# Cloud microphysics

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# Cloud formation and cloud dynamics

Cloud movies by B. Mayer

# Cloud types


http://www.wolkenatlas.de/

# Rain drops

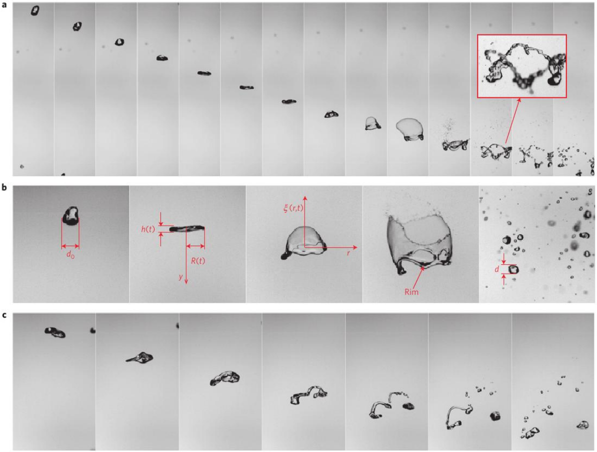
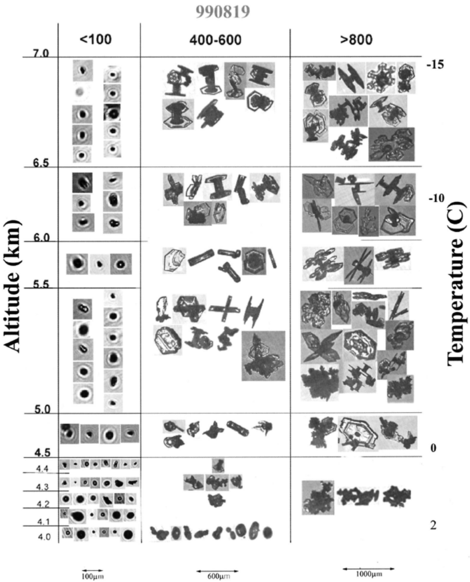



**Figure 2 | Topological changes of falling drops and fragmentation.** Top row: series of events of the fragmentation of a $d_0 = 6$ mm water drop falling in an ascending stream of air. The time interval between each image is $\Delta t = 4.7$ ms. The sequence shows first the flattening of the drop into a pancake shape, the inflation of a bag bordered by a thicker corrugated rim, its break-up and the destabilization of the rim itself (highlighted in the inset), leading to disjointed drops distributed in size. Middle row: a similar series defining the initial diameter $d_0$, the bag thickness $h(t)$, its radius $R(t)$ and shape $\xi(r,t)$, and the final drop size $d$. Bottom row: the formation of a bag is not mandatory for the initial drop to break up. However, its fragmentation is always preceded by a change of topology into a ligament shape, which often occurs without bag inflation. The sequence is for $d_0 = 6$ mm and $\Delta t = 7.9$ ms.

Villermaux et al. Nature Physics, 2009

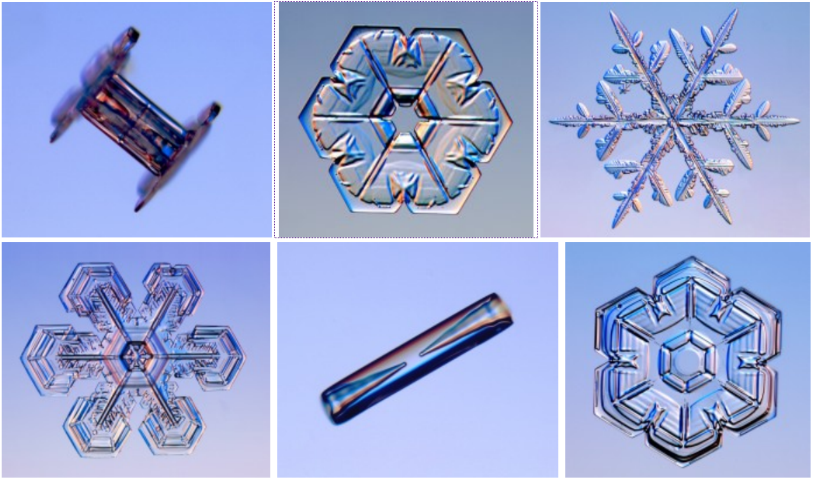
# Ice crystals




In situ measurements of ice crystals in a tropical cirrus cloud

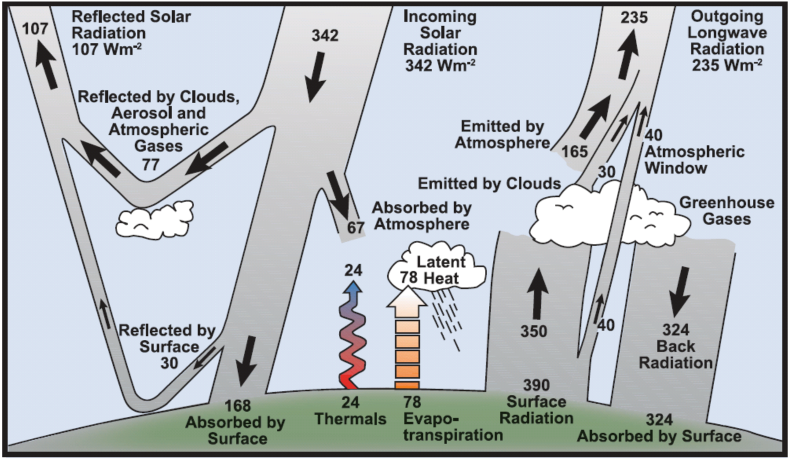
Heymsfield et al., Journal of Atmospheric Sciences, 2002

# Snow flakes



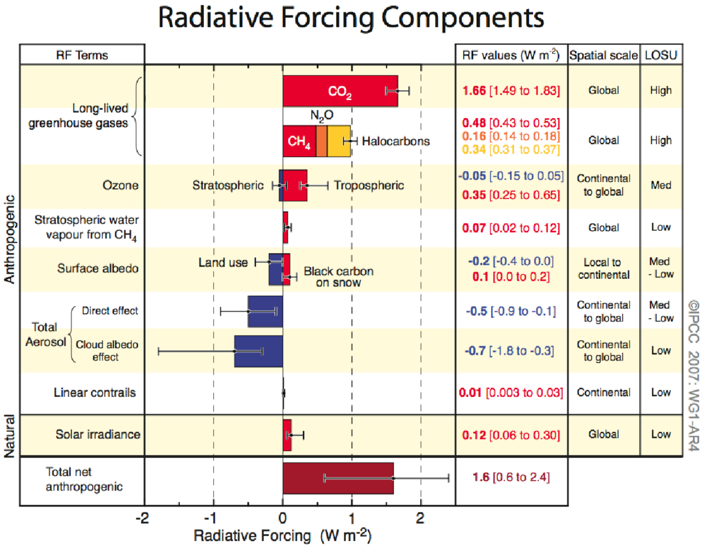
`www.snowflakes.com` by K.G. Libbrecht

# Energy balance of the Earth



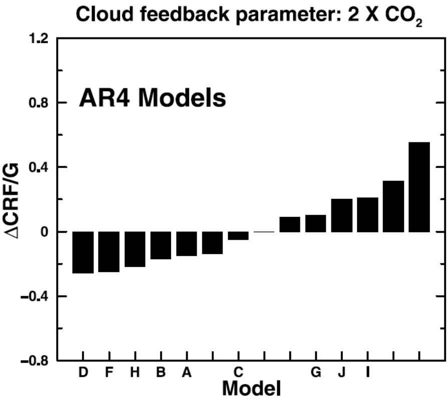

IPCC report, 2007

# Impact of clouds on climate change




IPCC report 2007

# IPCC Bericht 2007



Ringer et al., GRL 2006

*"Cloud feedbacks (particularly from low clouds) remain the largest source of uncertainty."*

IPCC Report 2007, Technical Summary

# Overview of cloud physics

- Atmospheric thermodynamics
- Microphysics of warm clouds
  - Nucleation of water vapor by condensation
  - Growth of cloud droplets in warm clouds (condensation, fall speed of droplets, collection, coalescence)
  - formation of rain
- Microphysics of cold clouds
  - homogeneous nucleation
  - heterogeneous nucleation
  - contact nucleation
  - crystal growth (from water phase, riming, aggregation)
  - formation of precipitation
- Observation of cloud microphysical properties
- Parameterization of clouds in climate and NWP models

# Literature

John M. Wallace and Peter V. Hobbs. *Atmospheric Science, An introductory survey*. Elsevier, 2006.

R. R. Rogers. *A short course in cloud physics*. Pergamon Press, 1976.

Hans R. Pruppacher and James D. Klett. *Microphysics of clouds and precipitation*. Springer, 1996.

IPCC. Climate change 2007. Technical report, Intergovernmental Panel of Global Climate Change, 2007.

Additional publications and slides on website:
`www.meteo.physik.uni-muenchen.de/~emde/doku.php?id=teaching:cloud_microphysics:cloud_microphysics`

# Exam

Written exam in last week of semester: 9th February 2012, 14-16 h

Please let me know if date is inconvenient!

# Gas laws and the ideal gas equation

Sir Robort Boyle (1627–1691)

Jacques Charles (1746–1823)

$$pV = mRT \qquad p\alpha = RT \qquad pV = nR^{*}T \qquad p = n_0 kT$$

John Dalton (1766–1844)

Amedeo Avogadro (1776–1856)

Ludwig Boltzmann (1844–1906)

Images from Wikipedia

# The hydrostatic equation

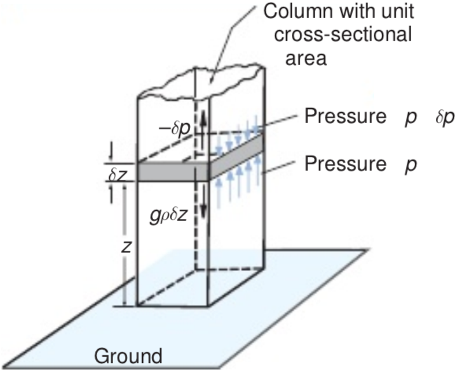



Figure from Wallace and Hobbs

$$\frac{\partial p}{\partial z} = -g\rho \qquad g dz = -\alpha dp$$

Sir Issac Newton (1642–1727)
Image from Wikipedia

# First law of thermodynamics

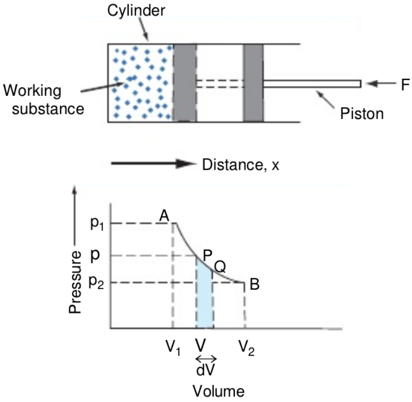



**Fig. 3.4** Representation of the state of a working substance in a cylinder on a $p$–$V$ diagram. The work done by the working substance in passing from P to Q is $p\,dV$, which is equal to the blue-shaded area. [Reprinted from *Atmospheric Science: An Introductory Survey*, 1st Edition, J. M. Wallace and P. V. Hobbs, p. 62, Copyright 1977, with permission from Elsevier.]

Figure from Wallace and Hobbs

**energy conservation**

$$
\begin{aligned}
dq &= du + dw \\
dq &= du + p d\alpha \\
dq &= c_p dT - \alpha dp \\
\dots
\end{aligned}
$$

# Adiabatic processes

adiabatic = change in physical state without heat exchange $\Rightarrow dq = 0$

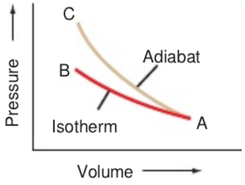



Fig. 3.5 An isotherm and an adiabat on a $p$–$V$ diagram.

Figure from Wallace and Hobbs

$$dq = du + pd\alpha$$

T rises in adiabatic compression

T=const. in isothermal process

$$T_C > T_B \Rightarrow p_C > p_B$$