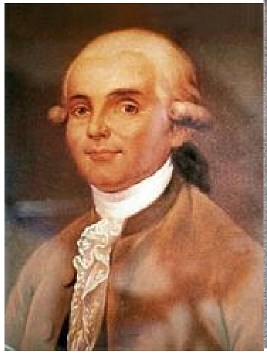
  $-\partial T/\partial z = g/C_p \fallingdotseq 10$ K/km

- Separation of stratosphere (radiative)

  and troposphere (convective)



Balloons, vertical observations



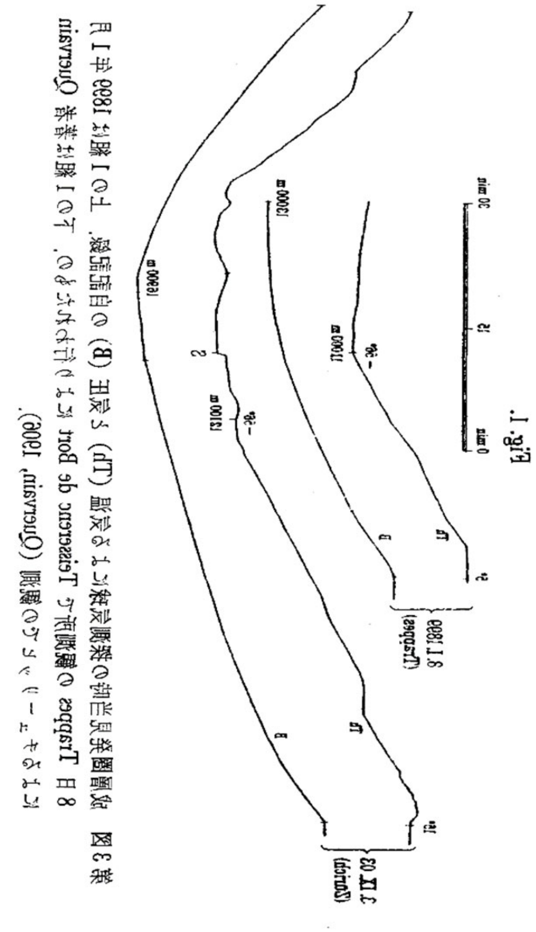

Joseph-Michel Montgolfier (1740 – 1810)
Jacques-Étienne Montgolfier (1745 – 1799)

Jacques Alexandre César Charles
(1746 – 1823)

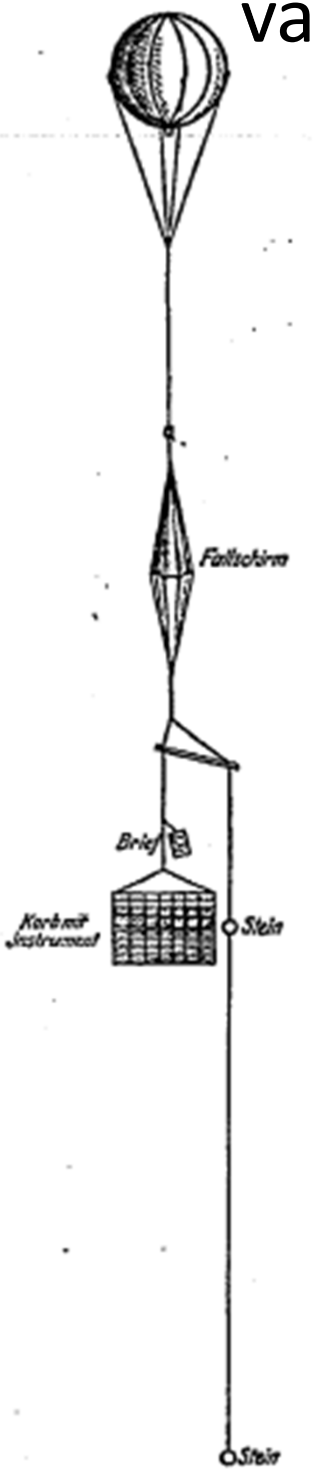
Leon Philippe Teisserenc de Bort
(1855 – 1913)

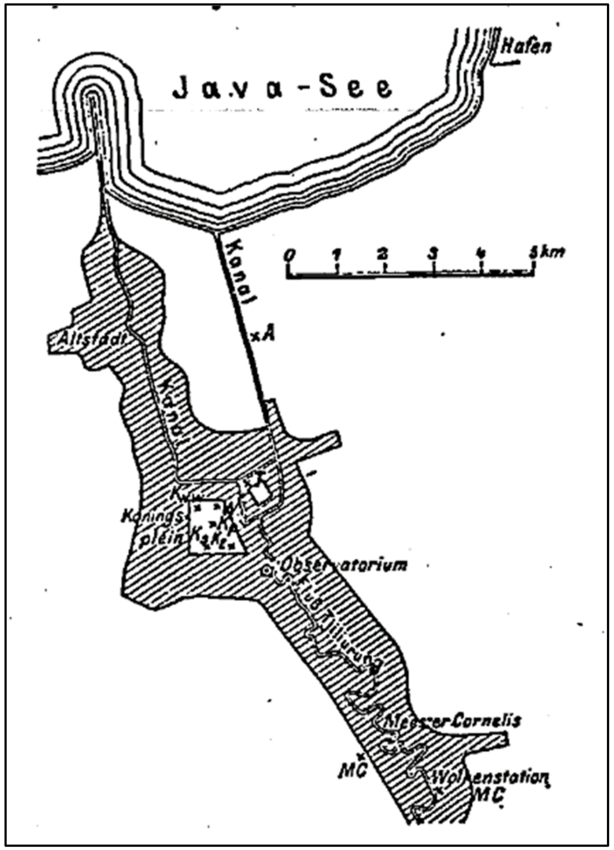
Montgolfière (hot air type) balloon
(at Annonay in June 4, 1783)

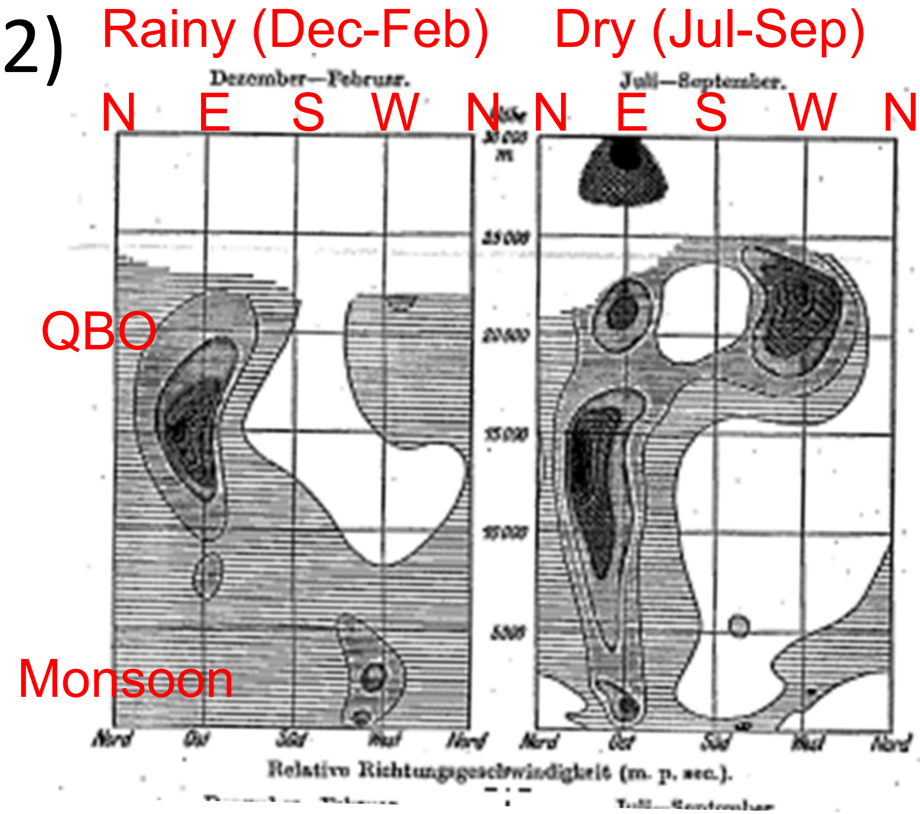
Charlière (light gas type) balloon
(at Paris in December 1, 1783)



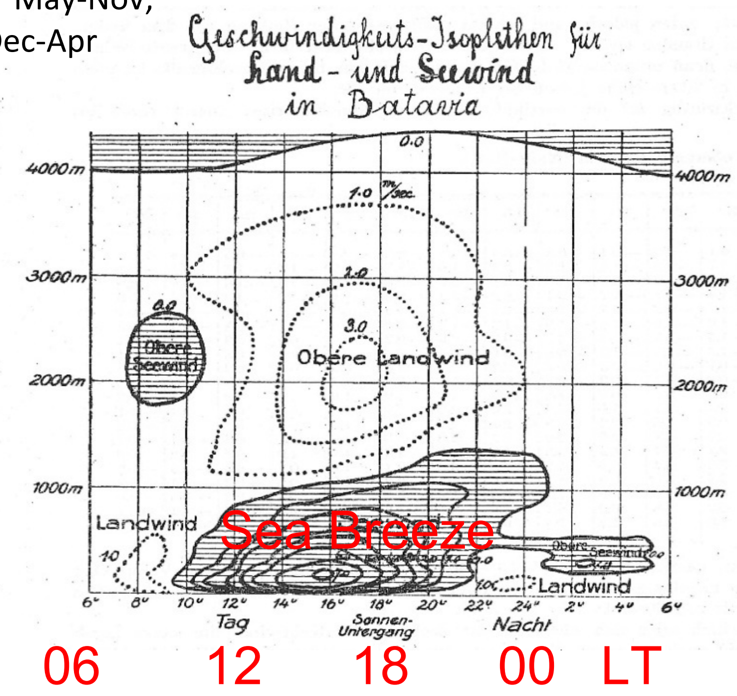
van Bemmelen (1913, 1922)





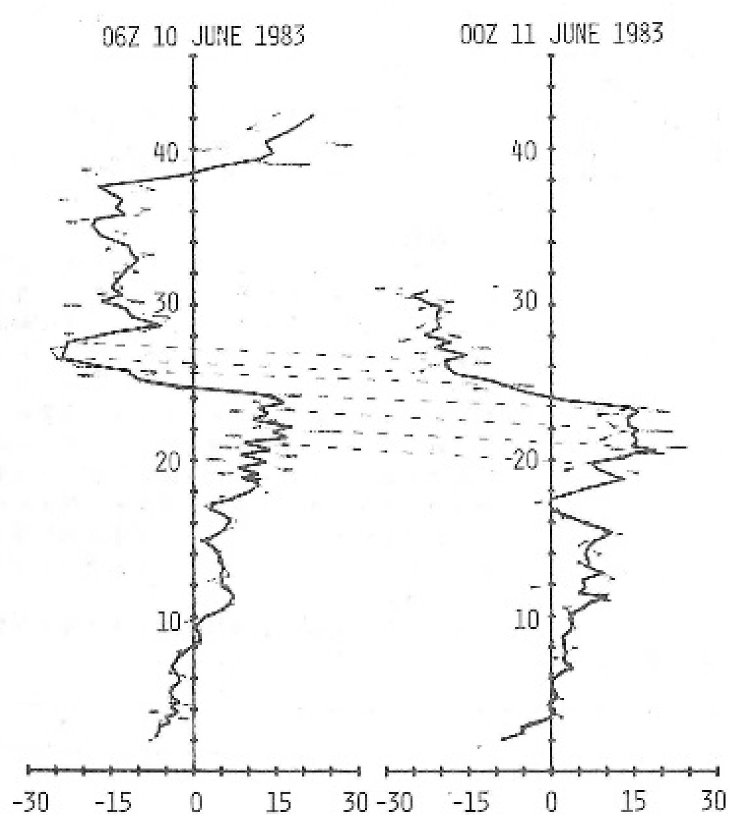


06-24 LT hourly for May-Nov;
08, 14, 19 LT for Dec-Apr
during 1905-15



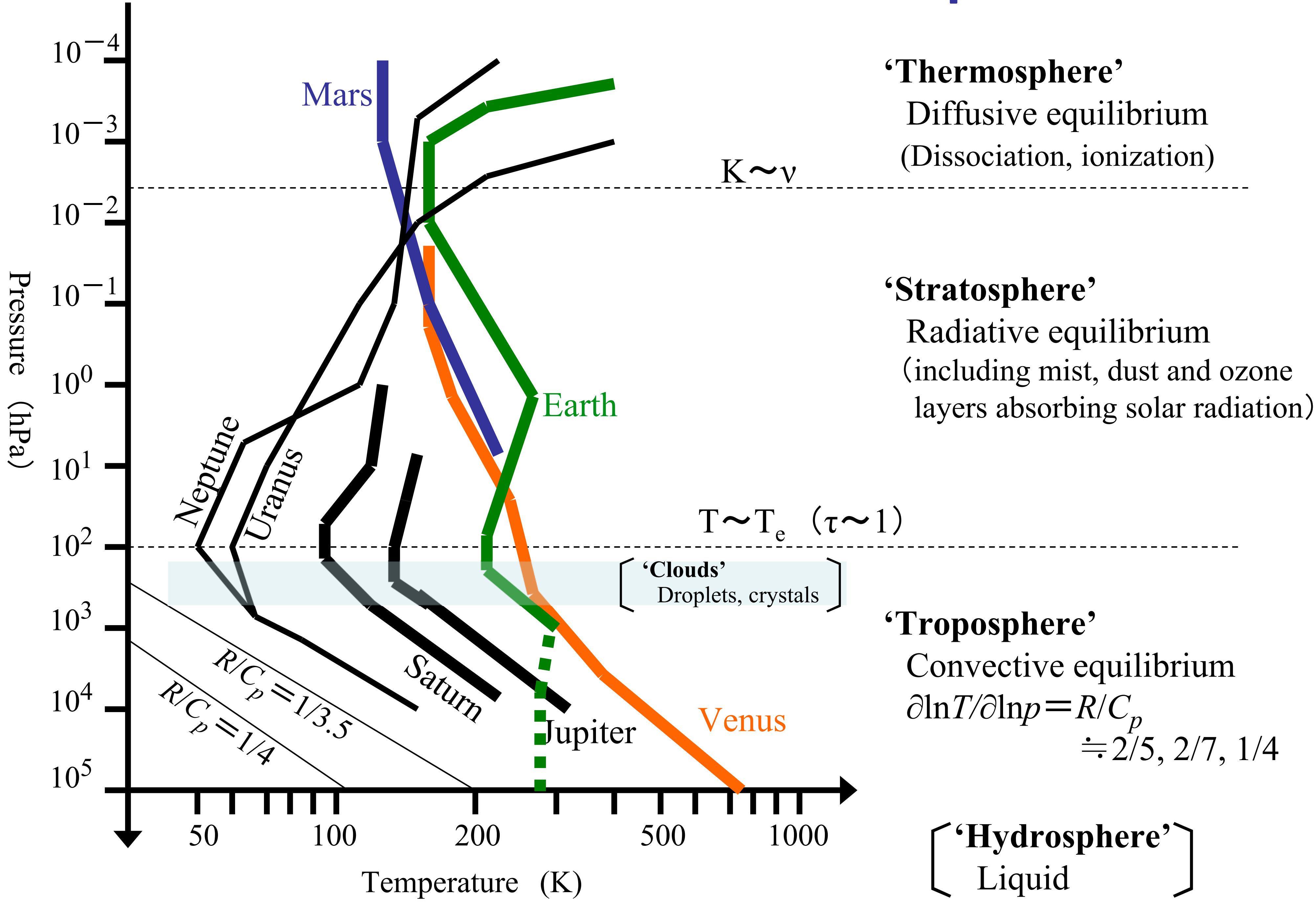
Balloon observation of Solar eclipse

(11 June 1983; Watukosek, JaTim; ISAS, NAO, LAPAN)

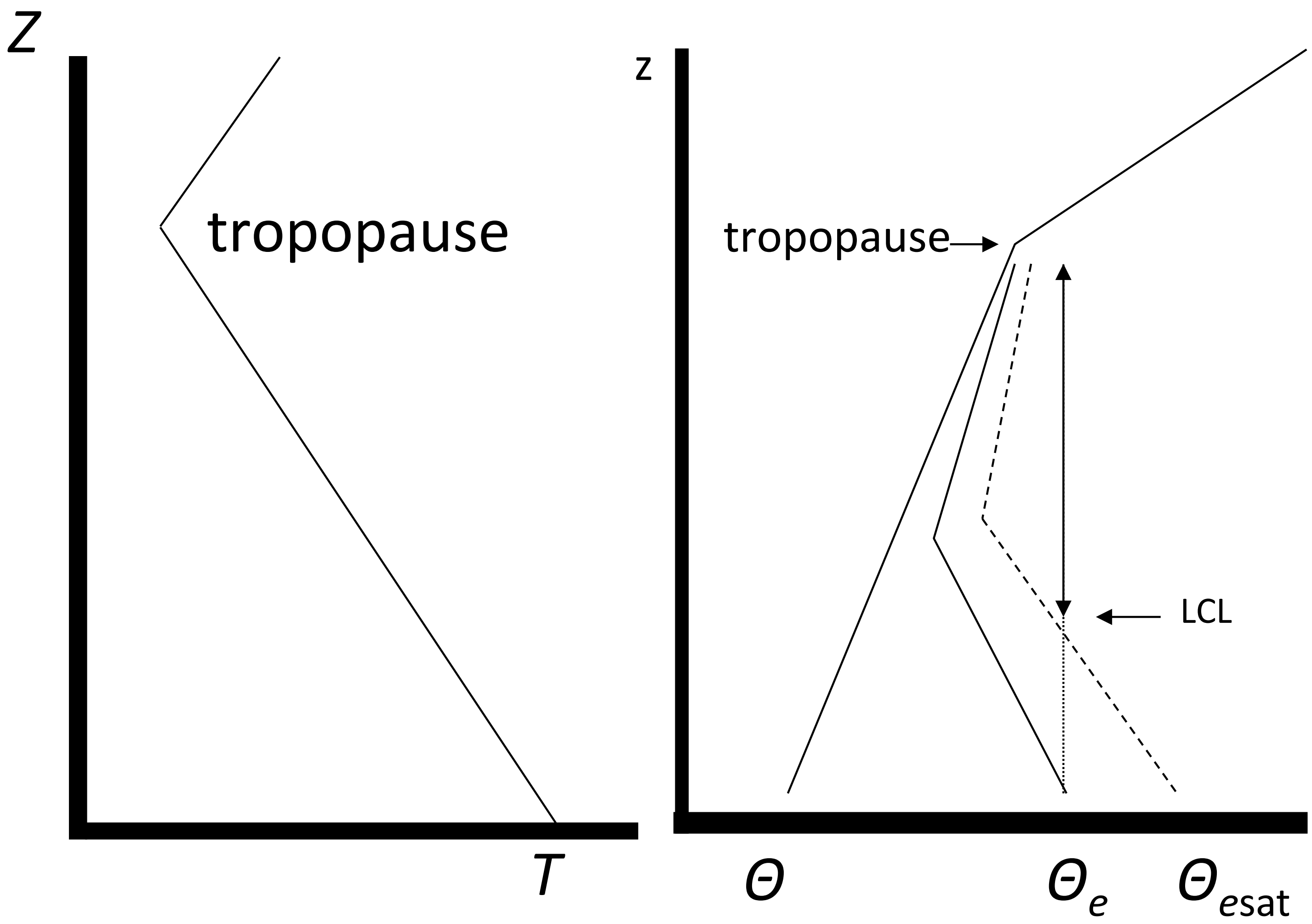


Vertical profile of zonal wind velocity
(Yamanaka et al., Oct 1983; MSJ)

Vertical structure of atmosphere



Equivalent potential temperature



(Dry) Adiabatic process:
Thermodynamic equation (5)

$$C_p \frac{D\theta}{Dt} = 0 \;\rightarrow$$

$$\theta = T \cdot \left(\frac{p_{00}}{p}\right)^{R/C_p}$$

Moist(Pseudo-)adiabatic process:
(5) and moisture eq. (6):

$$C_p \frac{D\theta_e}{Dt} = LS/T \;\rightarrow$$

$$\theta_e = \theta \cdot \exp\left(\frac{Lr_s}{C_p T}\right)$$

"Paradox" of conditional instability:
- Convection generated spontaneously only when cloud appears.
- Cloud becomes most active when convection is developed.

$\Rightarrow$ *Forced motions (waves, circulations), or CISK*