Sonia I. Seneviratne and Christoph Schär

**Land-Atmosphere-Climate Interactions**

Winter term 2006/07

# Land-surface processes in the global energy and water cycles. Part (c)


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## Outline

**Atmospheric transport**

- **residence times**
- **key circulations**
  - Hadley circulation
  - baroclinic eddies
- **analysis of transport in atmospheric models**
  - trajectories
  - integrated water flux
  - tagging of water vapor

**Precipitation**

**Energy and water movement in soils**

**Infiltration and formation of runoff**

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## Residence time and atmospheric transport

**Mean residence time of $H_2O$ molecules in the atmosphere: ~8 days**

**Mean transport distance: ~7000 km (assuming 10 m/s)**

**Fraction of land evapotranspiration: ~12%**

⇒ **In general regions of high evaporation are not identical to regions of high precipitation**

⇒ **Usually evaporation contributes little to precipitation in same region**

⇒ **Atmospheric transport is decisive. Requires an understanding of the general circulation of the atmosphere.**

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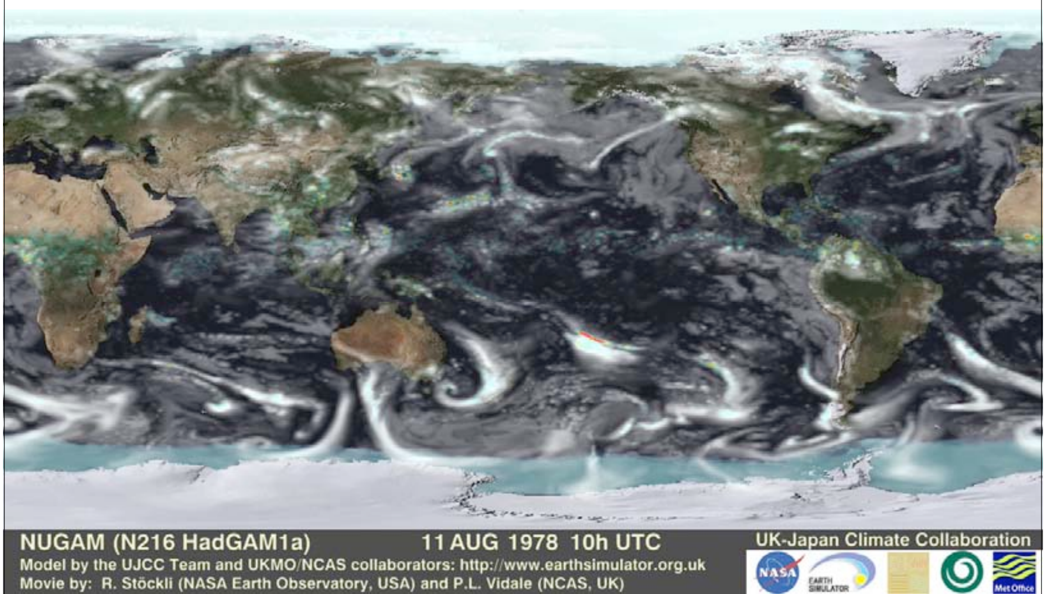
## Visualization of atmospheric moisture transport

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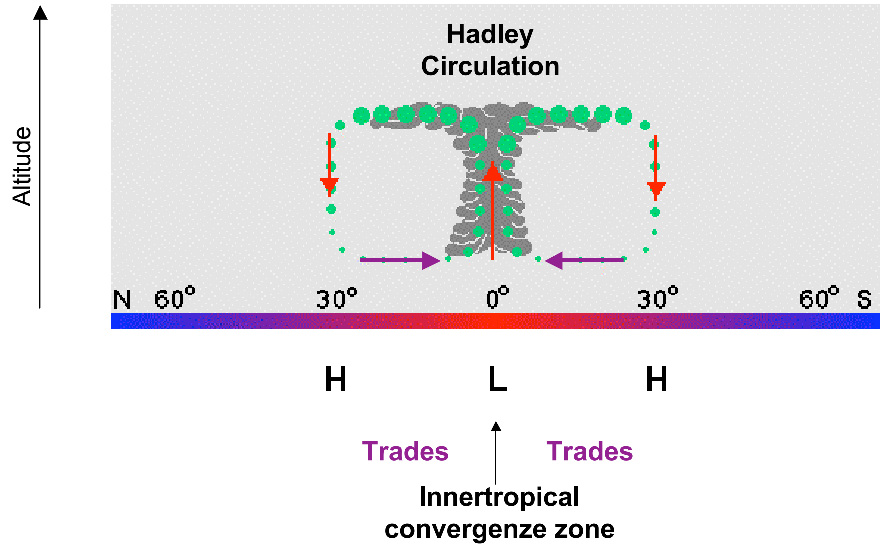
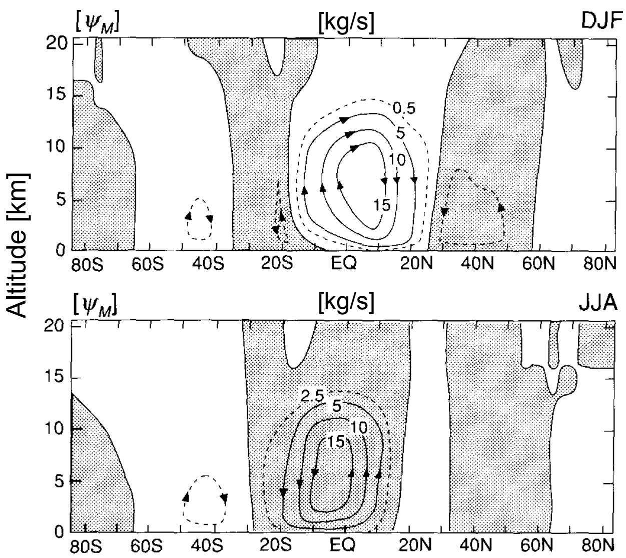
# Hadley Circulation








# Mean meridional circulation of the atmosphere




Zonal-mean mass flux

- Hadley circulation is much stronger on winter hemisphere
- Innertropical convergence zone (ITCZ) is displaced towards summer hemisphere (determines rainy seasons)
- Mean meridional circulation in extratropics is weak

(Hartmann, 1994)

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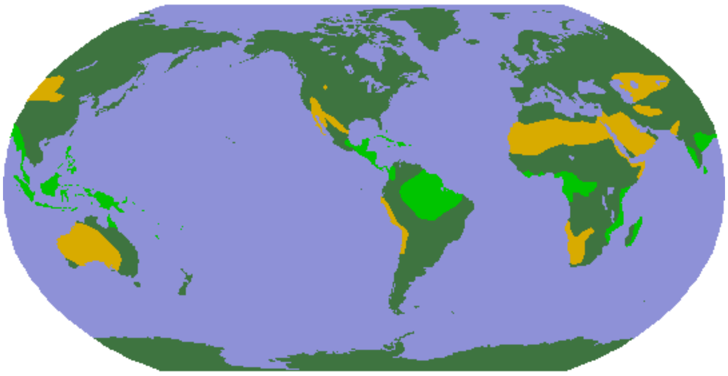
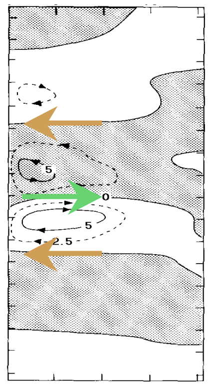
# Role of Hadley circulation for climate zones



Deserts  Rainforests




**Meridional circulation (Yearly mean)**

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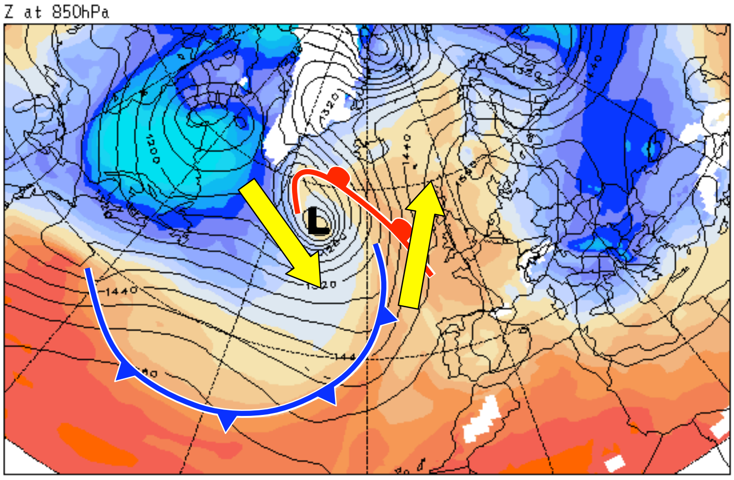
# Transport in extratropical cyclones (baroclinic eddies)

Z20020104_00 2002/01/04 Fr:00(+12)
Z at 850hPa




Example of a low-pressure system at 850 hPa (1.5 km above ground)

Temperature: colour

Geopotential: contours

T+273.15 at 850hPa
P20020104_00 2002/01/04 Fr:00(+12)

**Ahead of cyclone: transport of warm air from south to north**
**Behind cyclone: transport of cold air from north to south**

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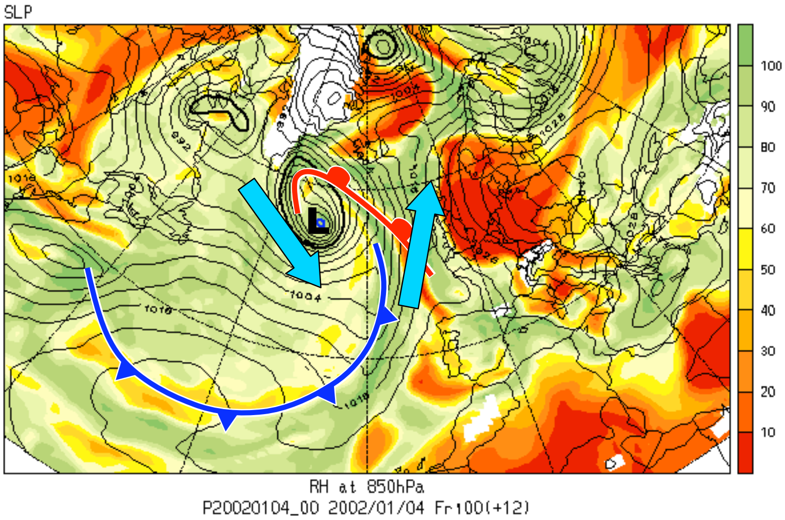
# Relative Humidity




Rel. humidity 850 hPa: color

Surface pressure: contours

**Transport of moist air toward north and dry air towards south**

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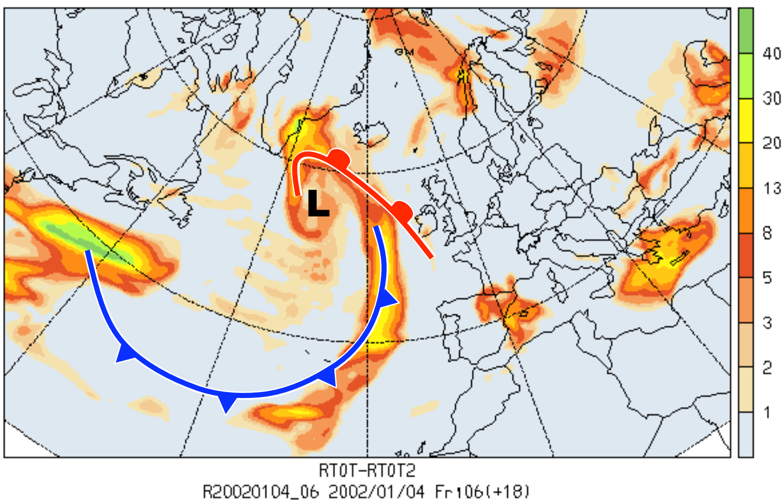
# Associated precipitation




**mm / 12 h**

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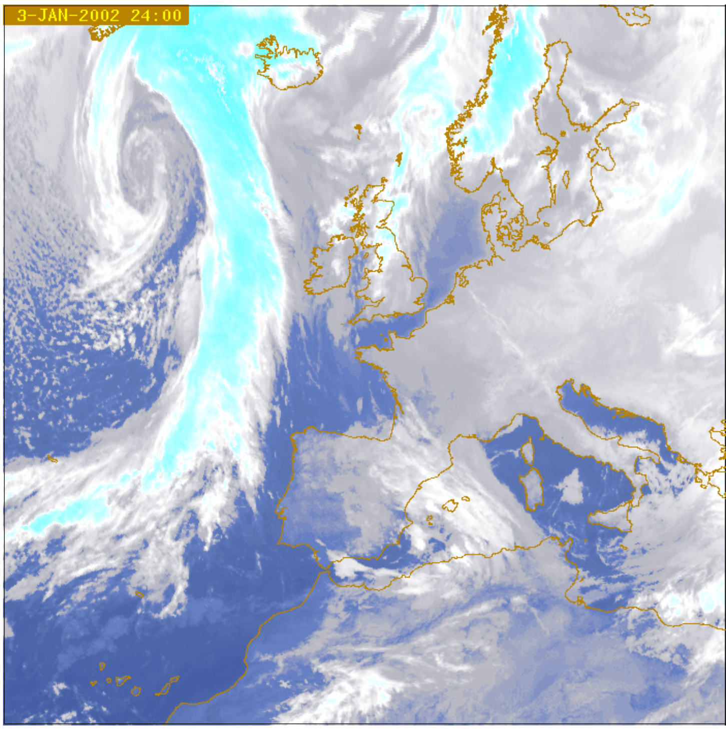


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## IR Satellite Picture

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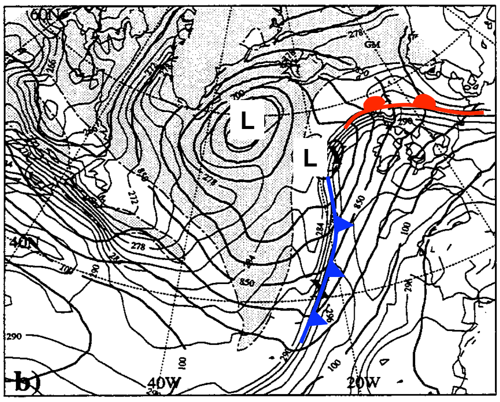
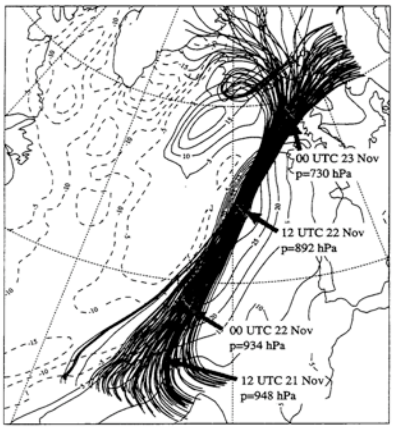
## Water transport in fronts and cyclones




22. Nov. 1992, 18 UTC:
900 hPa geopotential (bold lines)
and temperature (thin lines)




48 h trajectories,
950 hPa –> 730 hPa

**In general, the atmospheric transport in the extratropics takes place in comparatively narrow streams (referred to as conveyor belts or atmospheric rivers)**

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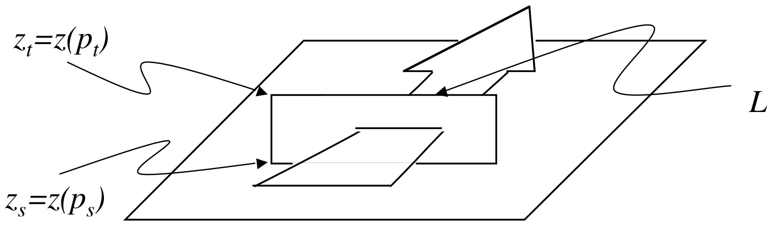
(Wernli 1994)

# Integrated atmospheric moisture flux

Moisture flux across an area $(0 \le x \le L,\ p_s \le p \le p_t)$




Massflux

$$\mathbf{F} = \rho_a\ q_v\ \mathbf{v}$$

**v**$=(u,v,w)$ = velocity
$q_v$ = specific humidity
$\rho_a$ = density of moist air
$v_n$ = normal compoment of **v**

Integration

$$F_{tot} = \int_0^L \int_{z_s}^{z_t} \rho_a\, q_v\, v_n\, dz\, dx$$





Change of integration variable with hydrostatic relation

$$\frac{\partial p}{\partial z} = -g\ \rho_a \quad => \quad dz = -\frac{1}{g\ \rho_a}\ dp$$

yields

$$F_{tot} = \frac{1}{g} \int_0^L \int_{p_t}^{p_s} q_v v_n dp\, dx$$

Approxmation:

$$F_{tot} \approx \frac{1}{g}\ q_v\ \ v_n\ \ \Delta p\ \ \Delta x$$

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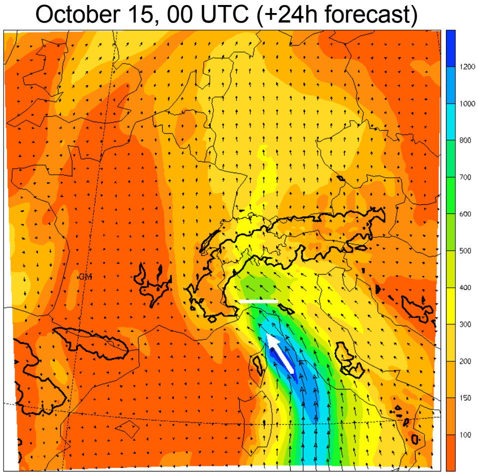
## Example: atmospheric transport during the October 2000 Alpine flood

Vertically integrated moisture flux
October 15, 00 UTC (+24h forecast)



[kg $s^{-1}$ $m^{-1}$]

### Cross section Liguria:

| | | |
|---|---|---|
| Total transport: | | 55,000 $m^3/s$ |
| Comparison: | | |
| Rhein (Rotterdam) | | 2,200 $m^3/s$ |
| Mississippi | (Rank 8) | 18,000 $m^3/s$ |
| Kongo | (Rank 2) | 42,000 $m^3/s$ |
| Amazonas | (Rank 1) | 210,000 $m^3/s$ |

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(Schär and Frei, based on SM forecast of MeteoSchweiz)



# Lagrangian trajectories

Integration of trajectories

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}(x,y,z,t)$$

Forward trajectories: integrate forward in time, from some initial location, with some numerical scheme

$$\mathbf{x}(t) = \mathbf{x}(t=0) + \int_0^t \mathbf{v}(\mathbf{x}(t),t)\ dt$$

$$\mathbf{x}^{n+1} = \mathbf{x}^{n-1} + 2\Delta t \cdot \mathbf{v}(\mathbf{x}^n, t)$$

Backward trajectories:

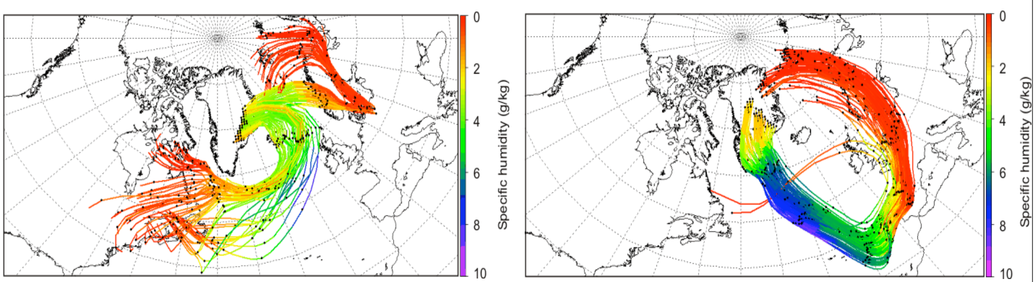
$$\mathbf{x}^{n-1} = \mathbf{x}^{n+1} - 2\Delta t \cdot \mathbf{v}(\mathbf{x}^n, t)$$





# Origin of Greenland precipitation

NAO+ NAO-




**Selected trajectories Feb 1997** **Selected trajectories Feb 1965**

(PhD Thesis Harald Sodemann, 2006, ETH Zürich)

# Tagging of water vapor

Conservation of water vapor

$$\frac{\partial(q_v \rho_a)}{\partial t} + \nabla \cdot (\mathbf{v} q_v \rho_a) = \underbrace{\text{sources} + \text{sinks}}$$

e.g. precipitation, evaporation, formation of droplets from water vapor, etc

Tagging: split $q_v$ into different contributions, for instance

$$q_v = q_v^{land-origin} + q_v^{sea-origin}$$

Each of the components will satisfy an own conservation equation.

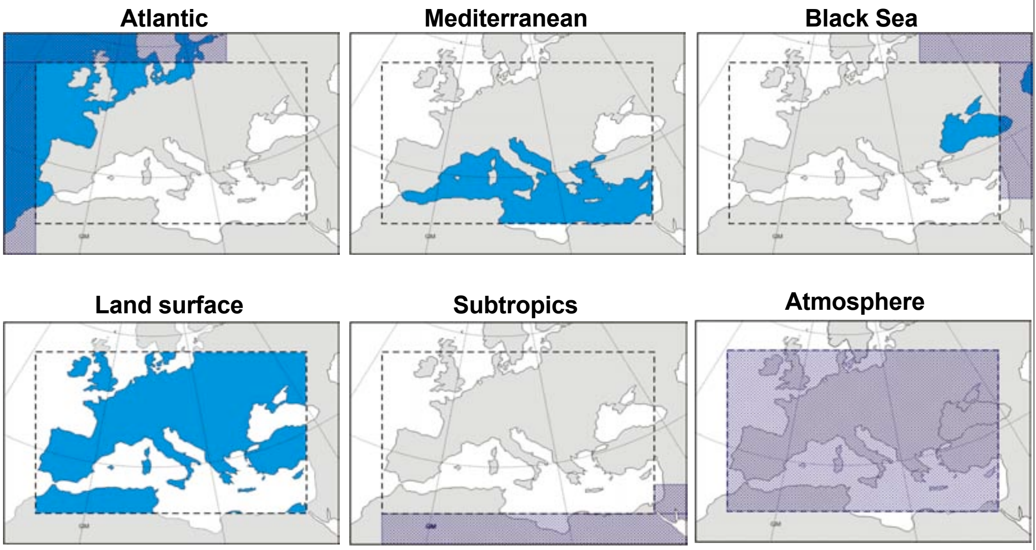




# Where did the moisture come from?

**August 2002, Dresden**

# Tagging with 6 moisture sources

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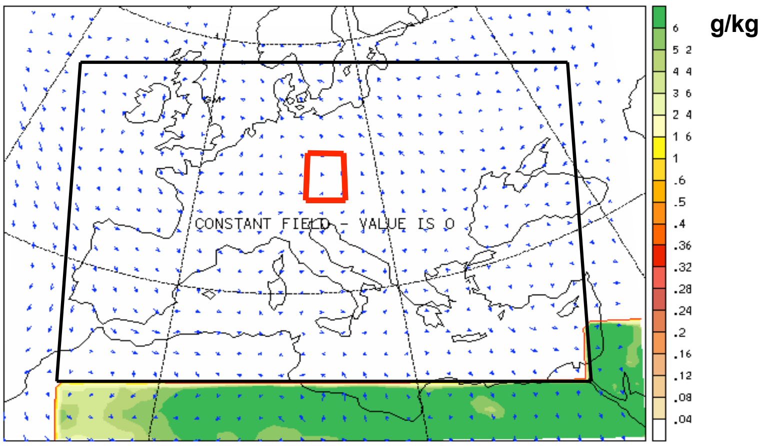
(PhD Thesis Harald Sodemann, 2006, ETH Zürich)



# Inflow of subtropical moisture

Tagged water vapour at model level 25 (925 hPa)

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(PhD Thesis Harald Sodemann, 2006, ETH Zürich)

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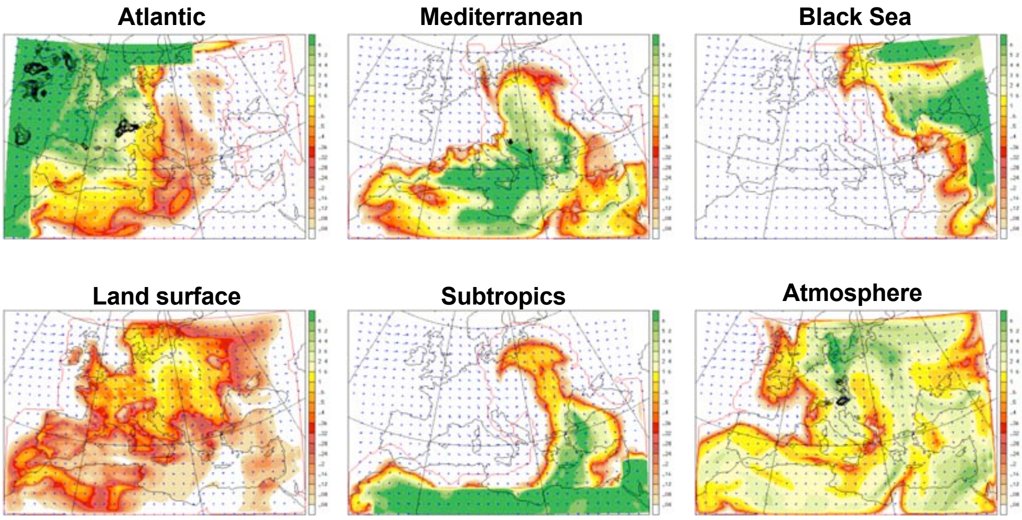
## Coherency of the water vapour tracer field

Tagged water vapour at model level 25 (925 hPa) at 12Z 2002/08/12

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(PhD Thesis Harald Sodemann, 2006, ETH Zürich)

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## Outline

Atmospheric transport

**Precipitation**
**- structure of the atmosphere**
**- particles in the atmosphere, cloud microphysics**
**- precipitation measurement**
**- convective versus stratiform precipitation**

**Energy and water movement in soils**
**- thermal conductivity in soils**
**- water conductivity and Darcy's law**

**Infiltration and formation of runoff**

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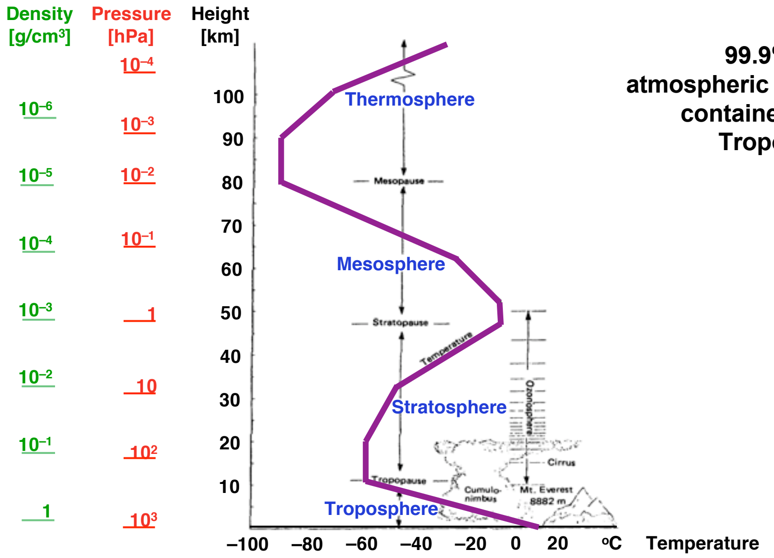
# Structure of the Atmosphere




**99.9% of the atmospheric water is contained in the Troposphere**

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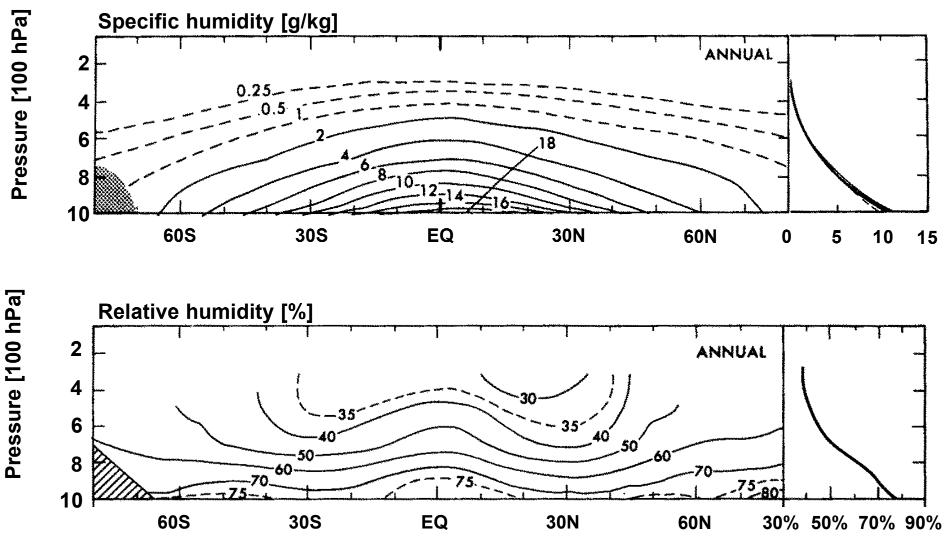
# Distribution of atmospheric humidity




(Peixoto and Oort 1992)

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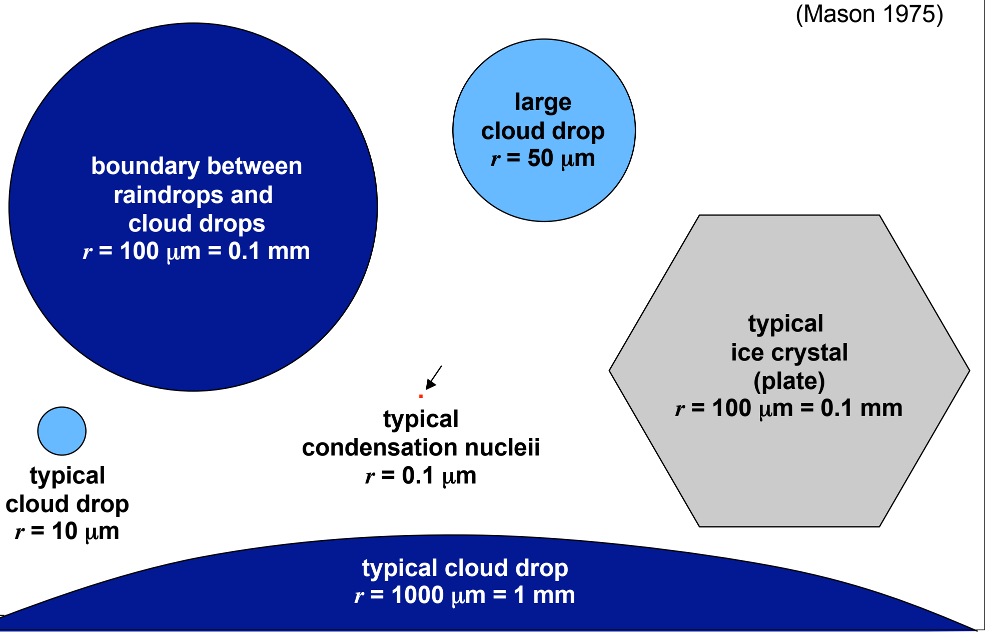
# Particles in the atmosphere

(Mason 1975)








# Snow crystals

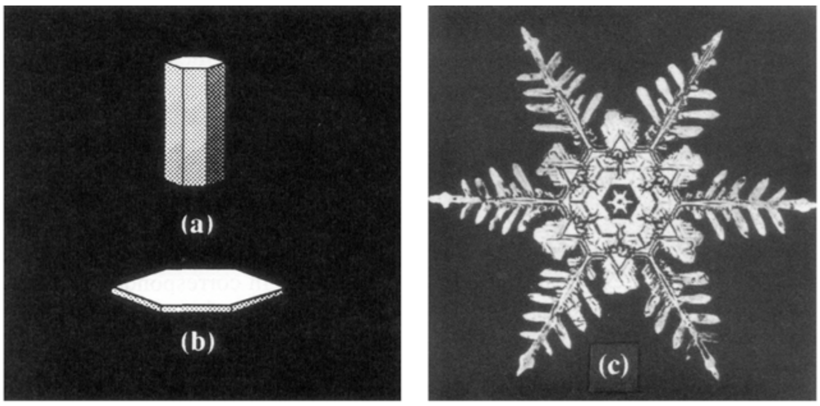
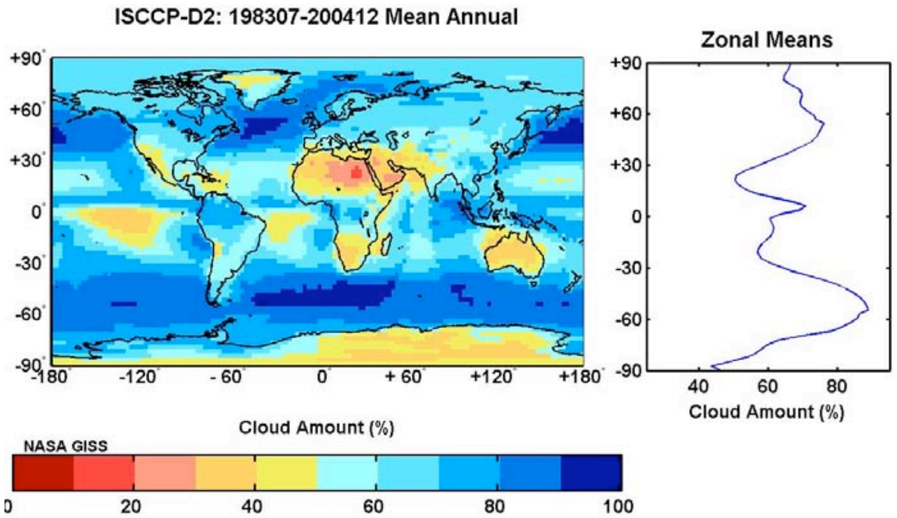



**Figure 3.8** Schematic representation of the main shapes of ice crystals: (a) columnar, or prismlike; (b) plate; (c) dendrite. (Adapted from Rogers and Yau, 1989.)

(Rogers and Yau, 1989)

# Global cloud cover

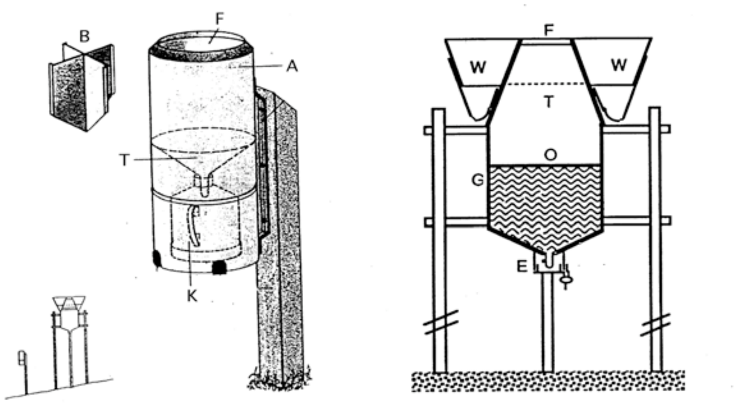





(ISCCP)



# Precipitation measurement: Pluviometer




Hellmann

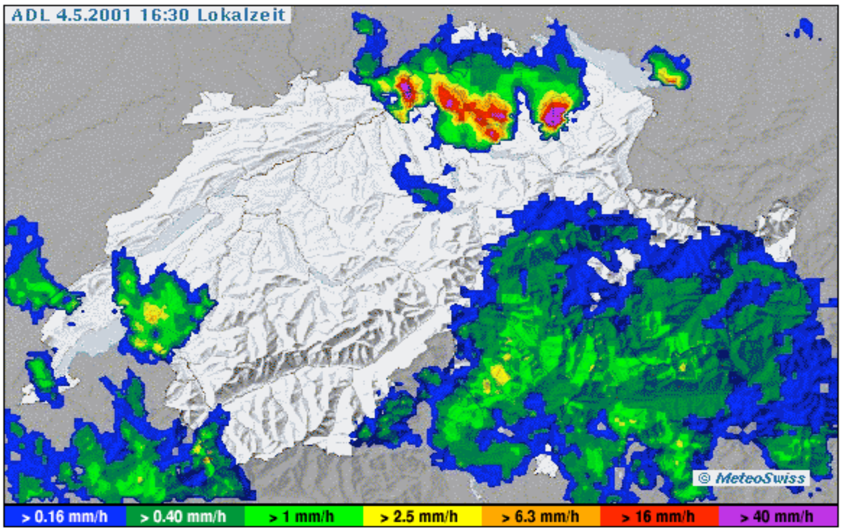
Totalisator

**A:** Auffanggefäss, abnehmbar
**B:** Schneekreuz
**E:** Entleerungshahn

**F:** Auffangöffnung
**G:** Auffang/Sammelgefäss
**K:** Sammelkanne

**O:** Oelschicht
**T:** Trichter
**W:** Windschutz

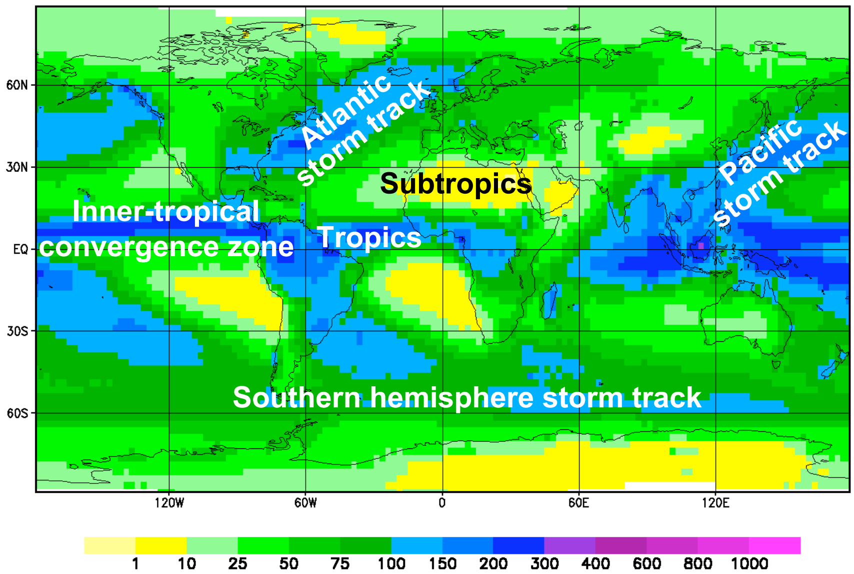
# Precipitation measurement: Radar








# Global precipitation distribution

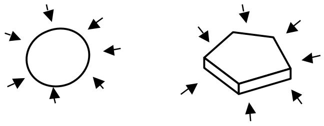



Mean annual precipitation 1980-2000 [mm/month] (GPCP, GPCC, DWD)

# Cloud microphysics and precipitation formation

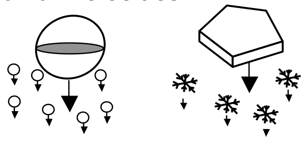
## *Condensation, Resublimation*

**Condensation of water vapor**



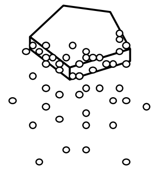
## *Coalescence, Aggregation*

**Collection of small particles due to differential fall velocities**



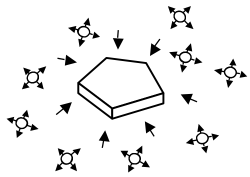
## *Riming*

**Collection of supercooled water droplets on an ice particle**



## *Findeisen-Bergeron*

**Flux of water vapor from water droplets to ice crystals**

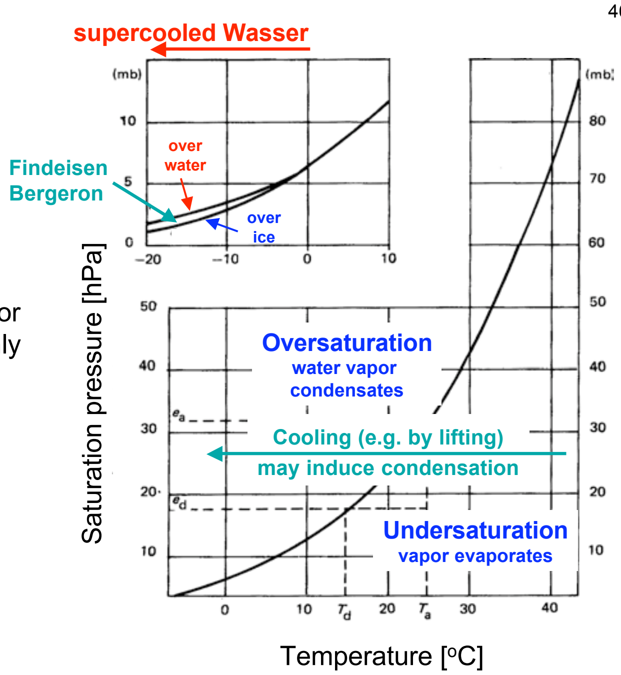






# Saturation vapor pressure

Saturation vapor pressure
= partial pressure of $H_2O$-vapor
• depends on temperature only



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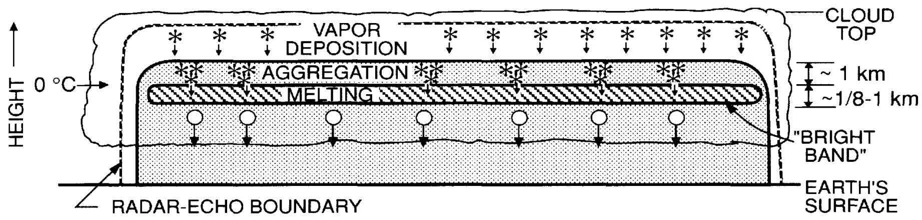
# Stratiform precipitation




- Long duration, small precipitation rates
- Vertical wind velocity: < ~ 1 m/s
- Horizontal scale: ~ 100 km
- Occurs in stably stratified atmosphere (density decreases with height, suppresses vertical motion)
- Vertical lifting due external factors (low-pressure systems, topography)
- Common in polar regions, during winter in mid-latitudes



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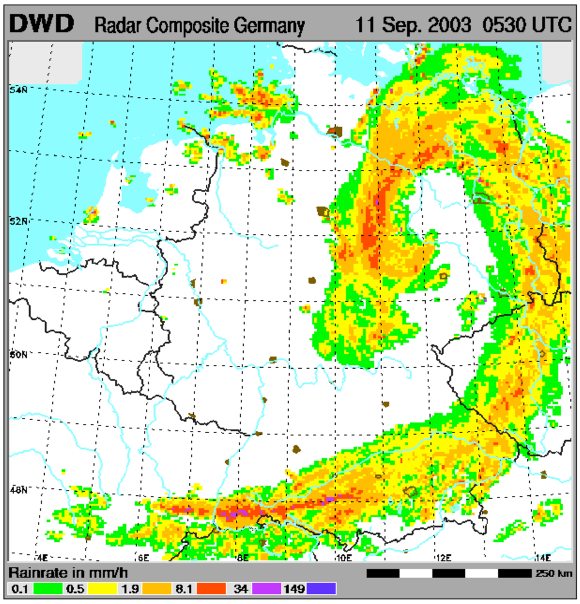
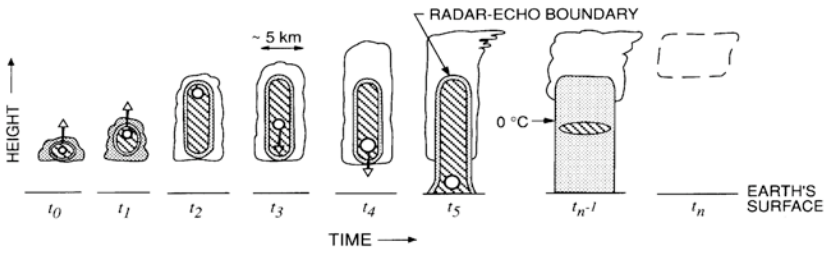
# Frontal passage dominated by stratiform precipitation



# Convective precipitation

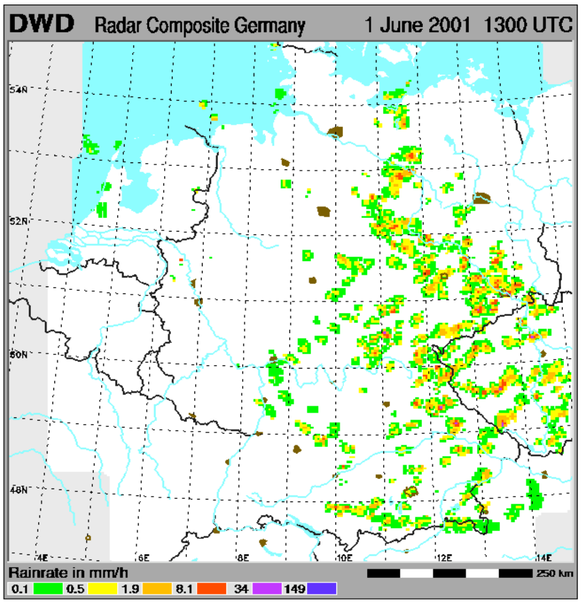



- Short duration, large precipitation rates
- Vertical wind velocities O(10 m/s), often associated with thunderstorms
- Horizontal scale ~ 3-10 km (individual convective cells)
- Lifting due to destabilazation (surface heating, upper-level cooling, release of latent heat)
- Common in tropics, during summer in mid-latitutes, during winter over warm ocean surfaces





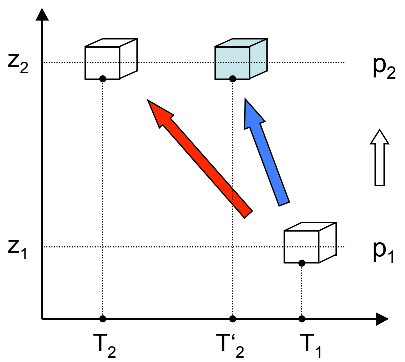
# Summer convective precipitation



# Lifting of an air parcel

- Dry adiabatic lifting:
  Dry (i.e. no clouds) air parcel, absence of condensation
  Air parcel does not exchange energy with surrounding (adiabatic cooling)

- Moist adiabatic lifting:
  Air parcel is saturated, lifting leads to condensation
  Release of latent heat implies partial compensation of adiabatic cooling








# Dry adiabatic lapse rate

**First law of thermodynamics**

$$\delta Q = c_p\, \delta T - \frac{1}{\rho}\, \delta p$$

**Hydostatic relation**

$$\frac{\partial p}{\partial z} = -g\rho \quad \Rightarrow \quad \delta p = -g\rho\, \delta z$$

**Adiabatic condition**

$$\delta Q = 0 \quad \Rightarrow \quad c_p\, \delta T + g\, \delta z = 0$$

**Dry adiabatic lapse rate**

$$\Gamma_d = -\frac{\partial T}{\partial z} = +\frac{g}{c_p} = +\frac{9.81\,\mathrm{m/s^2}}{1004\ \mathrm{J/kg\,K}} = 0.98\ \frac{\mathrm{K}}{100\,\mathrm{m}}$$

**With potential temp.**

$$\frac{\partial \theta}{\partial z} = 0$$

# Moist adiabatic lapse rate

**First law of thermodynamics including latent heat:**

$$\delta Q \approx c_p\ \delta T - \frac{1}{\rho}\ \delta p + L\ \delta q_s$$

with $L$=latent heat, $q_s$=specific humidity at saturation

**Moist adiabatic lapse rate:**

$$\Gamma_s \approx 0.5\ \frac{\mathrm{K}}{100\,\mathrm{m}} < \Gamma_d$$

(exact value depends upon temperature and pressure)





# Vertical stratification of the moist atmosphere

**I: absolutely unstable: $\Gamma_s < \Gamma_d < \gamma$**

Unstable irrespective of moisture content

Often happens in (dry) boundary layer

Rapid vertical mixing,
in saturated conditions conv. precipitation

**II: conditionally unstable: $\Gamma_s < \gamma < \Gamma_t$**

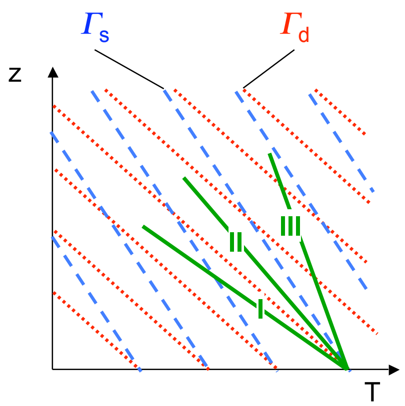
Stability depends upon moisture content,
Saturation implies instability

Deflected air parcels may rise unstably,
convective precipitation

**III: absolutely stable: $\gamma < \Gamma_s < \Gamma_t$**

Deflected air parcels try to swing back to their level of origin

Precipitation only if there is external lifting




Example of atmospheric profiles with $\gamma = -dT/dz$

# Temperature profile at a thunderstorm day

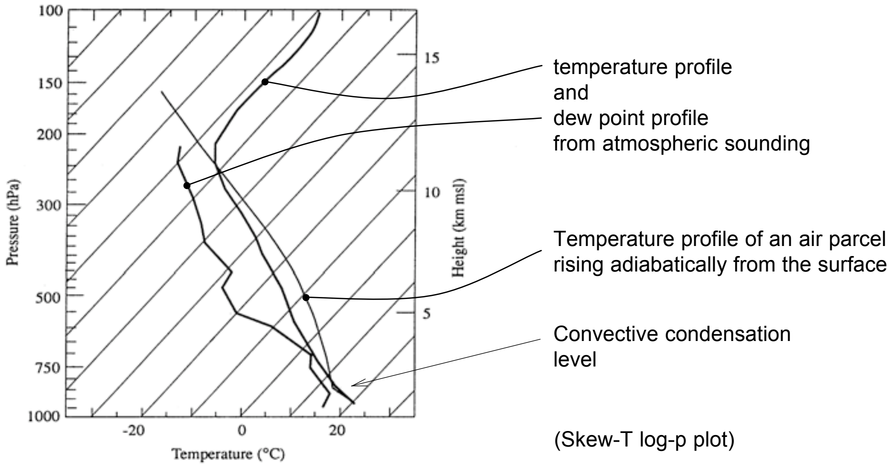



FIG. 10. Smoothed sounding used for initialization of the model simulation. Heavy solid curves mark the temperature and dewpoint. A thin solid line shows the path of the unsaturated parcel used to determine CAPE for this sounding (≈1100 J kg$^{-1}$).

(Skew-T log-p plot)

# Outline

Atmospheric transport

Precipitation

**Energy and water movement in soils**

- Thermal conductivity in soils
- Soil water potential
- Water conductivity and Darcy's law
- Flow in saturated soils (groundwater flow)
- Flow in unsaturated soils

**Infiltration and formation of runoff**





# Vertical heat conduction in soils

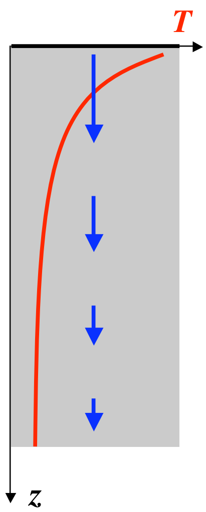
**Fourier's law:**

The heat flux is directed against the temperature gradient and proportional to its magnitude:

$$q_h = -\kappa \frac{\partial T}{\partial z}$$

heat flux [W/m²]

thermal conductivity [W/(m K)]




**Conservation of energy:**

A divergent heat flux implies heating / cooling:

$$\rho c_m \frac{\partial T}{\partial t} = -\frac{\partial q_h}{\partial z}$$

specific heat [J/(kg K)]

Combine with Fournier's law:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_m} \frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z}\right)$$

If $\kappa$ = constant

$$\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial z^2} \quad \text{with} \quad D = \frac{\kappa}{\rho \; c_m}$$

thermal diffusivity [m²/s]

# Three-dimensional heat conduction

**Fourier's law:**

The heat flux is directed against the temperature gradient and proportional to its magnitude:

$$\mathbf{q}_h = -\kappa \nabla T$$

heat flux [W/m$^2$]

thermal conductivity [W/(m K)]

**Conservation of energy:**

A divergent heat flux implies heating / cooling:

$$\rho c_m \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{q}_h$$

specific heat [J/(kg K)]

Combine with Fournier's law:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_m} \nabla \cdot (\kappa \nabla T)$$

If $\kappa$ = constant

$$\frac{\partial T}{\partial t} = D \ \nabla^2 T \quad \text{with} \quad D = \frac{\kappa}{\rho \ c_m}$$

thermal diffusivity [m$^2$/s]



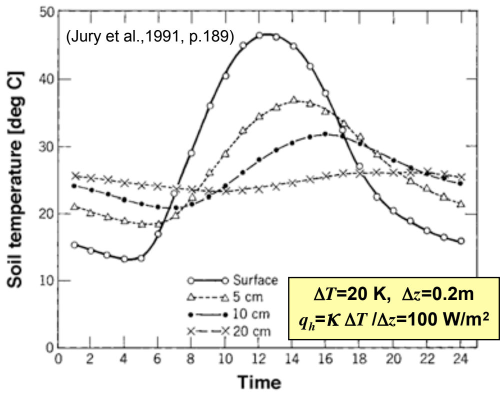


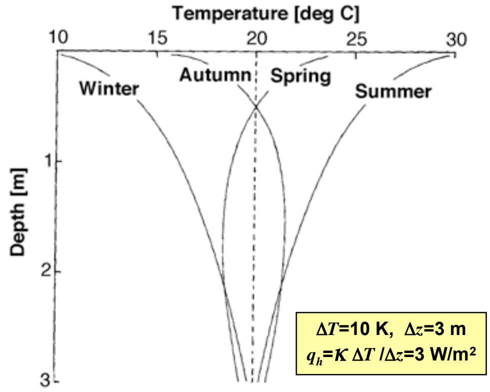
# Thermal diffusivity for soil constituents and soils

| Soils | Conductivity $\kappa$ [W K m$^{-1}$] | Diffusivity $D$ [ $10^{-7}$ m$^2$ s$^{-1}$ ] | $d$ for $P$=24h [cm] | $d$ for $P$=1y [m] |
|---|---|---|---|---|
| Quartz | 8.8 | 44 | 35 | 6.7 |
| Minerals (average) | 2.9 | 14.5 | 20 | 3.8 |
| Water (liquid) | 0.57 | 1.36 | 6 | 1.2 |
| Ice | 2.2 | 11.6 | 18 | 3.4 |
| Air | 0.025 | 200 | 74 | 14 |
| **Sand** | **0.3 – 2.2** | **2.3 – 7.4** | **8 – 14.3** | **1.5 – 2.7** |
| **Clay** | **0.25 – 1.6** | **2.0 – 5.4** | **7.4 – 12.2** | **1.4 – 2.3** |
| | dry $\theta$=0 wet $\theta$=0.4 | dry $\theta$=0 wet $\theta$=0.4 | dry $\theta$=0 wet $\theta$=0.4 | dry $\theta$=0 wet $\theta$=0.4 |

# Diurnal and seasonal cycle of soil temperature

Flux estimates assume
$\kappa$ = 1 WK/m




Analytical solution:

$$T(z,t) = T_o \; + \; A \; e^{z/d} \; \sin(\omega t + z/d) \quad \text{with} \quad d = \sqrt{2D/\omega} = \sqrt{DP/\pi}$$

damping depth — period





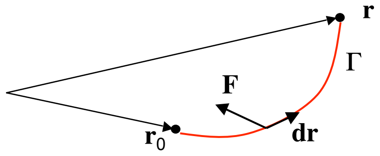
# Soil water potential

## Forces between water and the soil matrix

- **Adhesive (repelling) forces:**
  Intermolecular binding forces between water and soil matrix:
  => removing water from soil particles requires energy
- **Capillary forces:**
  Surface tension:
  => increasing the water surface requires energy
  => keeps water pockets together
- **Gravitational forces:**
  Vertical force due to gravity:
  => in unsaturated zone water is pulled downwards
  => in saturated zone, gradients in the ground water table imply horizontal pressure forces within ground water
- **Osmotic forces:**
  Force due to solutes. Not considered in this lecture.

# Potential, general considerations

- Energy of a mass point in a conservative force field $F$.
- Potential $\phi$ = Energy that is needed to bring the mass point from a reference location $\mathbf{r}_0$ to its actual location $\mathbf{r}$.




$$\phi(\mathbf{r}) = -\int_{\Gamma} \mathbf{F} \cdot d\mathbf{r}, \quad \mathbf{F} = -\nabla\phi$$

- The term „conservative“ implies that the required energy does not depend upon the selected path

- Example: Gravitational potential:

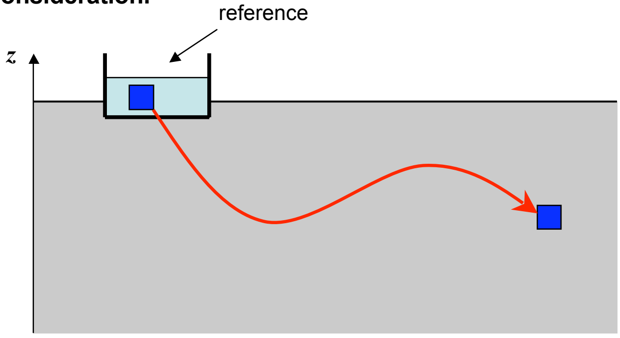
$$\phi_g = \rho g (z - z_0), \quad \mathbf{F}_g = -\nabla\phi_g = -\begin{pmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{pmatrix} \phi_g = \begin{pmatrix} 0 \\ 0 \\ -\rho g \end{pmatrix}$$





# Soil water potential

**The total potential of soil water is the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a reference pool of pure water at a specified elevation at atmospheric pressure to the soil water at the point under consideration.**




In general the water potential is negative, i.e. energy is needed to extract water from the soil to the surface.

**Unit:** $\frac{\text{energy}}{\text{volume}} = \frac{J}{m^3} = \frac{Nm}{m^3} = \frac{N}{m^2} = Pa$

# Soil water potential in unsaturated soils

- **Soil water potential**

$$\phi = \phi_g + \psi$$

**This is a simplified version:**
In general, additional factors have to be considered: air pressure potential, solute potential, etc.

**Gravitational potential** $\phi_g = \rho\, g\, (z-z_0)$

Potential of gravitational force

**Matric potential** $\psi$

Potential of binding adhesion and capillary forces in the soil matrix.
$\psi$ is negative, as energy that is required to extract water from soil matrix.

- **Units: Energy per unit volume**

| | | |
|---|---|---|
| Pressure units: | $\phi = \phi_g + \psi$ | [J / m$^3$] = [N / m$^2$] = [Pa] |
| Equivalent depth (head): | $\phi_h = \phi / \rho\, g$ | [m] |
| pF-Value: | $\log_{10}(\phi_h/1\text{ cm})$ | [1] |

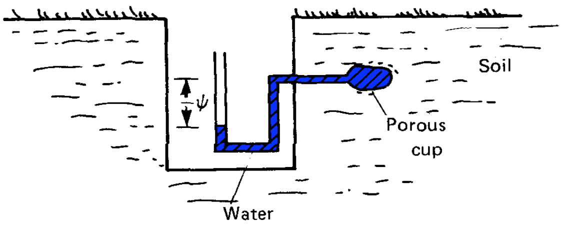




*Nicht im Skript*

# Tensiometer: measurement of matric potential

**Principle of tensiometer**

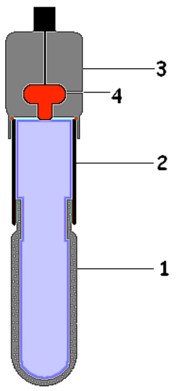



**A matric potential of *0* indicates that the soil is saturated.**

**Because water is held by capillary and adhesive forces within unsaturated soil pores, the matric potential of unsaturated soils is negative. The water is under tension and work must be done to extract it from the soil.**

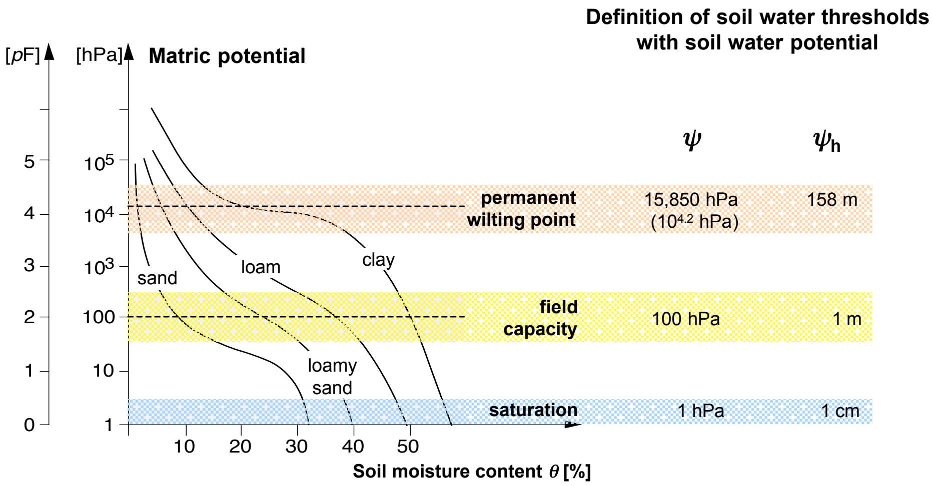
**The negative sign is usually omitted for convenience.**

**Instrument**




Tensiometer:
(1) porous cup
(2) water-filled tube
(3) sensor-head
(4) pressure sensor;

# Matric potential and soil moisture content








# Groundwater potential (quiescent case)

**Capillary and adhesive forces are negligeble ($\psi \approx 0$), but hydrostatic pressure force must be accounted for.**

**Groundwater potential:**

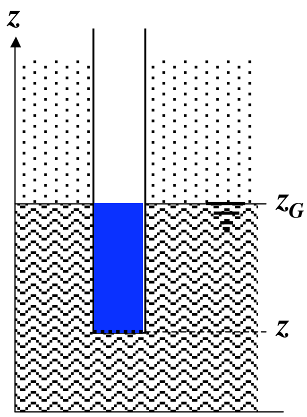
$$\phi = \rho g z + \rho g (z_G - z) = \rho g z_G$$

gravitational potential

hydrostatic pressure potential

In the quiescent case, the potential is uniform within the groundwater.

The groundwater table is horizontal, there are not forces and no motion.



# Darcy's law for saturated flows

**The water flux in saturated soil zone is proportional to the gradient of the water potential.**

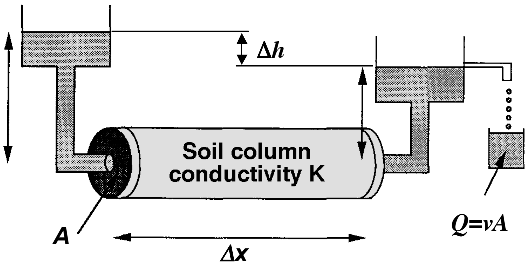
$$v = Q/A = K_s \ \Delta h / \Delta x$$

**Three-dimensional:**

$$\mathbf{v} = -K_s \ \nabla \phi_h$$

$K_s$ is the hydraulic conductivity at saturation. It depends upon the properties of the soil, temperature, and additional factors.

$\boldsymbol{v}$ is the "filter velocity". It does not correspond to the true velocity, but to a mean velocity assuming flow within the cross section A.



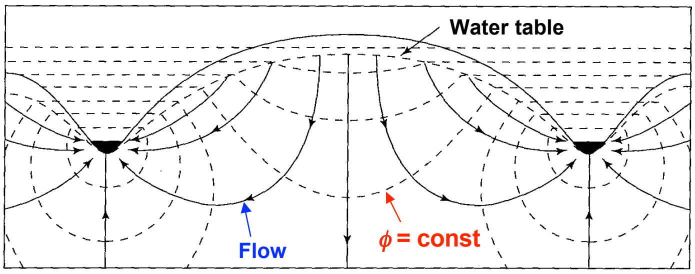

| $K_s$ | m/s | cm/d |
|---|---|---|
| Sand: | $3\cdot10^{-5}$ | 260 |
| Loamy sand: | $1\cdot10^{-6}$ | 8.6 |
| Loam: | $5\cdot10^{-7}$ | 4.3 |
| Clay: | $1\cdot10^{-7}$ | 0.9 |



Darcy, H., 1856: *Les Fontaines Publiques de la Ville de Dijon*. Dalmont, Paris



# Stationary groundwater flow




Combine Darcy's law $\mathbf{v} = -K_s \ \nabla \phi_h$

with incompressibility of water $\nabla \cdot \mathbf{v} = 0$

to obtain $\nabla \cdot K_s \nabla \phi_h = 0$

If $K_s$=*const* this yields the Laplace equation $\nabla^2 \phi_h = 0$

Thus, solving the Laplace equation for given boundary conditions (groundwater table) yields the flow field. In general, however, inhomogeneities will complicate the situation (e.g. inpermeable layers).

# Darcy‘s law for unsaturated soils

**In unsaturated soils, the flow can be approximated by Darcy‘s law in the following form:**

$$\mathbf{v} = K_h(\theta) \cdot \nabla\phi_h$$

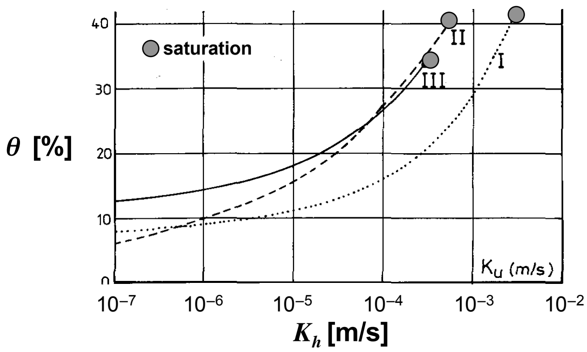
**Here:**

- **$\phi_h$ = soil moisture potential in unsaturated zone, accounting for gravitational and matric potential**
- **$K_h$ = hydraulic conductivity, is a function of soil moisture content and soil properties**





# Hydraulic conductivity of unsaturated soils




Hydraulic conductivity for different types of sand:

I: 0.5-1 mm

II: 0.25-0.5 mm

III: 0-2 mm

- **Hydraulic conductivity increases strongly with soil moisture content $\theta$. Has maximum value at saturation**
- **Is very small for small $\theta$. In dry soils, water fluxes are exceedingly small.**
- **Highly non-linear. Variations of $\theta$ by 10% may imply changes of $K_h$ by several orders of magnitude.**

# Outline

Atmospheric transport

Precipitation

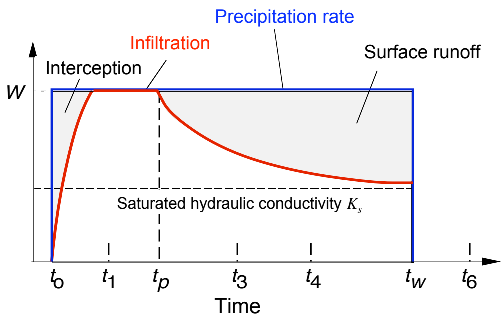
Energy and water movement in soils

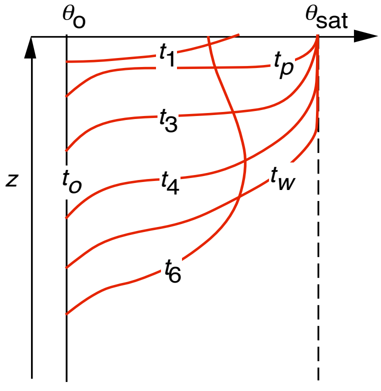
Infiltration and formation of runoff





# Infiltration of precipitation




- **Once the surface is saturated, a infiltration front forms.**
- **If precipitation rate exceeds infiltration capacity, there is surface runoff.**
- **The asymptotic infiltration is given by the saturated hydraulic conductivity**

  Sand: 108 mm/h

  Loam: 1.8 mm/h

  Clay: 0.4 mm/h

This is a (grossly) simplified version of the Green-Ampt model

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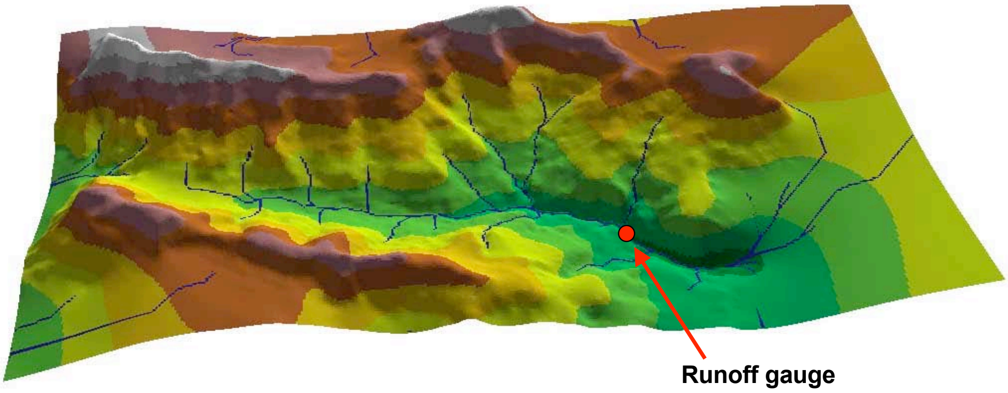
# Runoff concentration in a catchment




Schär, ETH Zürich

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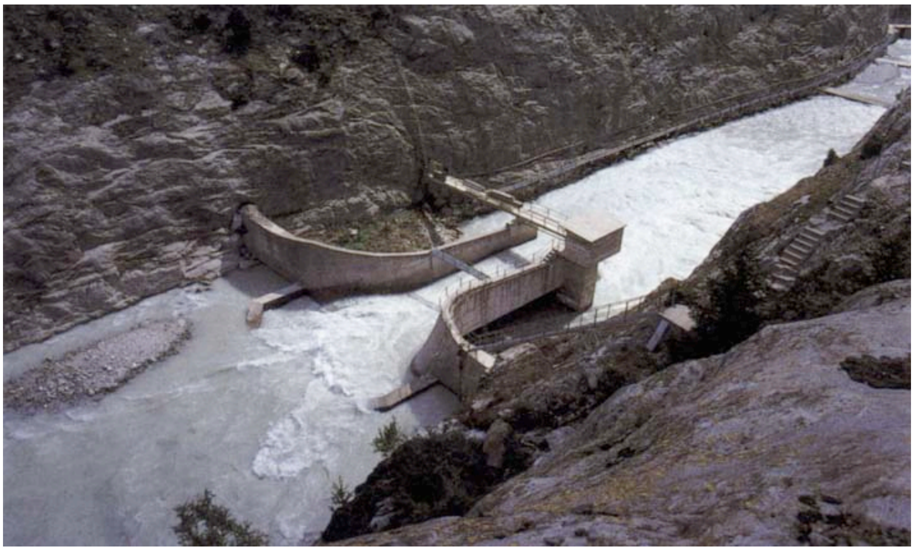
# Runoff gauge at the Rhône

Level measurement

Schär, ETH Zürich

# Runoff gauge at the Massa (Aletschglacier)

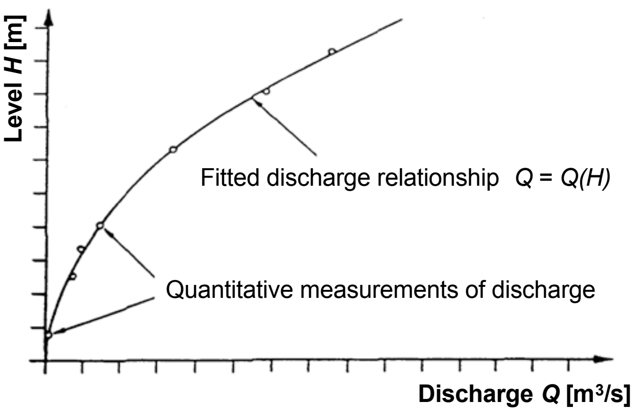


Gauging weir





# Level-discharge relationship




**The relationship *Q*=*Q(H)* is determined**

- **direct measurements at different point**
- **Hydraulics of the gauging weir (if of standard design)**