Hochschule
für nachhaltige Entwicklung
Eberswalde

P I K

Mit der Natur für den Menschen – seit mehr als 185 Jahren.

Earth System Analysis & Stewardship

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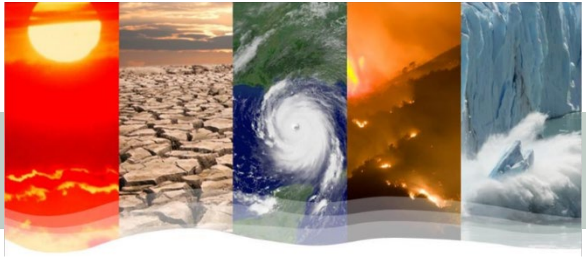
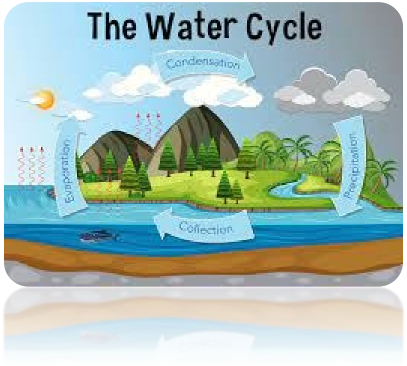
Key questions addressed

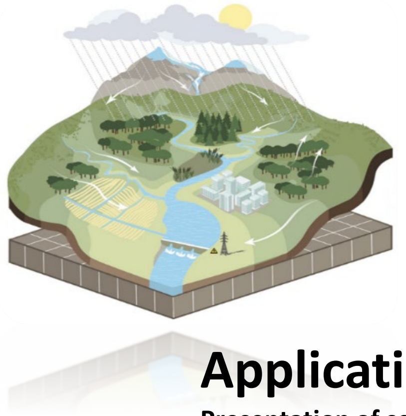
- Why is water so relevant?
- What is the role of water in the climate cycle?
- Which processes are important?
- What are the interactions with vegetation?
- How can the water cycle and the water nexus be modelled?
- What are possible adaptation measures and strategies?



What we will do

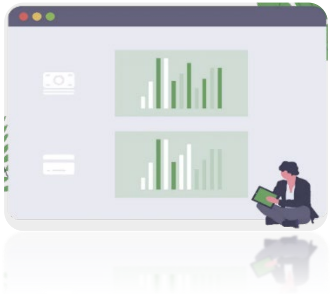
Theory
Background and conceptualization



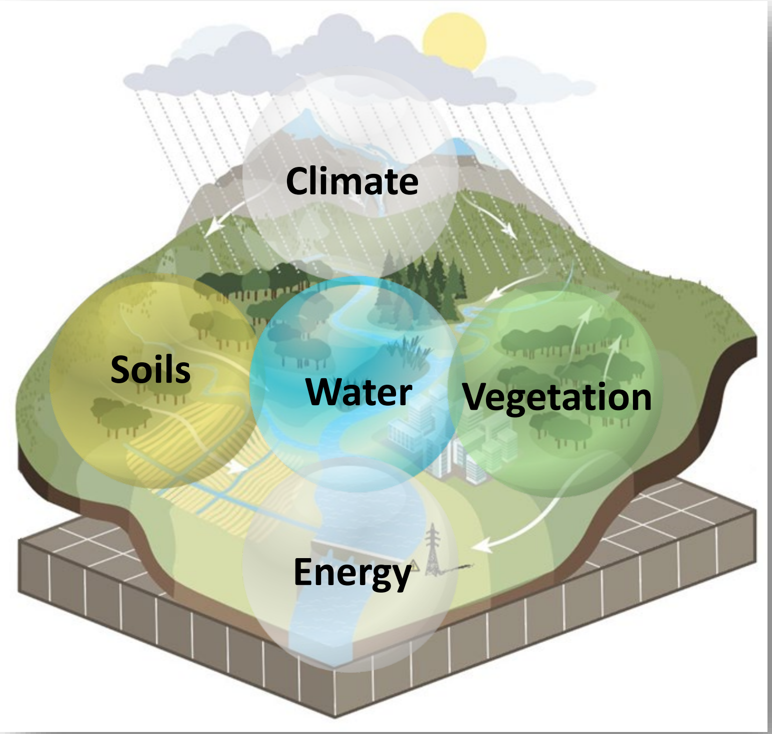


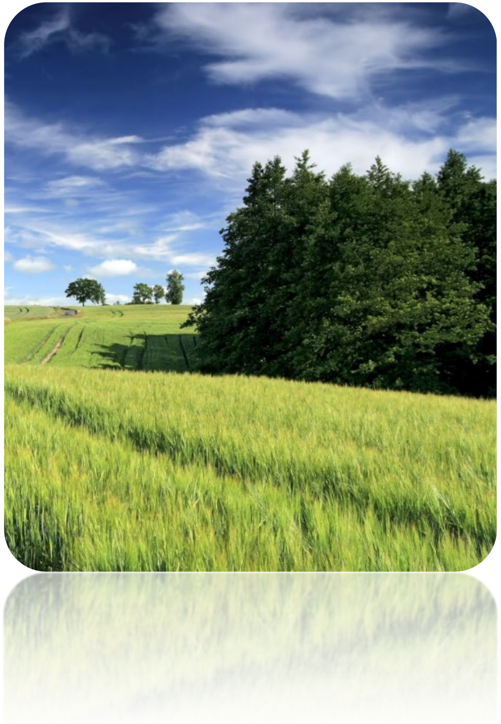
Examples
Modelling and interpretation

Application
Presentation of selected topics



The water nexus, processes and interpretation





Solutions

Outline

Monday Nov. 18

- The water cycle: From hydrological processes to observations,
- presentation of topics, groupwork

Tuesday Nov. 19

- The nexus water – energy – food. Water as a basic need, water as a threat: health, hydrological extremes, erosion,
- Selection of topics, groupwork

• Wednesday Nov. 20

- Eco-hydrological modelling,
- Groupwork

Thursday Nov. 21

- Groupwork

Friday Nov. 22

- Presentation of selected tasks, visiting PIK

Water is life

- Nearly 97% of the world's water is salty or otherwise undrinkable. Another 2% is locked in ice caps and glaciers. That leaves just 1% for all of humanity's needs.
- Water regulates the Earth's temperature and the temperature of the human body, carries nutrients and oxygen to cells, and removes wastes.
- 75% of the human brain is water and 75% of a living tree is water.
- A person can live about a month without food, but only a few days without water.

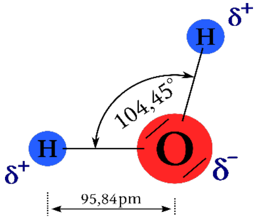
Water can be a threat

Water is a problem, when

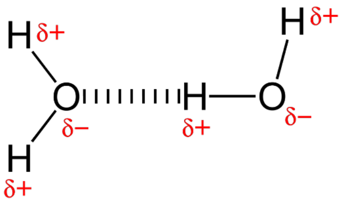
- having too much;
- having too low;
- having water of low quality.

Properties of water

Dipol

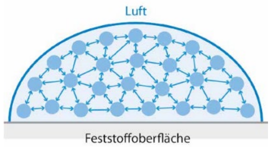


Wassermolekül, Wikimedia Commons contributors, CC BY-SA.



Wasserstoffbrückenbindung, Wikimedia Commons contributors, public domain.

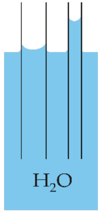
Water surface tension



Aus: Fohrer, 2016.

Wasserläufer auf Wasseroberfläche, Wikimedia Commons contributors, CC BY-SA.

Kapillary effect



Kapillareffekt beim Wasser, Wikimedia Commons contributors, verändert, CC BY-SA.

Conversion millimeter into litre

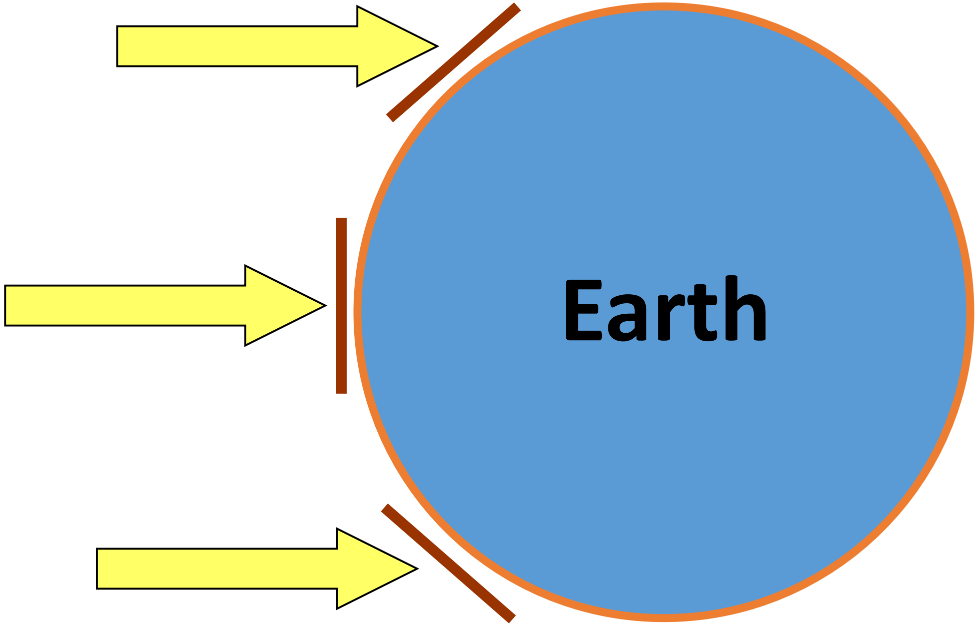
1 mm (rain) = 1 litre / m²

Repetition: Energy distribution on Earth's surface

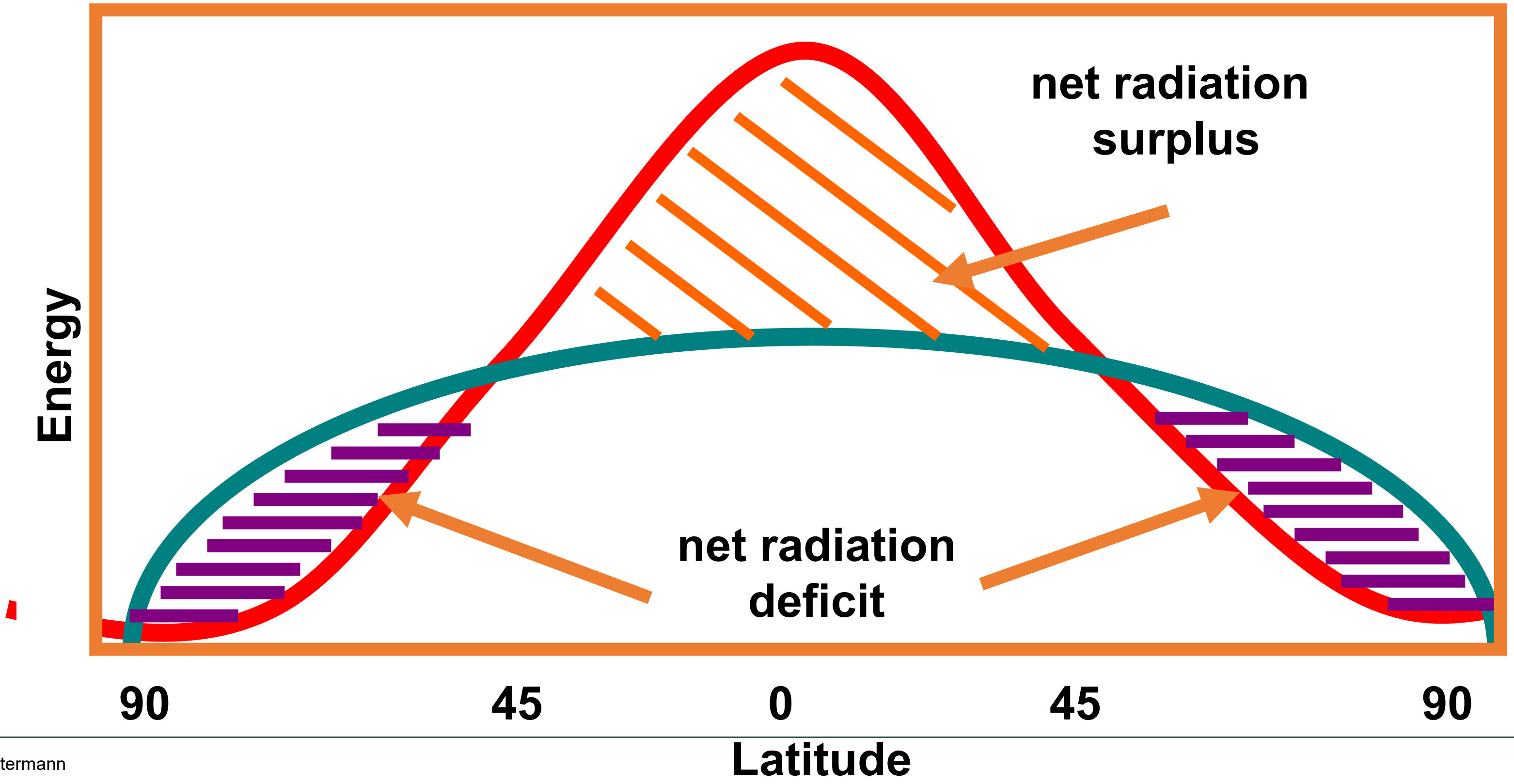
High latitudes receive light at low angles

Regions near the equator receive light at 90°

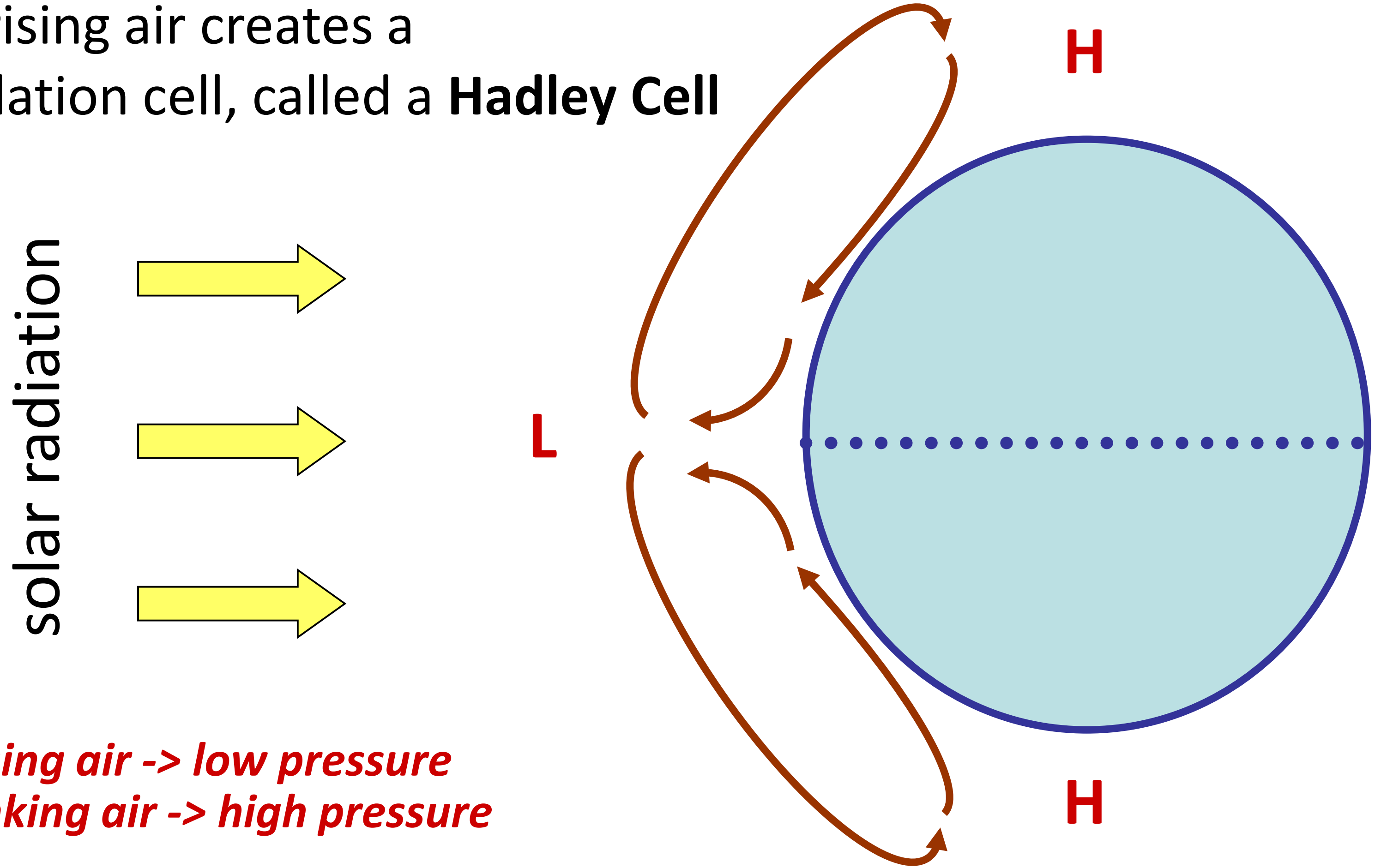
-> Light energy is more concentrated near the equator. In other words, there is a greater flux per unit area (W/m^2)



Excess energy at the equator is transferred towards the poles by convection cells

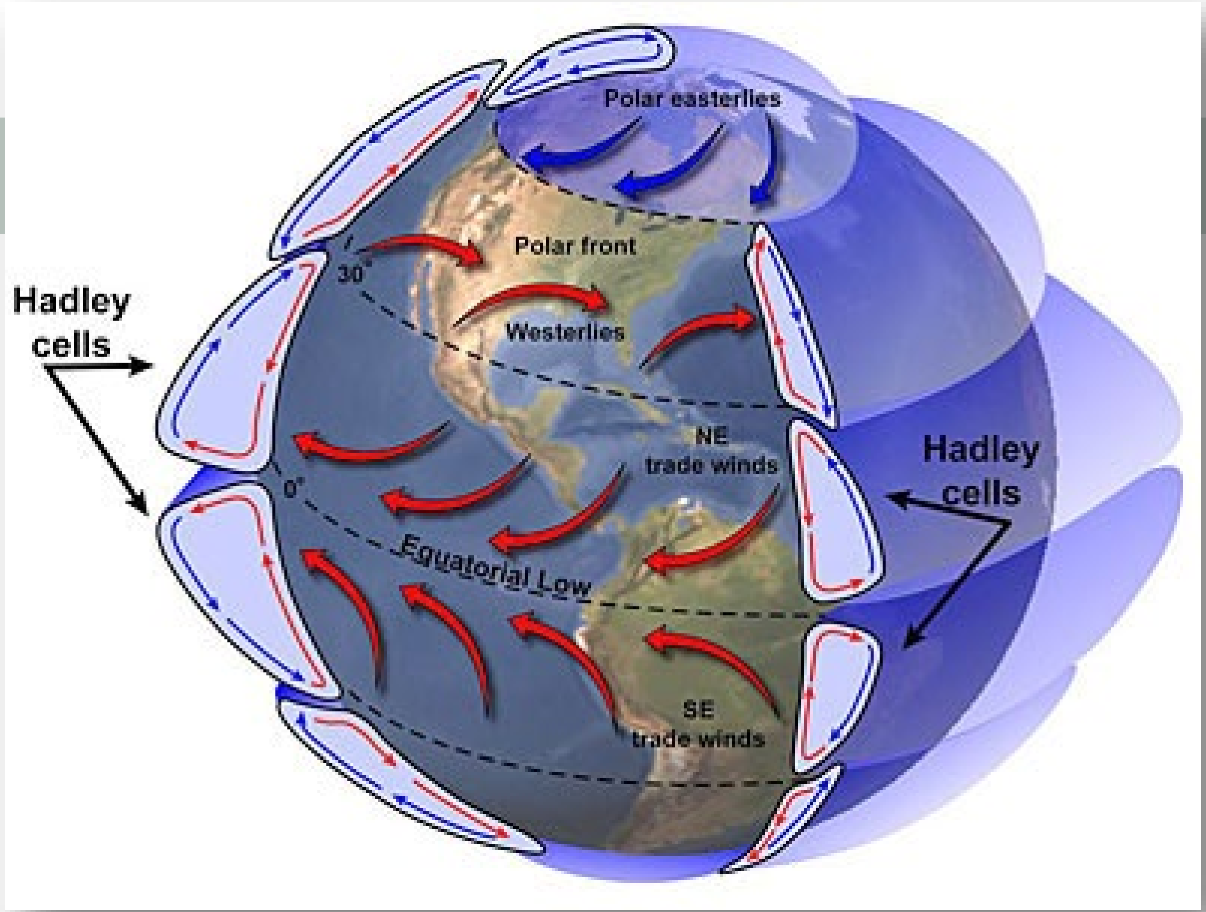


The rising air creates a circulation cell, called a **Hadley Cell**



Rising air -> low pressure
Sinking air -> high pressure

Global Atmospheric Flux and Ciculation Cells



Credit: NASA

Energy Transport in the Earth System

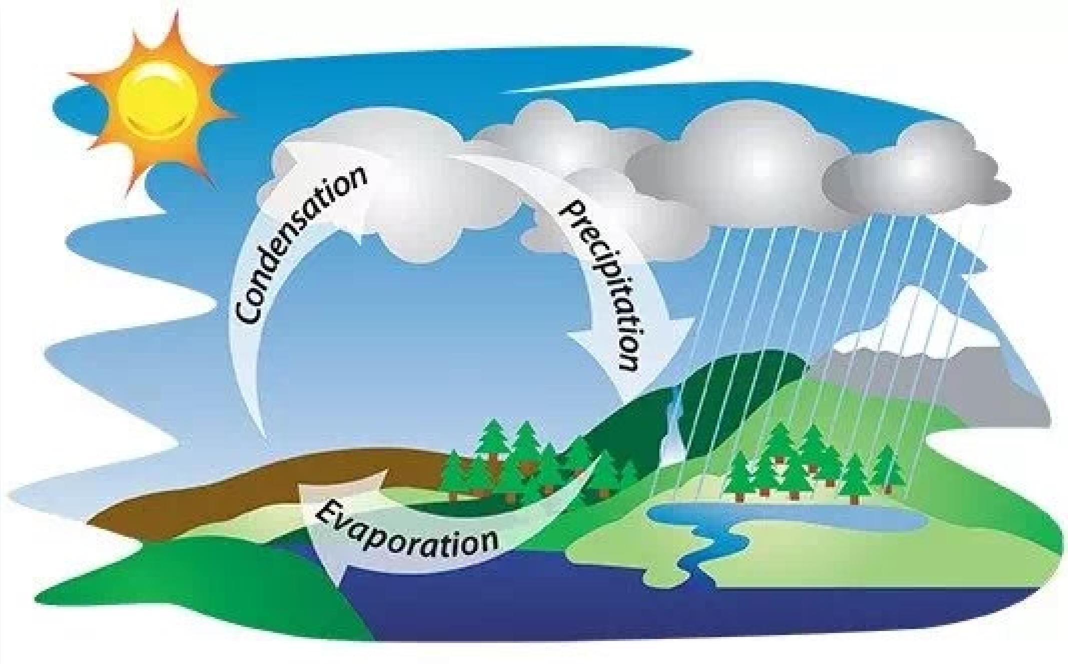
Solar energy received is greatest near the equator.

Energy is moved from the equator to the poles.

Energy is transferred by wind and ocean currents and these are coupled!

Examples: Monsoon and ENSO

Water cycle, simple



Main processes:

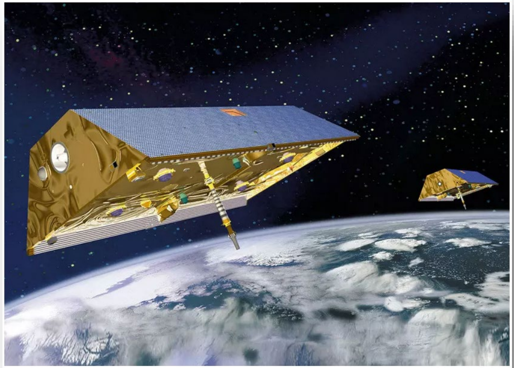
- Precipitation
- Evaporation
- Condensation

Driver:

- Solar radiation
- Gravity

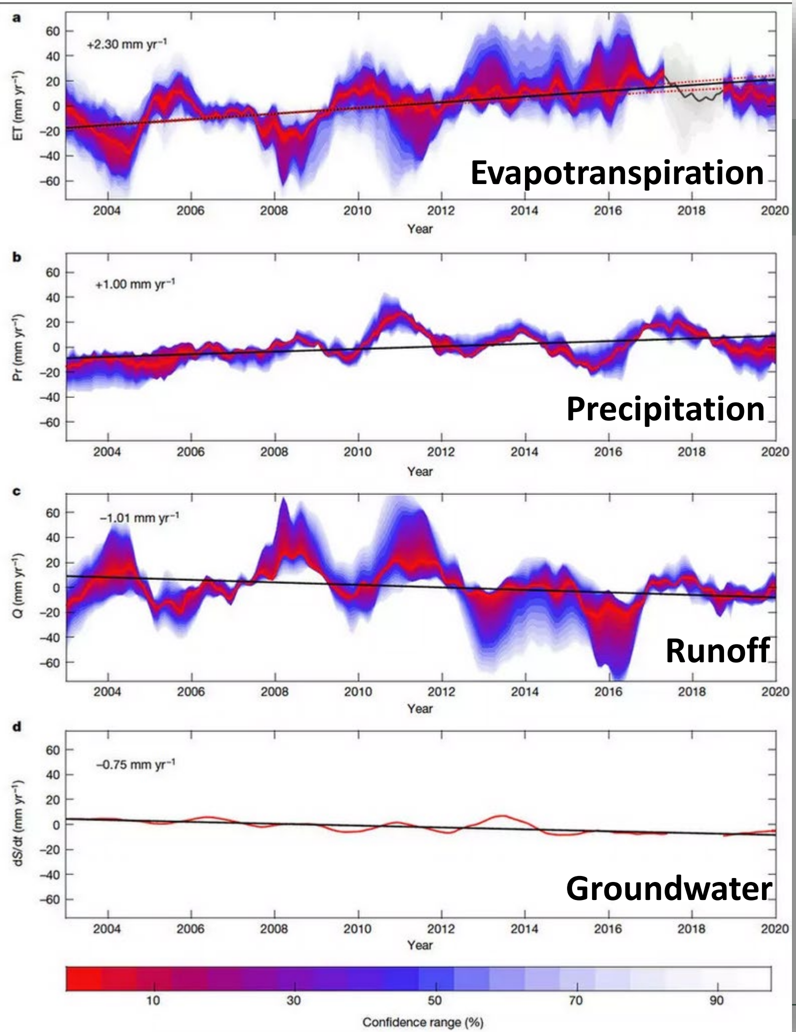

Is this climate change?


Global water trends



NASA Gravity Recovery and Climate Experiment (GRACE mission) Twin Satellites, concept art Image: NASA PO.DAAC.

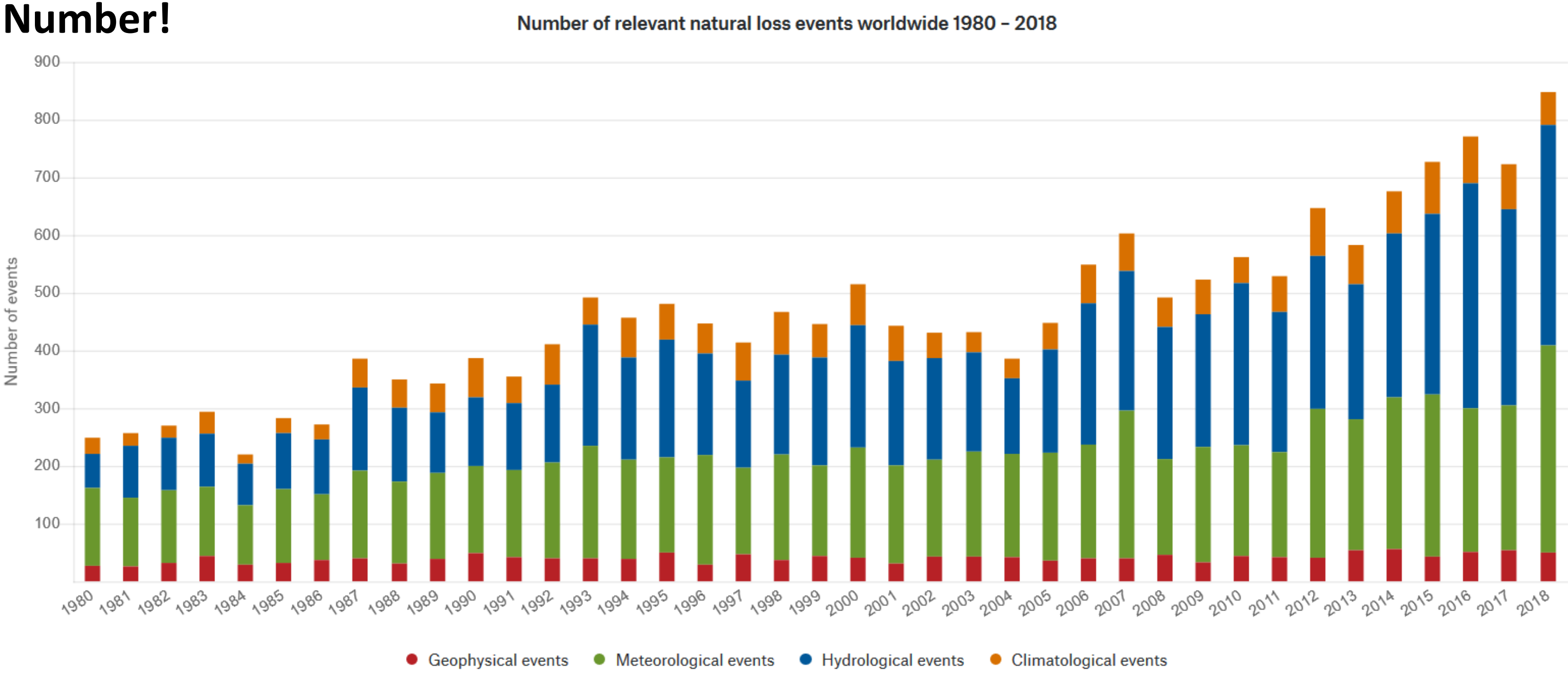
Gravity Recovery and Climate Experiment (GRACE)



Pascolini-Campbell et al (2021)

Number of events worldwide (Munich Re NatCat)

Number!



Hydrological tasks

After Dyck & Peschke (1995):

- **Exploration of the water cycle**
- **Calculation of the water balance** over different scales (earth, continents, river basins, water management systems) for different periods of time
- **Determination of water resources** (usable share of groundwater and surface water)
- **Hydrological forecasts** (water level, runoff, groundwater recharge, ice)
- **Investigation of runoff regimes** (especially extreme runoff)
- **Use and management** of water ressources

Literatur

Maidment, D.R. (1993): Handbook of Hydrology, McGraw-Hill, New York.

Fohrer, N. (2016): Hydrologie. Utb Taschenbuchreihe. (Sehr gutes Lehrbuch für „Einsteiger*innen“).

Dyck, S. & Peschke, G. (1995): Grundlagen der Hydrologie, 3. Auflage, Verlag für Bauwesen, Berlin.

Baumgartner, A. & Liebscher, H.J. (1996): Allgemeine Hydrologie: quantitative Hydrologie, 2. Auflage, Borntraeger, Stuttgart.

Nützmann, G. & Moser, H. (2016): Elemente einer analytischen Hydrologie. Springer Verlag. (sehr aktuell, gute Abbildungen, verständlich)

Wohlrab, B., Ernstberger, H., Meuser, A., Sokollek, V. (1992): Landschaftswasserhaushalt. Verlag Paul Parey Berlin. 352 S. Fachübergreifendes Lehrbuch, das Bezug auf die Wasserhaushaltskomponenten auf der Landschaftsebene Bezug nimmt. Umfassende Begriffsdefinitionen.

Maniak, U. (2005): Hydrologie und Wasserwirtschaft: Eine Einführung für Ingenieure. 5. Aufl., Springer, Berlin. Grundlagen zum Wasserhaushalt, sehr viel hydrologische Modellierung.

„The hydrological classics“

1. The water cycle
2. Precipitation
3. Evapotranspiration
4. Discharge
5. Storage

1. The water cycle

Definition (DIN 4049)

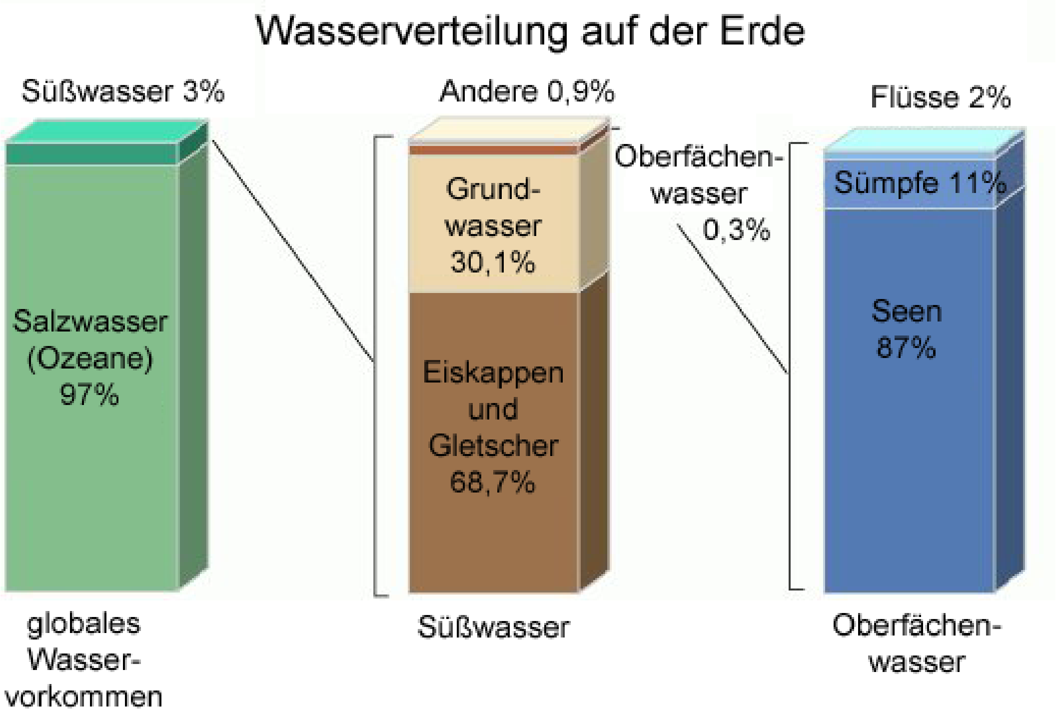
Water cycle

Continuous sequence of changes in the state and location of water with the main components precipitation, runoff, evaporation and atmospheric water vapour transport.

Water balance

Quantitative recording of the components of the water cycle and the change in supply in an area under consideration during a period of observation.

Water balance, global

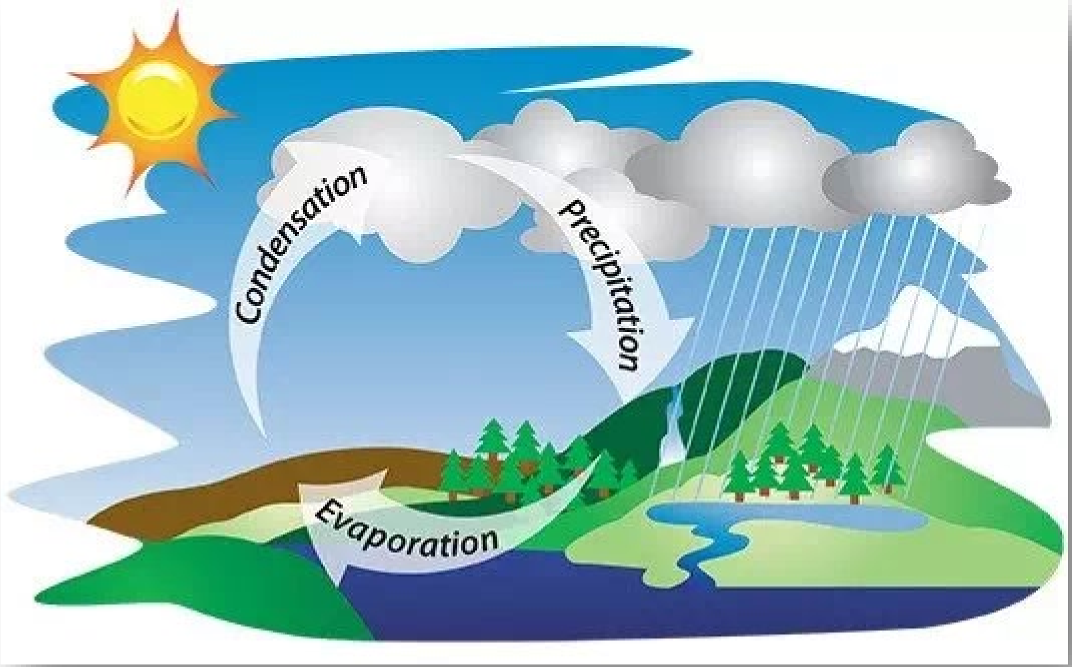


Roughly:

Ca. 3 % freshwater, of that:

- 2/3 in glaciers
- 1/3 in groundwater
- < 1 % surface water (directly usable)

Water cycle, simple



Main processes:

- Precipitation
- Evaporation
- Condensation

Driver:

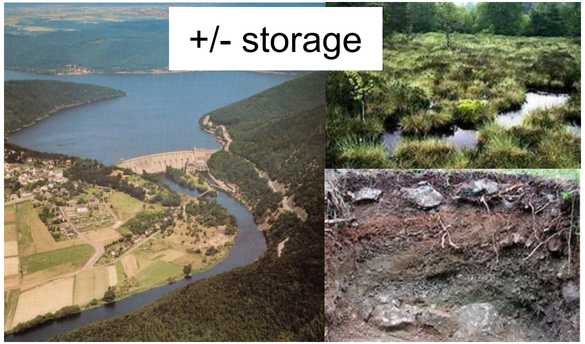
Solar radiation and gravity

Water balance equation

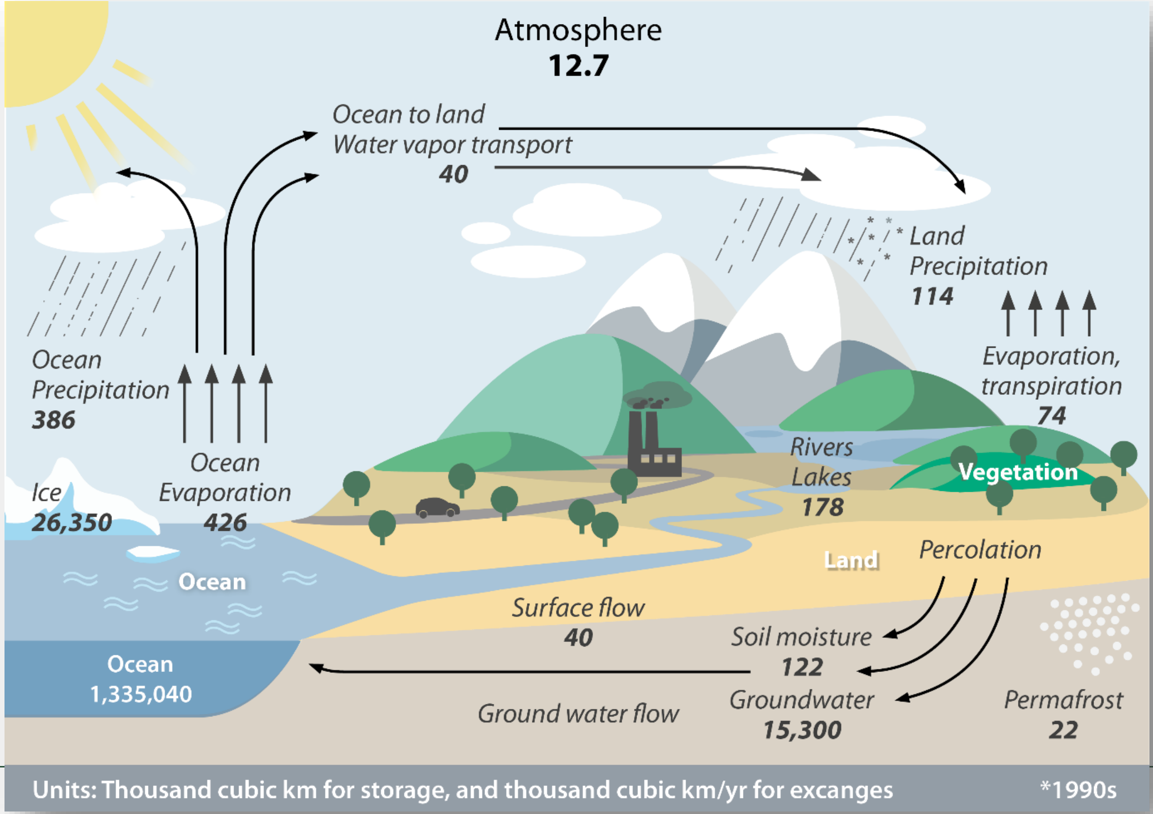
=

+

+



Water cycle, global



Water reservoirs

- Oceans, inland waters, glaciers, groundwater, atmosphere, soil water, organisms ...

Processes

- Precipitation,
- evaporation,
- seepage,
- Runoff

The global water cycle. Illustration: GIZ (2020) with data from Trenberth et al. (2011).

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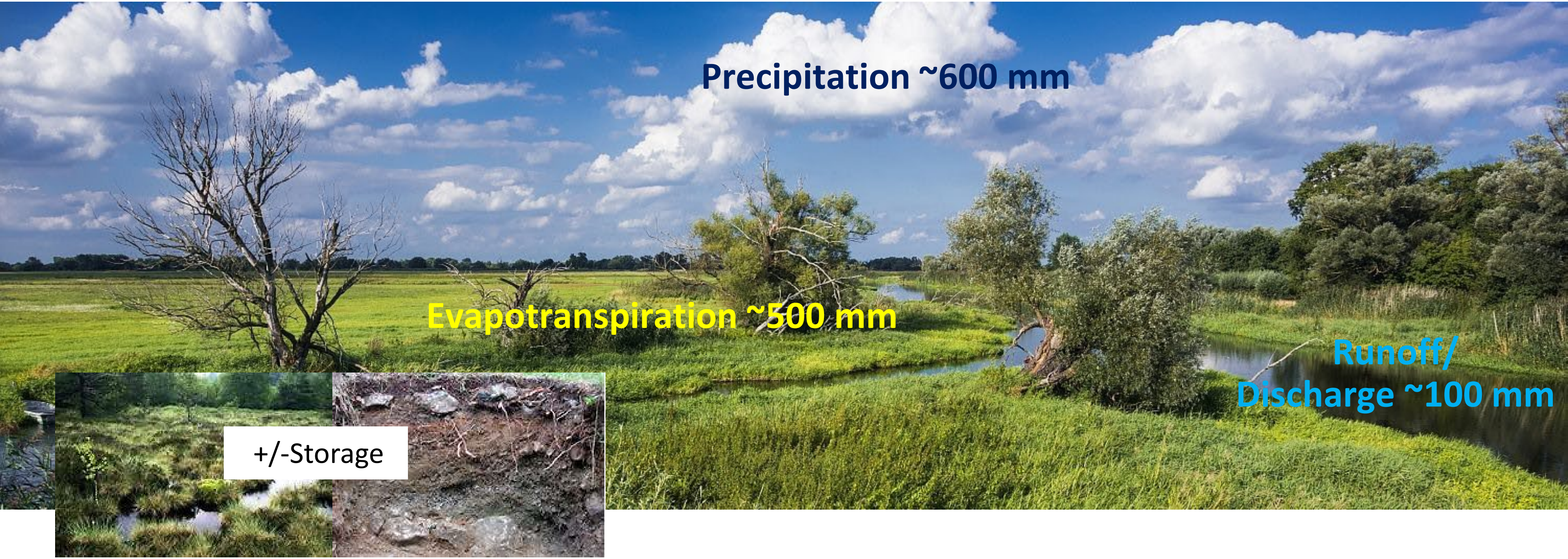
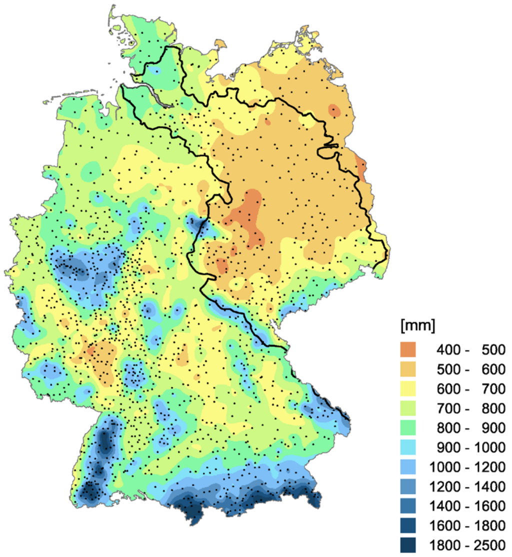
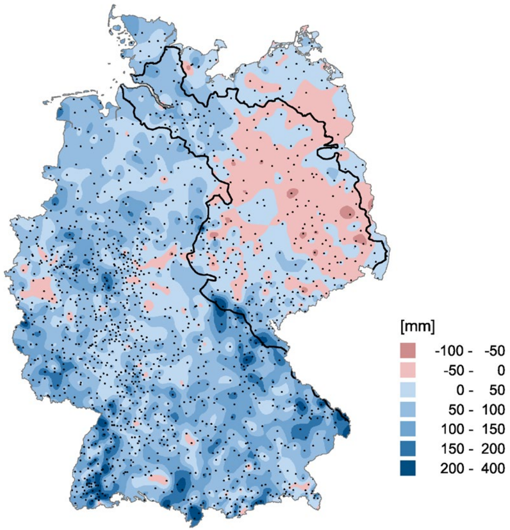
Water balance Brandenburg



Precipitation in Germany



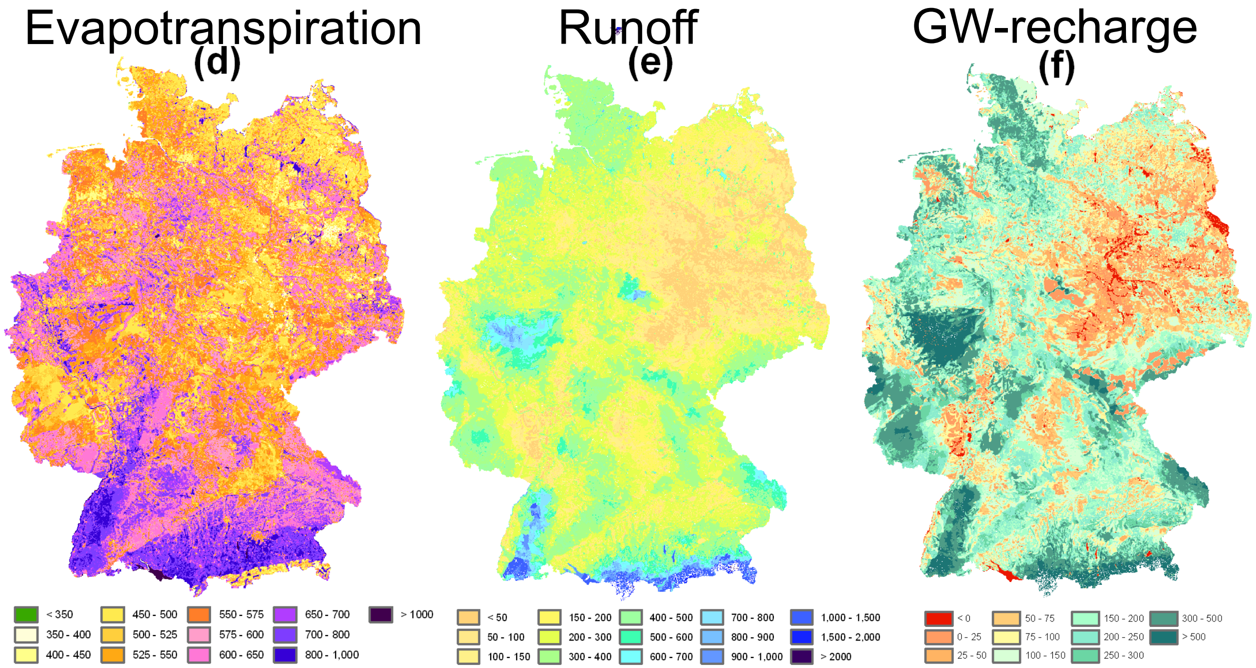
Mean precipitation 1951-2003



Trend in precipitation 1951-2003

Data: Wodinski, Gerstengarbe and Werner, PIK Potsdam

Components of the water balance Germany



Huang et al. 2010

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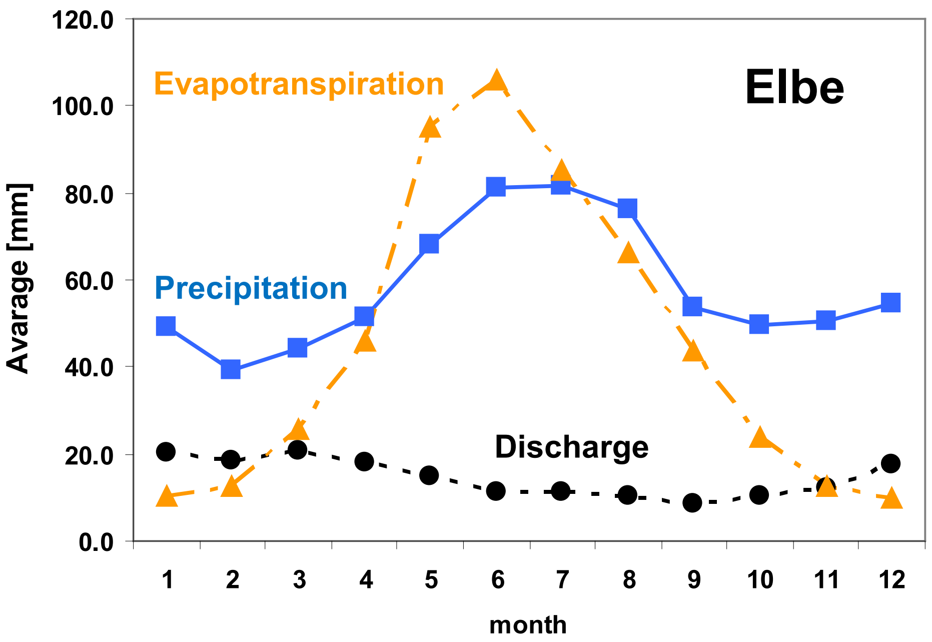
Seasonal water balance Elbe EZG



2 Precipitation

Precipitation

2.1 Formation of precipitation

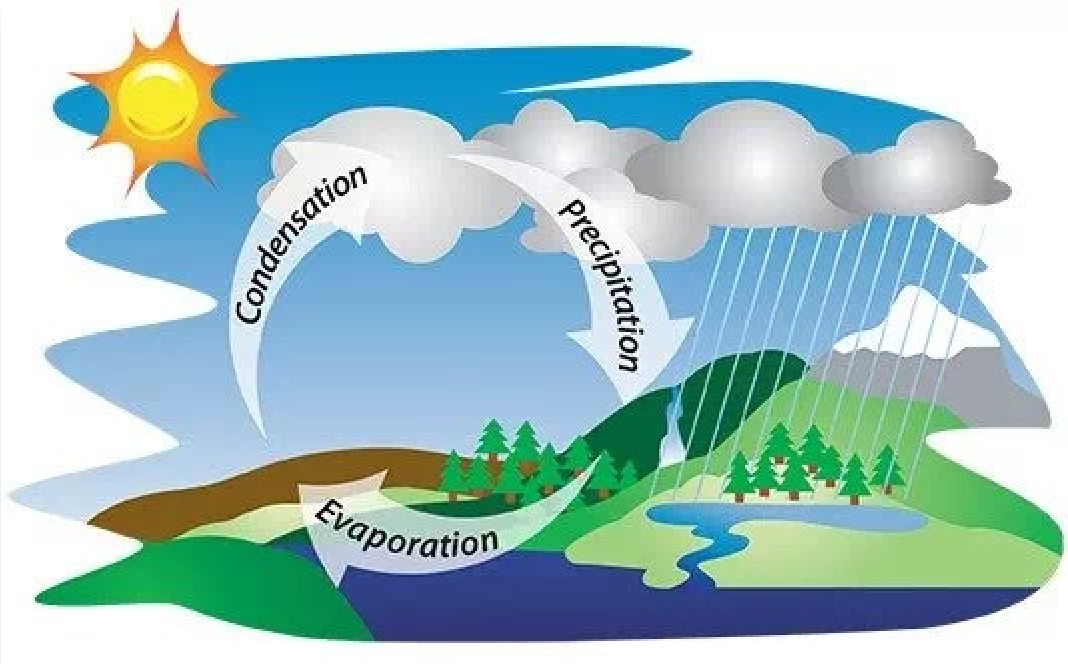
2.2 Precipitation monitoring

2.3 Precipitation in Germany and global

2 Precipitation

2.1 Formation of precipitation

Water cycle, simple



Main processes:

- **Precipitation**
- Evaporation
- Condensation

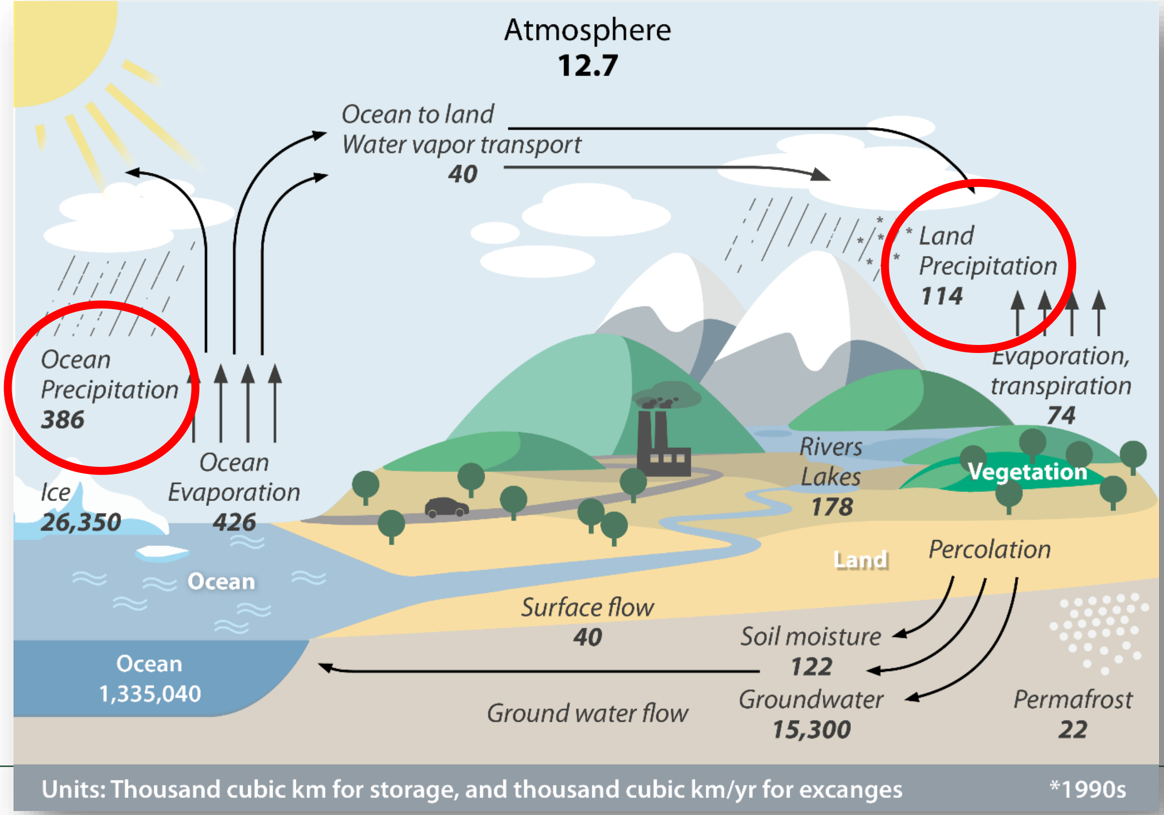
Driver:

Solar radiation and gravity

Conversion millimeter into litre

1 mm (rain) = 1 litre / m^2

Water cycle, global



Water reservoir

Oceans, inland waters, glaciers, groundwater, atmosphere, soil water, organisms ...

Processes

Precipitation,
evaporation,
seepage,
Runoff

The global water cycle. Illustration: GIZ (2020) with data from Trenberth et al. (2011).

Definition of precipitation

- Precipitation is generally understood to be the water precipitated from the atmosphere that has previously passed from the gaseous phase (water vapour) into the liquid or solid phase.
- In meteorology, a distinction is made between precipitation that has settled on surfaces (dew, hoarfrost, etc.) and precipitation that is falling (rain, snow, hail, etc.).
- Metéoron (Greek) means sky or air phenomena.

Definition of precipitation

According to DIN 1996, precipitation is: "Water of the atmosphere that has been formed in the air after condensation or sublimation of water vapour and, as a result of gravity, either moves to the earth's surface (falling precipitation) or has reached the earth's surface (settled precipitation)".

Formation of precipitation

The three preconditions for the formation of precipitation:

1. **Saturation of the air with water vapour** (relative humidity > 100%). For this to happen, the temperature of the air must be equal to the dew point temperature*. This is usually the result of cooling experienced by a rising or expanding air parcel.
2. **Phase transition** (condensation, freezing).
3. **Growth of droplets** and ice particles (aerosols important).

*** Dew point = temperature corresponding to the saturation vapour pressure. If temperature below dew point -> condensation, precipitation**

Calculation of saturation vapour pressure

For the calculation of the saturation vapour pressure *Ew* or especially for the phase transition liquid to gaseous, one can use the Clausius-Clapeyron equation. But it is difficult to integrate. Therefore, approximate solutions are applied, the simplest of which are the **Magnus formulae**:

For (flat) water surfaces: $E_w(T) = 6.112\ hPa * exp\ (\frac{17.62*T}{243.12°C+T})$

for $= -45°C \leq T \leq 60°C$

For (flat) ice surfaces: $E_w(T) = 6.112\ hPa * exp\ (\frac{22.46*T}{272.62°C+T})$

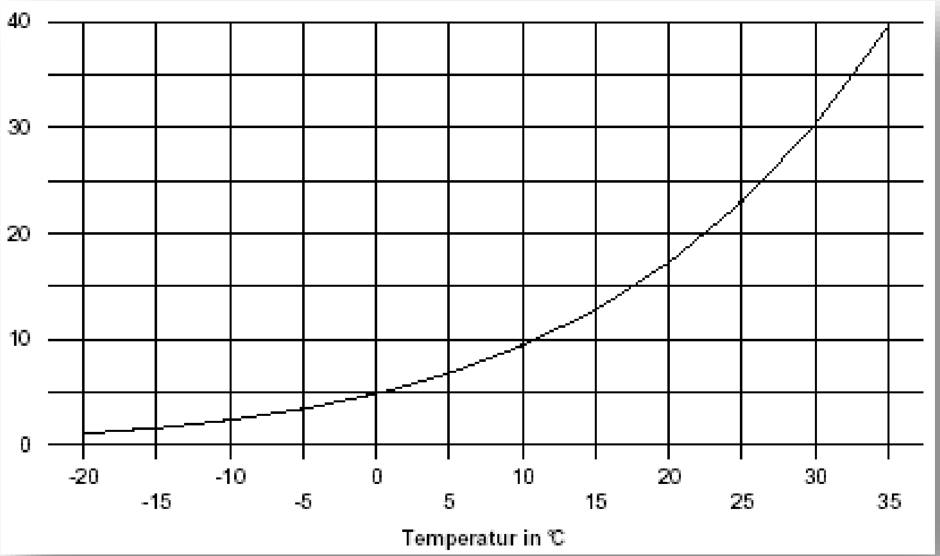
for $= -65°C \leq T \leq 0.01°C$

Some results of the Magnus formula

Temperature [°C]	-20	-10	0	+10	+20	+30
Saturation water content [g/m³]	1,1	2,4	4,8	9,4	17,2	30,3
Saturation vapour pressure $p_{v,s}$ [Pa], 1 Pa = 1 N/m²	124	285	611	1228	2339	4244

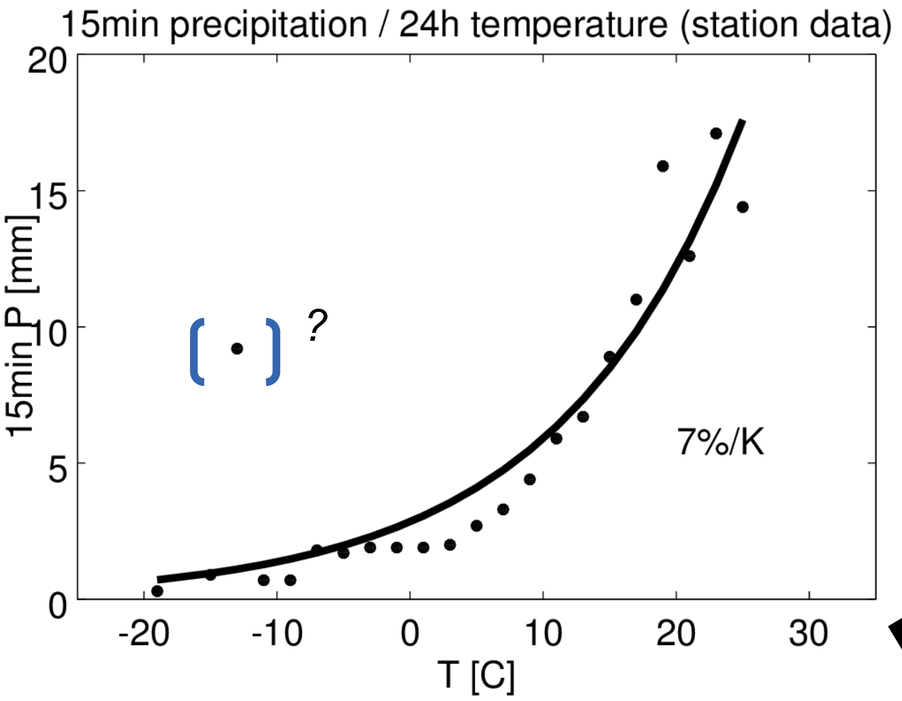
Saturated water content of the atmosphere is a non-linear function of temperature

θ [g/m³]



$\theta(18°C) - \theta(15°C) = 2.5\ g/m^3$ (= 19,4 %)

Increase of intense precipitation with temperature

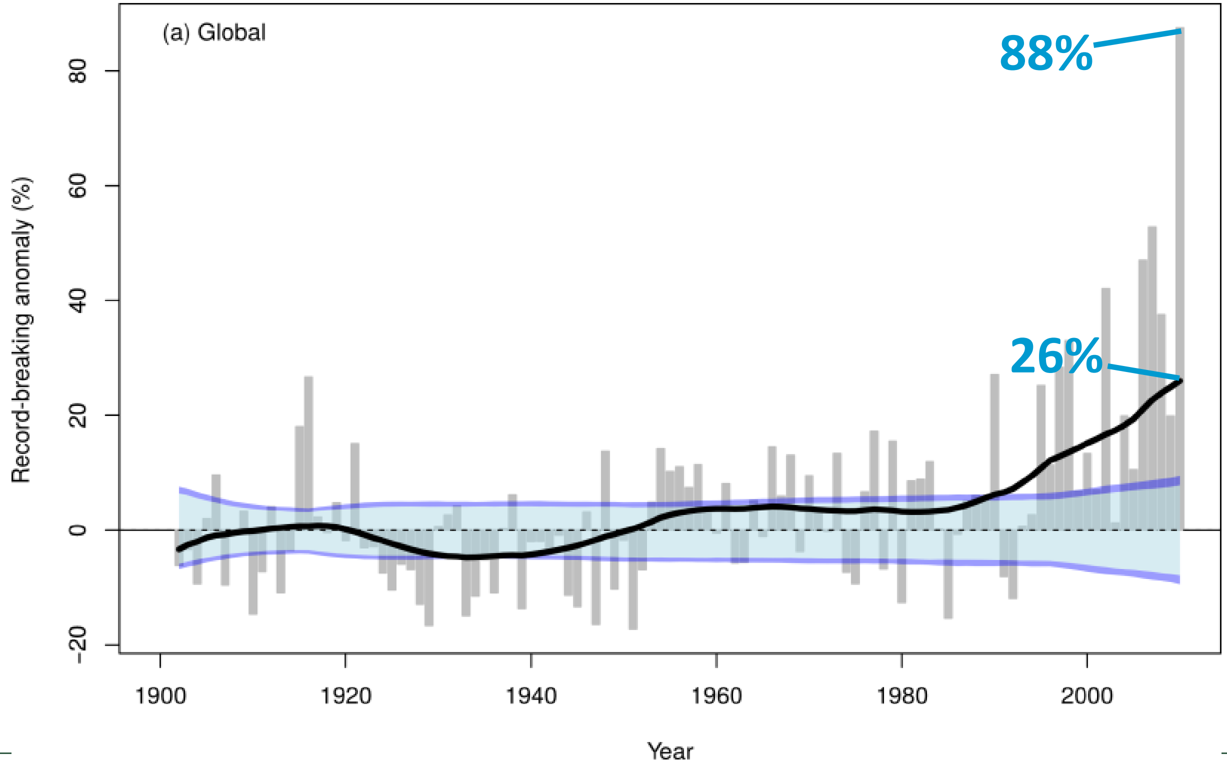


- 15min precipitation,
- 99.9% Quantile,
- Stations Brixenbachtal, Längental, Ruggbachtal

15min

Bürger, Uni Potsdam, personal communication

Daily Rainfall Records Increase Globally



- The saturation vapour pressure regulates the daily amounts of heavy rainfall.
- This increases at a rate of 7% per degree of warming (Clausius-Clapeyron).

Lehmann et al., Climatic Change, 2015

Precipitation types

Direct condensation or sublimation of water vapour at or near the earth's surface:

- **Liquid form:** Dew (condensation)
- **Solid forms:** Frost (resublimation), frozen dew

Falling precipitation: condensation or sublimation in the free atmosphere, precipitation from clouds:

- **Liquid form:** Rain
- **Solid forms:** Snow, hail, sleet

Frost

Source: Karlsruher Wolkenatlas

Snow

Source: Karlsruher Wolkenatlas

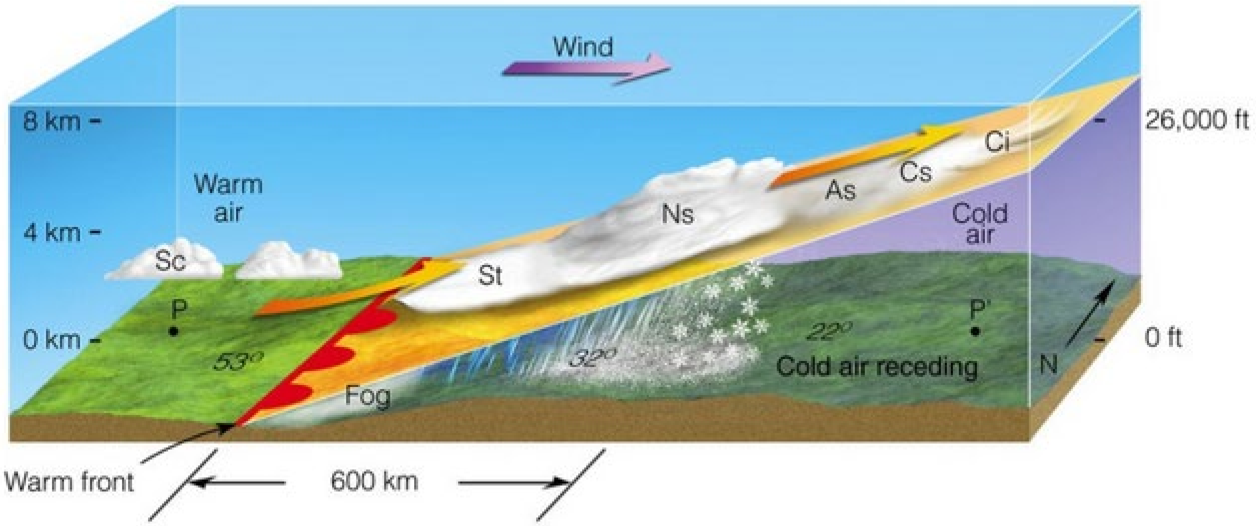
Hail

Source: Karlsruher Wolkenatlas

Hail

Quelle: http://www.chaseday.com/hail.htm

Advective (front) precipitation



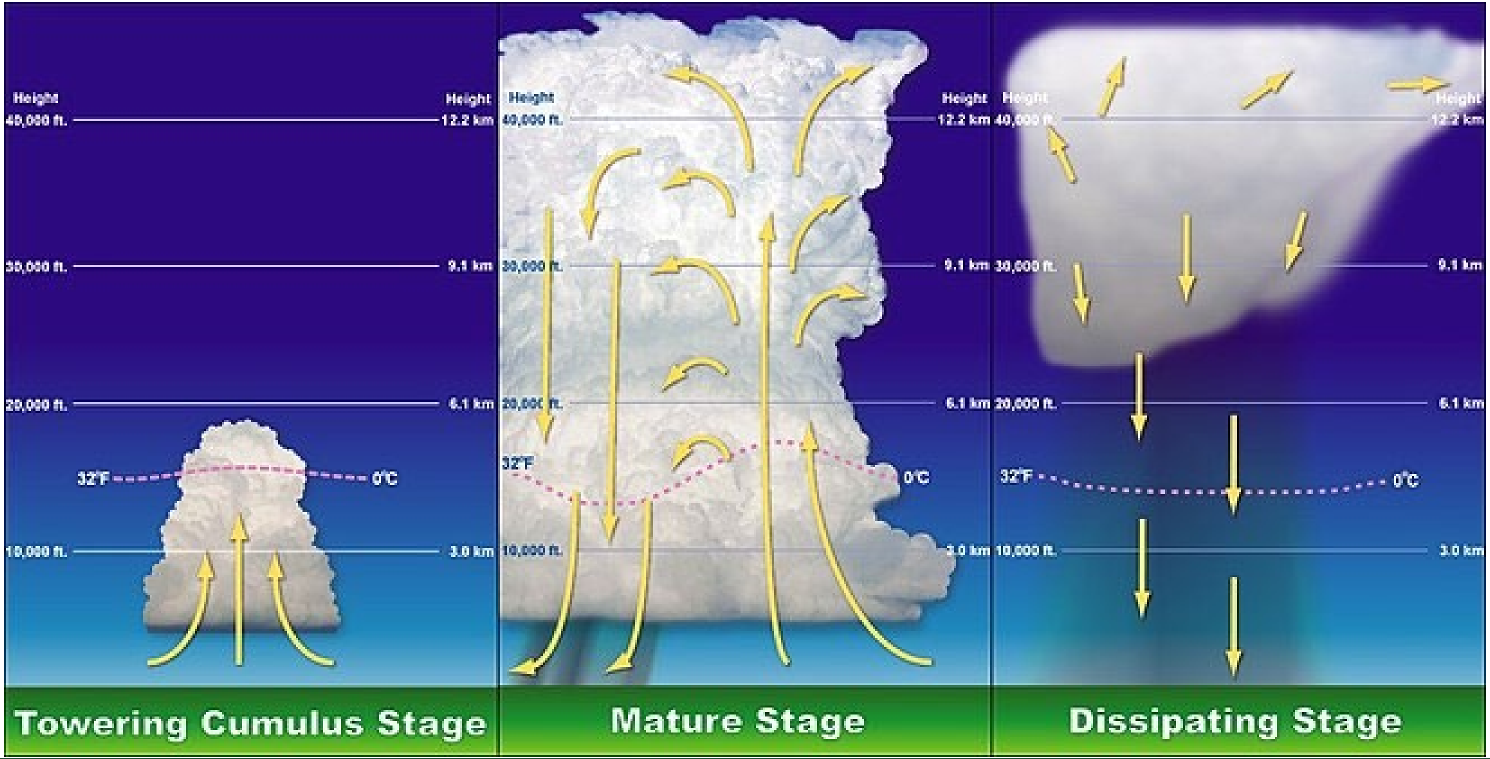
Typical precipitation types associated with a warm front advancing over cold air masses

https://www.stratusdeck.co.uk/fronts

Advective (front)

Source: Karlsruher Wolkenatlas

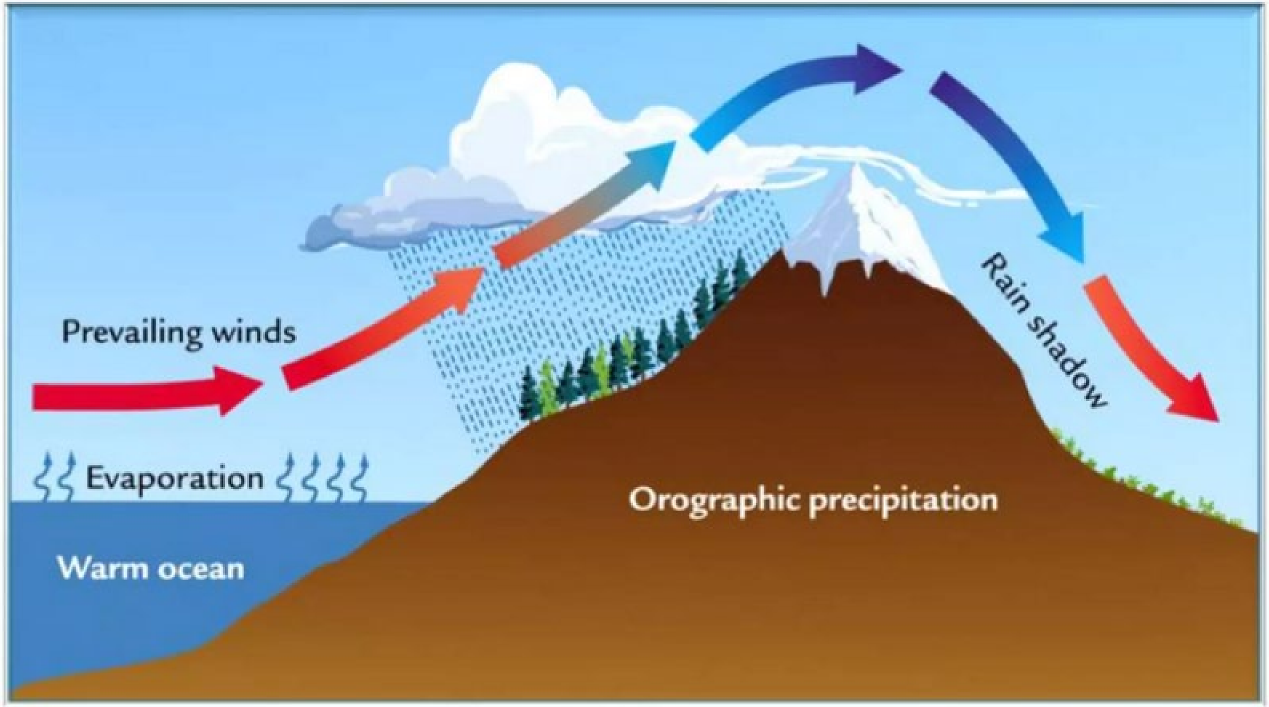
Convective


Height
40,000 ft.
30,000 ft.
20,000 ft.
10,000 ft.
12.2 km
9.1 km
6.1 km
3.0 km
32°F
0°C
Towering Cumulus Stage
Mature Stage
Dissipating Stage

Convective rain – thunder storms

Source: Karlsruher Wolkenatlas

Orographic



https://www.slideshare.net/slideshow/types-of-rainfall/27227404#8

Orographic

Source: Karlsruher Wolkenatlas

Settled precipitation

This form of precipitation has its special significance in:

- **Cloud forests** (e.g. Andes, Canary Islands)
- **Coastal deserts** (e.g. Southwest Africa, Northern Chile)

2 Precipitation

2.2 Monitoring of precipitation

Conversion millimeter into litre

1 mm (rain) = 1 litre / m²

Hellmann rain gauge (ombrometer)

- Reference area: 200 cm^2
- 1 m above surface (snow free)
- 1,5 m above surface (snow)

https://www.spektrum.de/lexikon/geographie/hellmann-regenmesser/3425

Undercatch

Classical observartions techniques underestimate precipitation by 10-20% at least, due to:

- the influence of evaporation and spray water,
- snow bonnets, wind influence as well as wetting influence.
- In addition, inhomogeneities in the environment interfere, e.g. with plant growth, high-rise construction.

Undercatch larger for snow

Empirical and physically based methods to correct exist

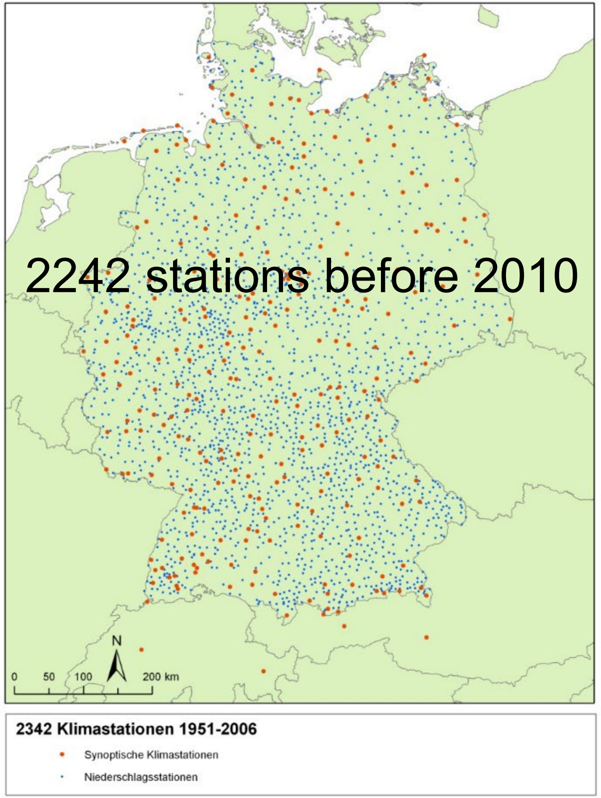
Advanced rain gauges

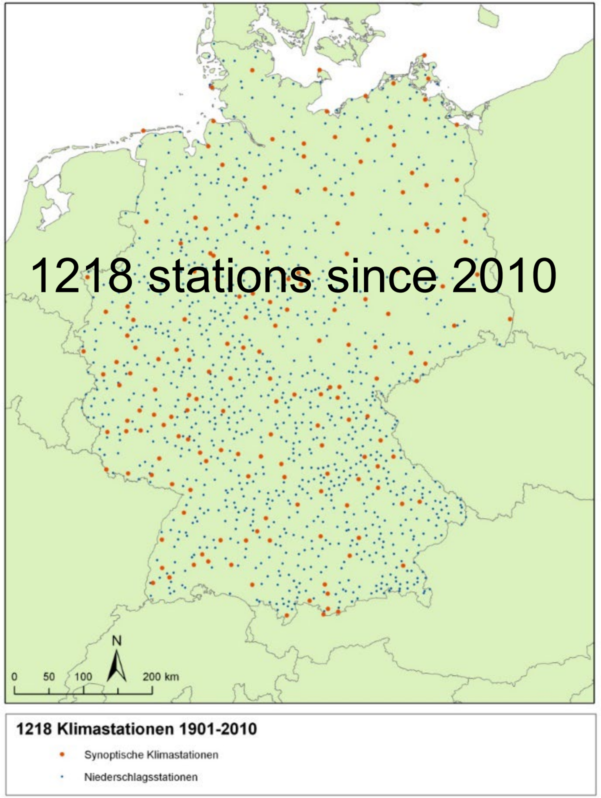
- Precipitation gauge based on the weighing principle with wind protection
- Many types and variations exist
- Often digital

- Comparability!?

Synoptic station

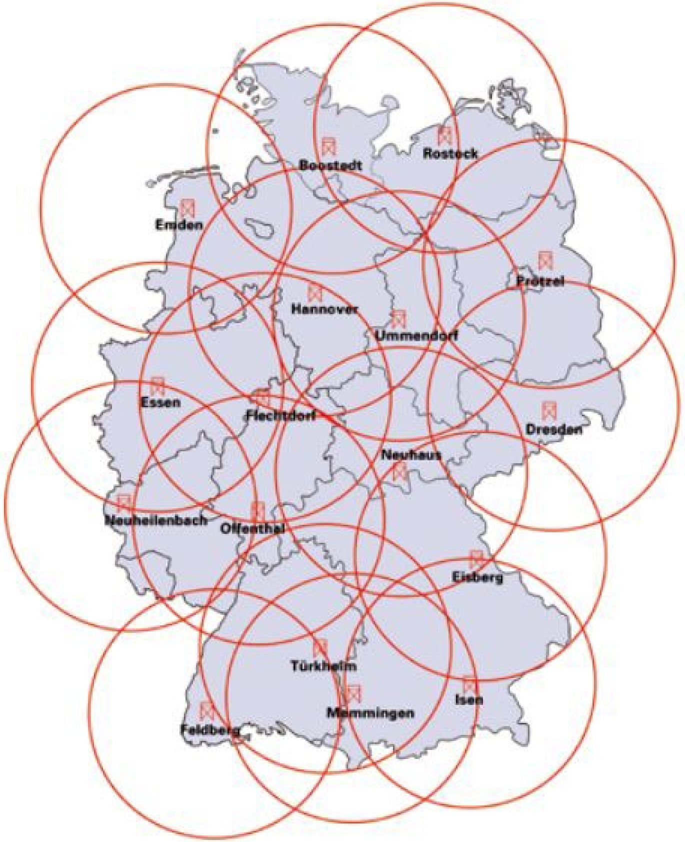
Observation network in Germany





Radar monitoring of precipitation

Radar station of the DWD
(Reach per station 150 km)



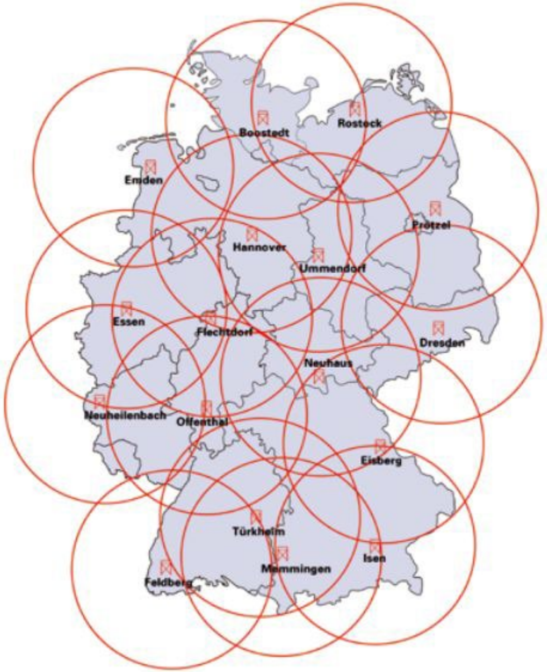
https://www.dwd.de/DE/leistungen/radarprodukte/radarprodukte.html

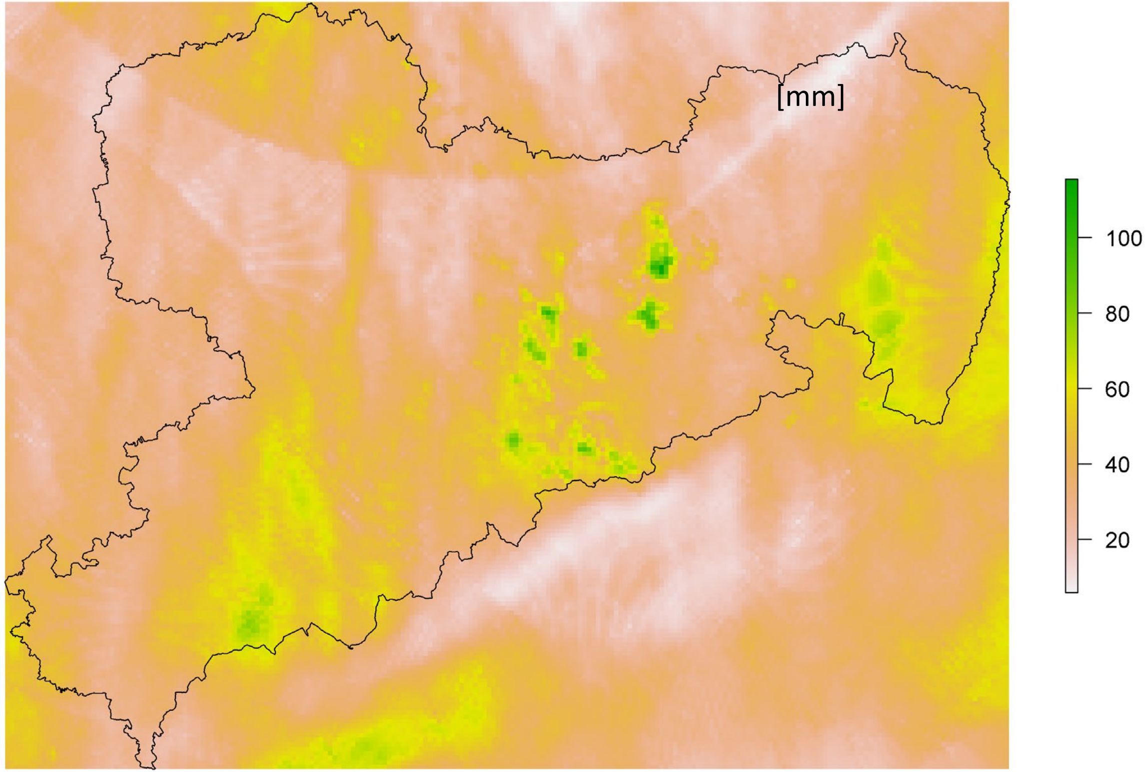
Radar monitoring

- Radar cannot directly measure the precipitation height.
- The radar impulses reflected by raindrops only provide an areal distribution of the strength of the radar echoes. Since the strength of the backscatter depends on the size and quantity of the raindrops, the precipitation height can be calculated using empirical relationships and correction methods.
- The radar data are calibrated by means of precipitation measurements on the ground.
- The DWD radar network comprises 16 radar sites, each with a radius of 128 km, which ensure extensive coverage of Germany.

https://www.dwd.de/DE/leistungen/radarprodukte/radarprodukte.html

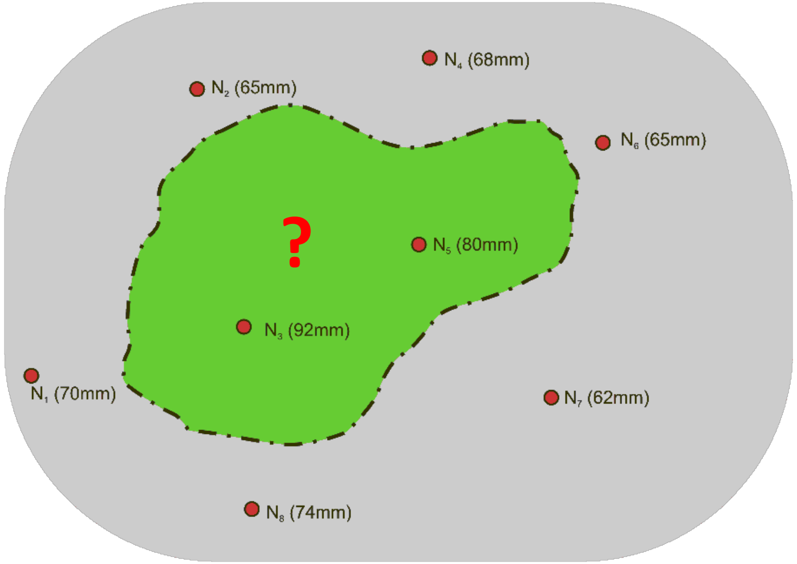
Radar monitoring

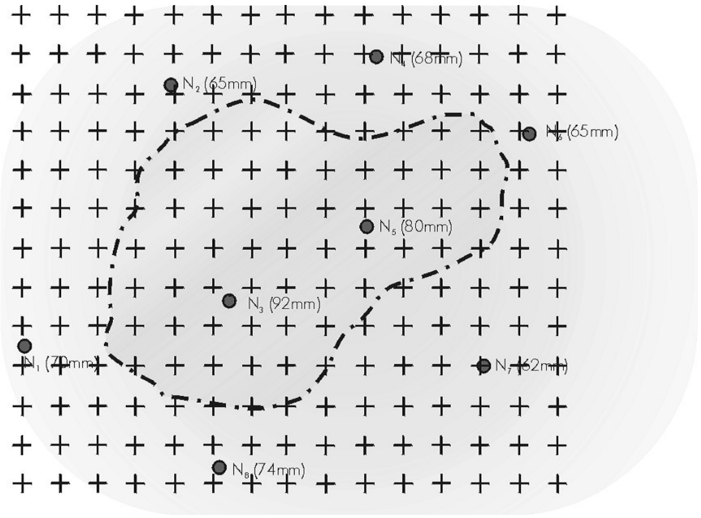




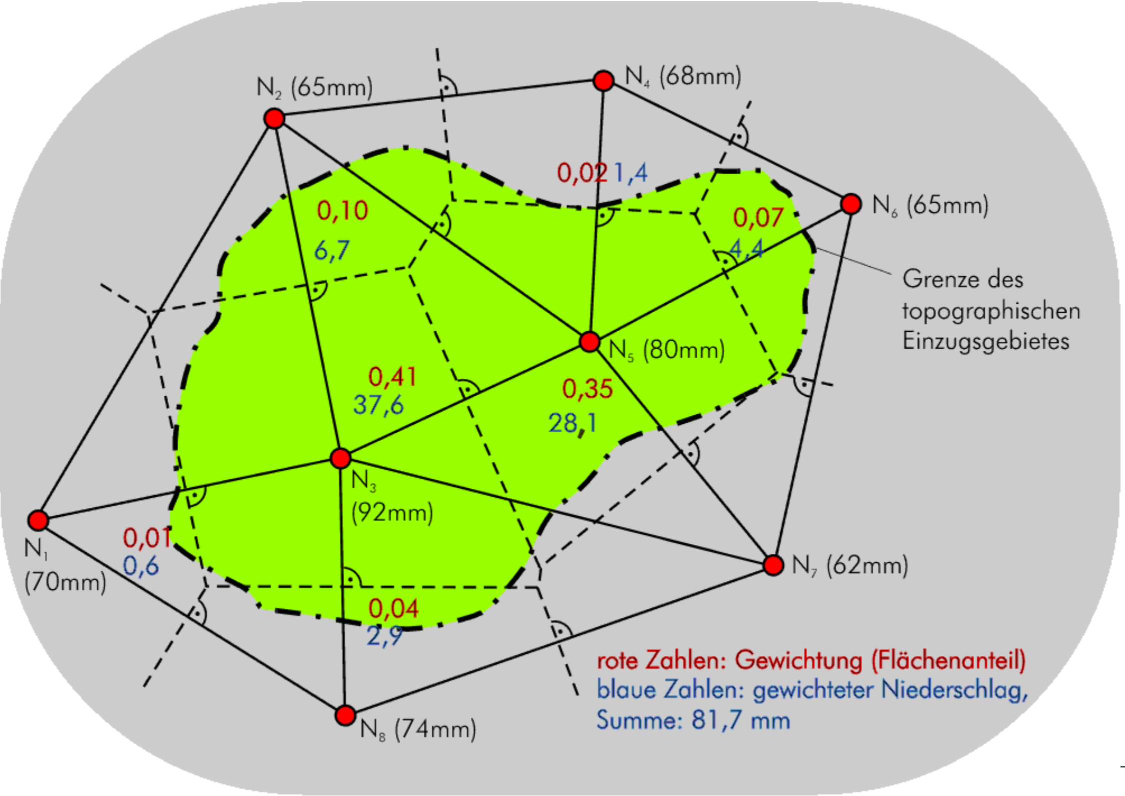
https://www.dwd.de/DE/leistungen/radarprodukte/radarprodukte.html

Interpolation of point measurements

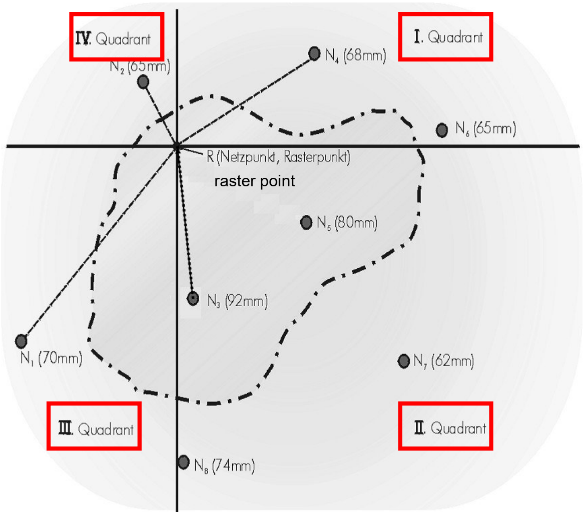




Weighted mean and polygon method



Inverse distance



Inverse distance

$$h_{p,j} = \sum_{i=1}^{4} W_{i,j} \cdot h_{p,i} \quad , \quad W_{i,j} = \frac{1/d_{i,j}^2}{\sum_{i=1}^{4} 1/d_{i,j}^2} \quad , \quad h_p = \frac{1}{nr} \sum_{i=1}^{nr} h_{p,i}$$

$h_{p,j}$: Niederschlagshöhe am Rasterpunkt j

$h_{p,i}$: Niederschlagshöhe an Station i

$W_{i,j}$: Gewichtungsfaktor am Rasterpunkt j für Station i

$d_{i,j}$: Distanz des Rasterpunktes j zu Station i

h_p : Gebietsniederschlag

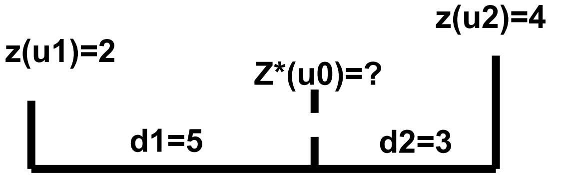
nr : Anzahl der Rasterpunkte im Einzugsgebiet

Good for non-uniformly distributed stations, as an interpolation method for soft transitions

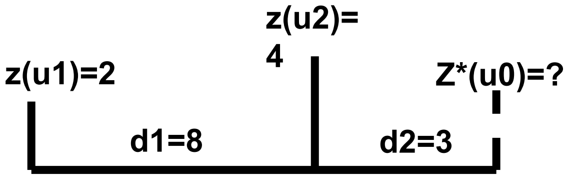
Inverse distance

Example (with p=1, n=2):

$$Z^*(u_0) = \frac{\sum_{i=1}^{n} \frac{z(u_i)}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}}$$

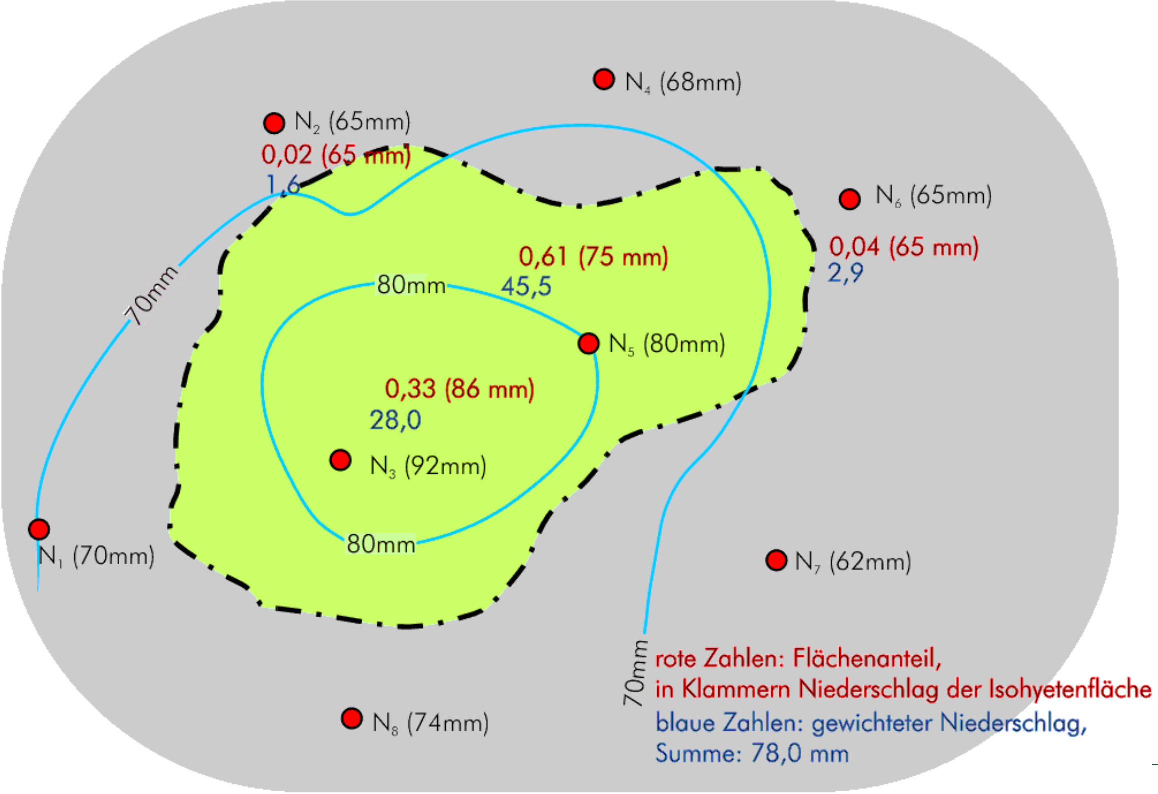


$$Z^*(u_0) = \frac{\frac{2}{5} + \frac{4}{3}}{\frac{1}{5} + \frac{1}{3}} = \frac{\frac{6}{15} + \frac{20}{15}}{\frac{3}{15} + \frac{5}{15}} = \frac{26}{8} = 3\frac{1}{4}$$



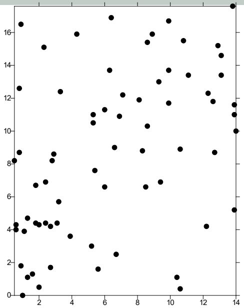
$$Z^*(u_0) = \frac{\frac{2}{8} + \frac{4}{3}}{\frac{1}{8} + \frac{1}{3}} = \frac{\frac{6}{24} + \frac{32}{24}}{\frac{3}{24} + \frac{8}{24}} = \frac{38}{11} = 3\frac{5}{11}$$

Isohyetes (zones of the same hight)

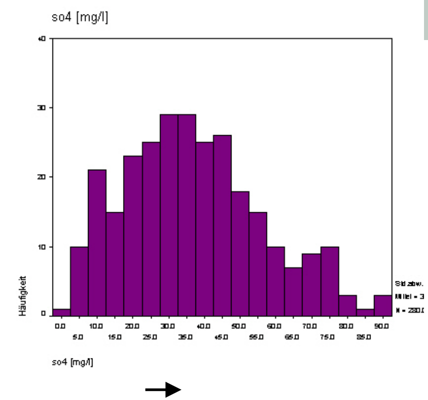


Geostatistical methods

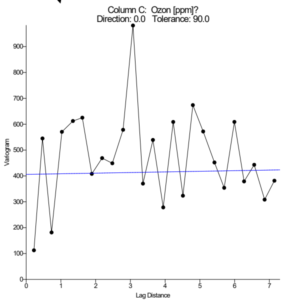
2) Observations



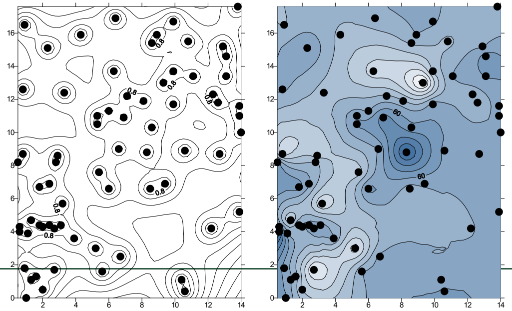
2) Data analysis



3) Variogram

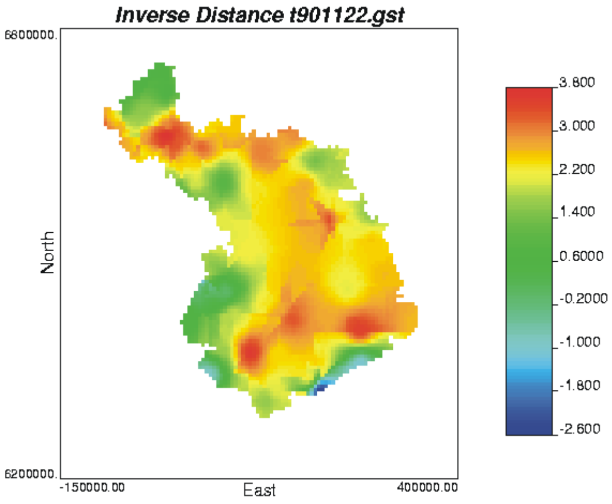


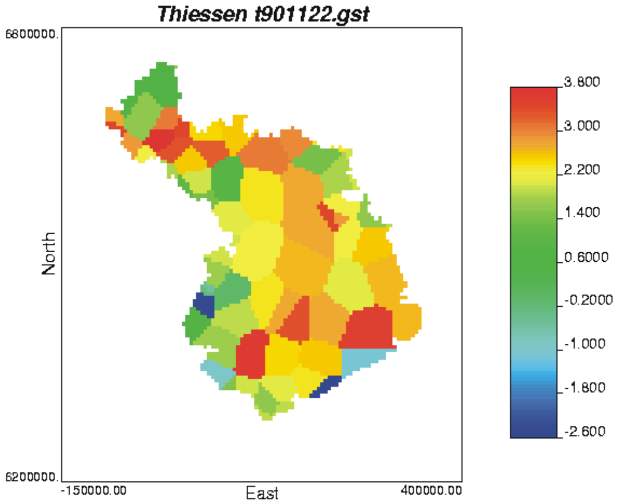
4) Interpolation with Kriging

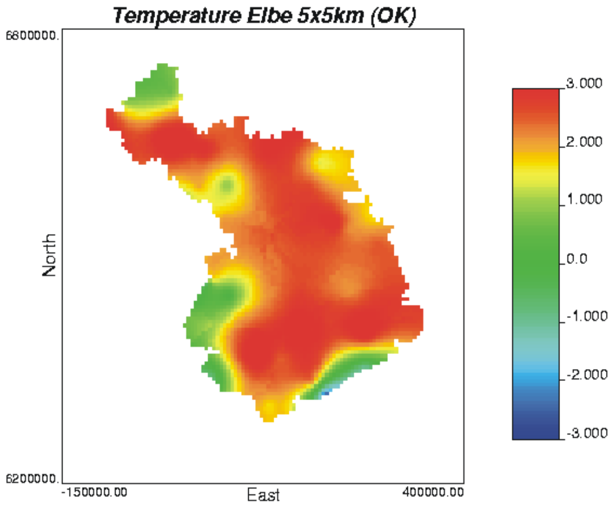


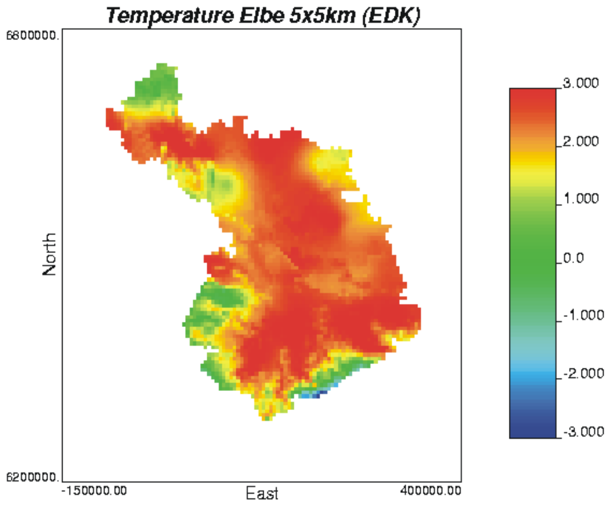
5) Error analysis!

Comparison of the methods





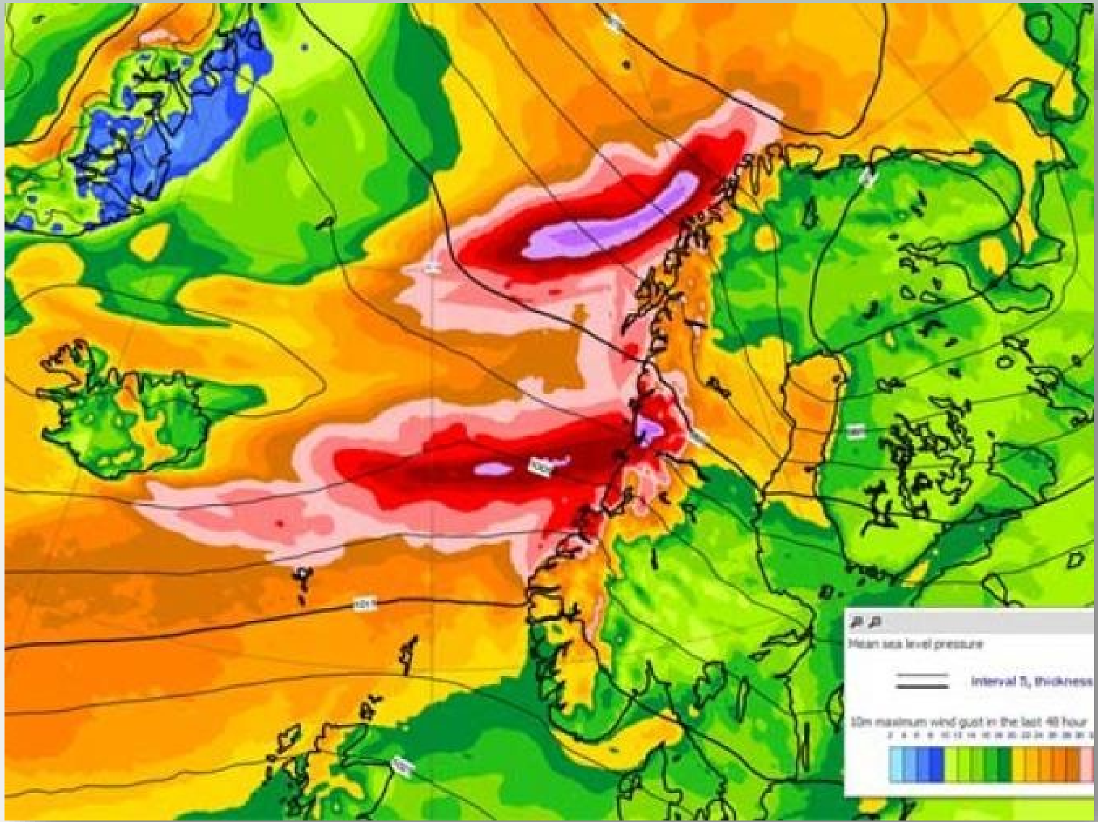




Reanalysis data is another possible combination of spatial and point data

- **Weather forecast data and station data are combined;**
- **In the process, a weighted combination of measured values and older model predictions is interpolated onto the model grid** using various mathematical methods (so-called data assimilation);
- In a numerical forecast model, the computational domain is discretised with grid cells so that the relevant physical quantities, such as temperature, precipitation, air pressure, density and wind speed, can be represented in three-dimensional space and as a function of time.

Reanalysis data



- Weather forecasts are available worldwide in high temporal and spatial resolution
- They are constantly updated with observations (data assimilation)

(Source: European Meteorological Service)

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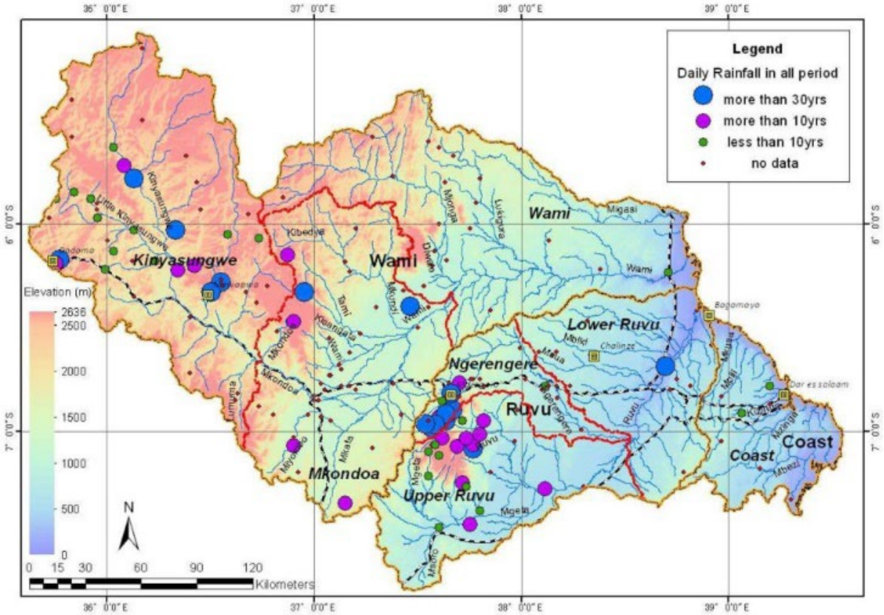
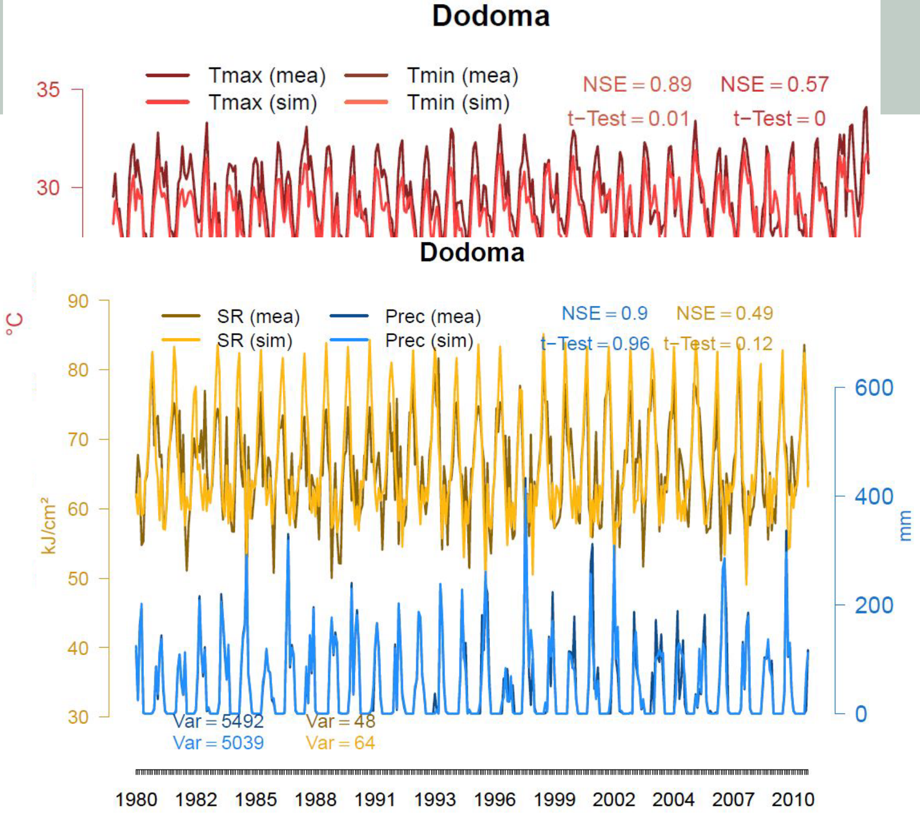
Example: Re-analysis data for Tanzania





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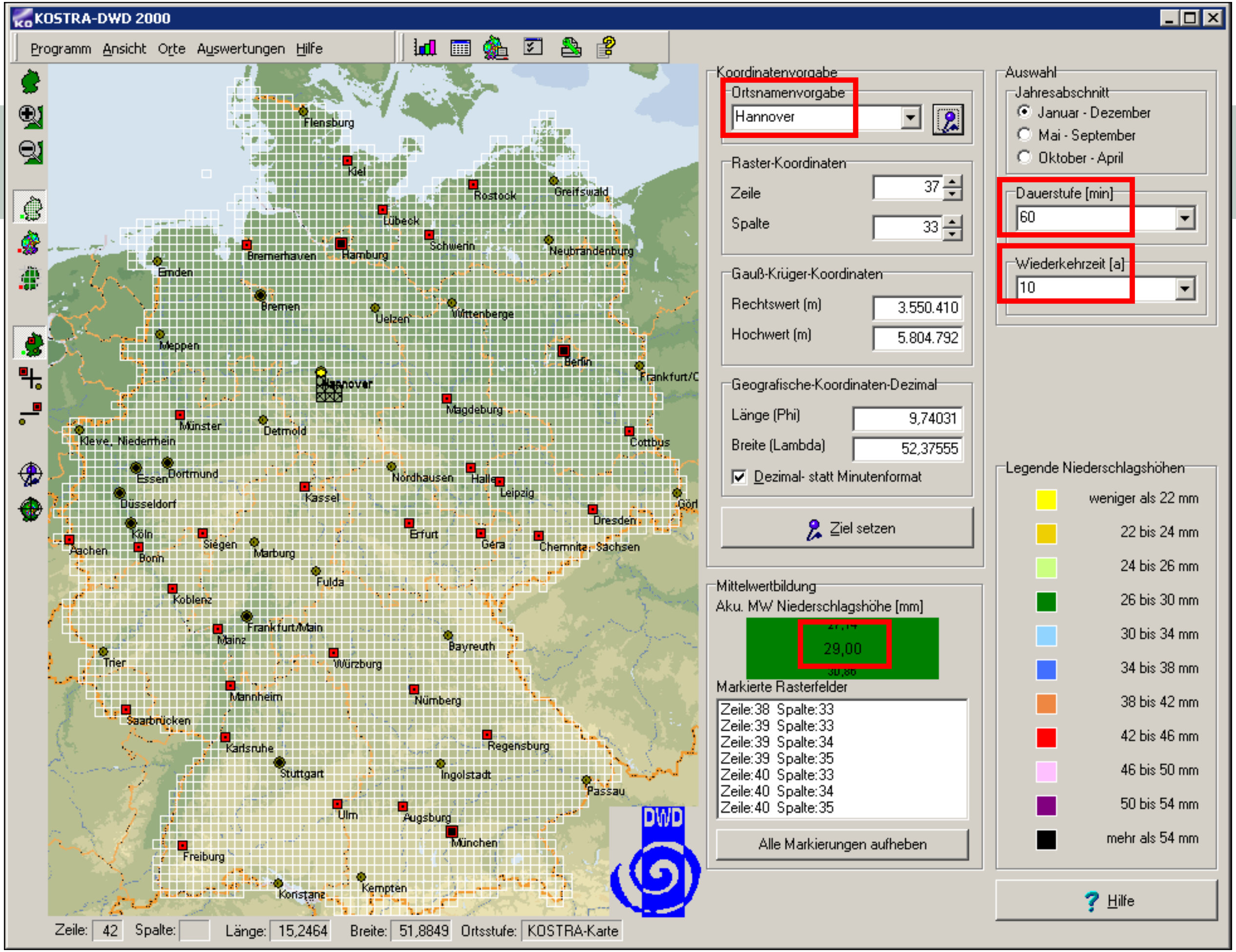
The COSTRA system of the DWD: Information about intense precipitation



https://www.dwd.de/DE/leistungen/kostra_dwd_rasterwerte/kostra_dwd_rasterwerte.html

2 Precipitation

2.3 Precipitation in Germany and global

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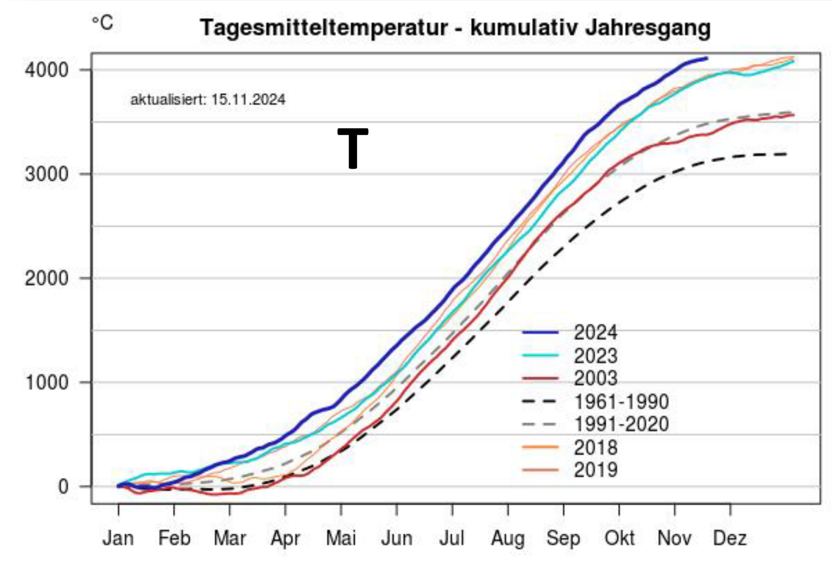
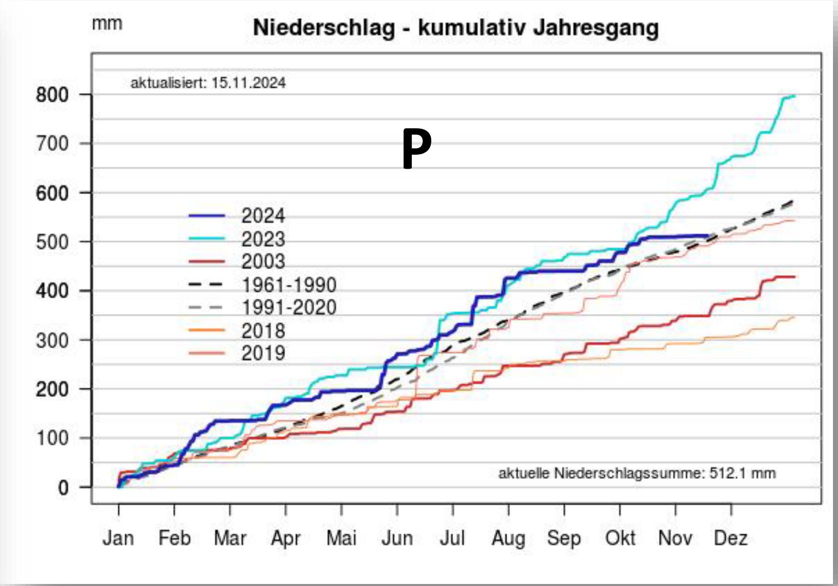
P I K

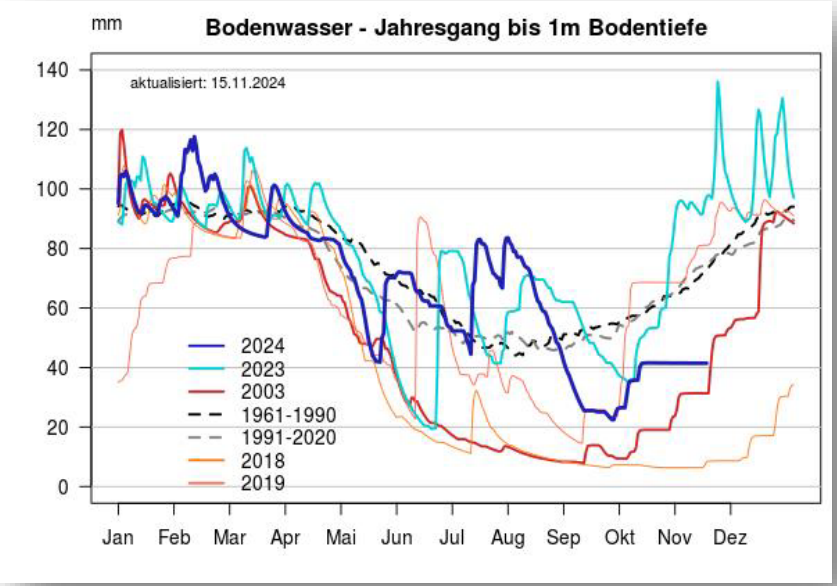
Recent precipitation Potsdam

https://www.pik-potsdam.de/de/produkte/klima-wetter-potsdam/wetteranalyse

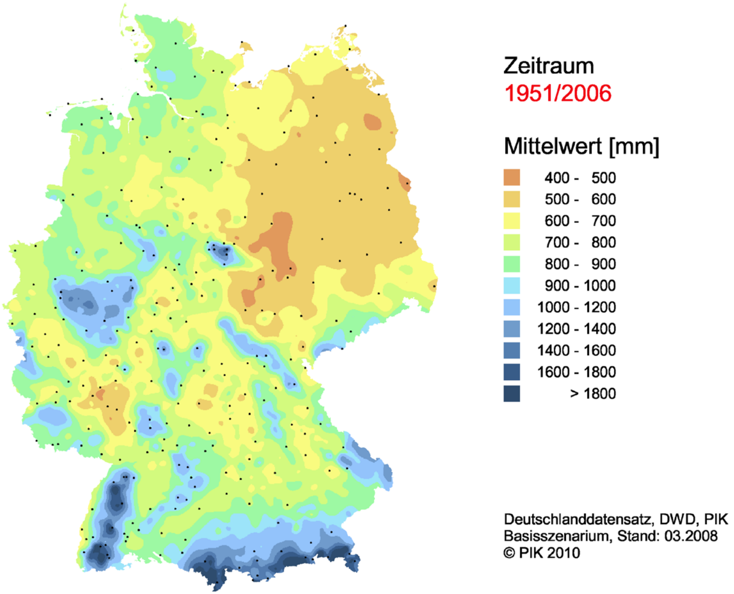


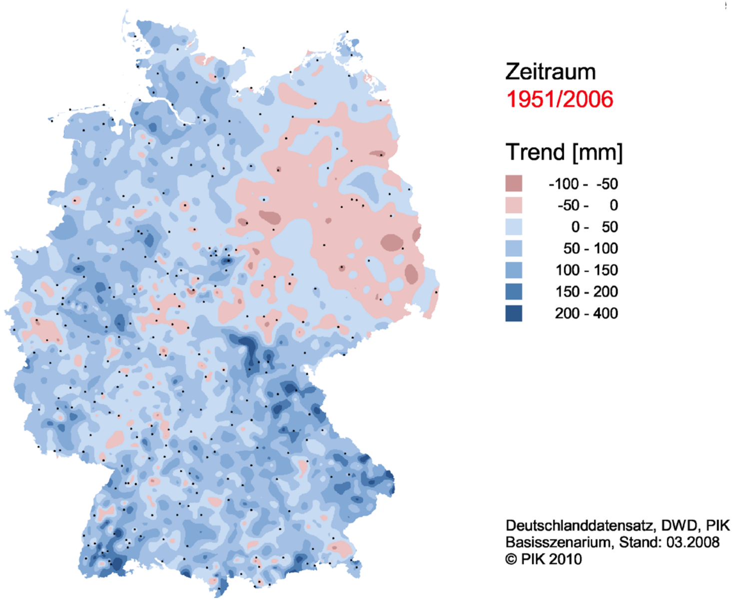


Soil moisture station Potsdam



Annual precipitation total (left) and trend (right)





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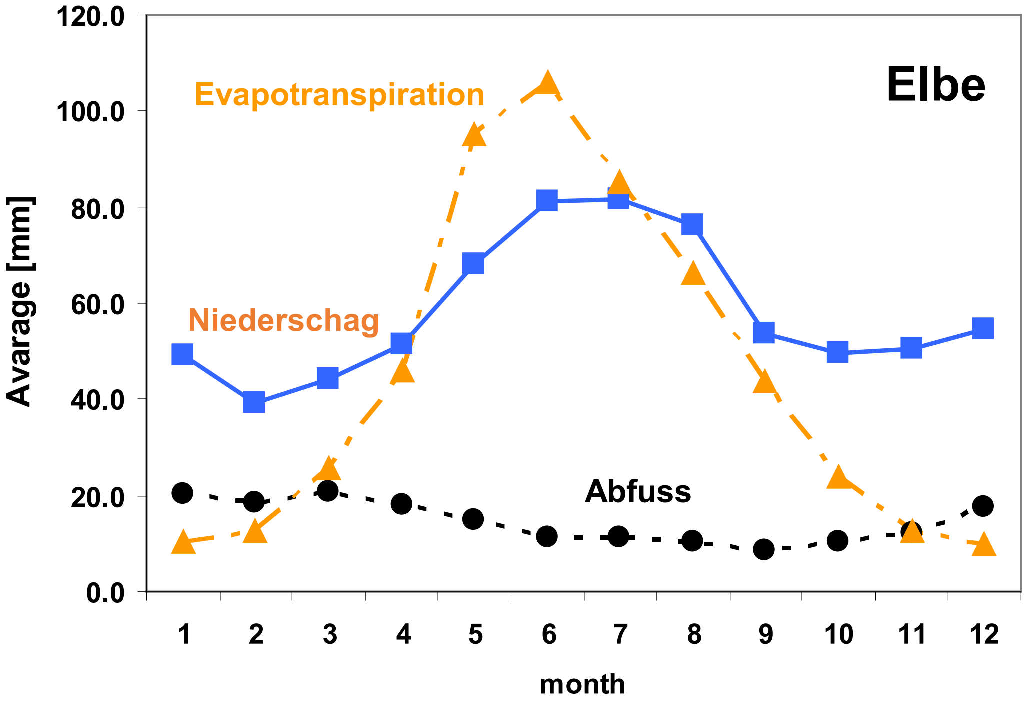
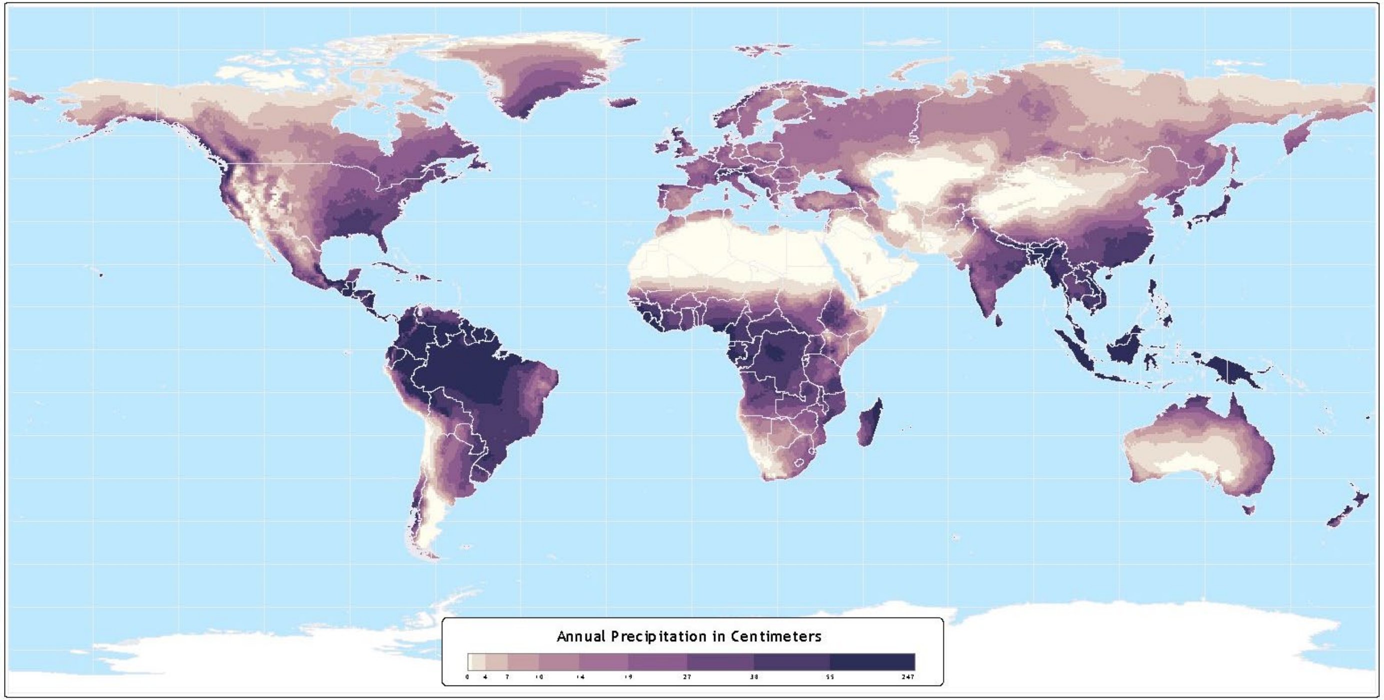
Seasonal distribution of precipitation



Global precipitation



Data taken from: CRU 0.5 Degree Dataset (New et al)

Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

Precipitation records (annual)

Precipitation records				
Continent	**Land**	**Location**	**Value**	**Year**
Europe	Croatia	Crkvice	4648 mm	1881
	Germany	Balderschwang (Allgäu) Potsdam	3503,1 mm 788,8 mm	1970 1981
Africa	Kamerun	Debundscha	10287 mm	1932
America	USA	Paradise (Mt. Rainier)	31100 mm (Snow)	1970/71
	Kolumbia	Lloro	13299 mm	1929
Asia	India	Cherrapunji	26461 mm	1860/61
Australia	Queensland	Bellenden Ker	8636 mm	1909

Precipitation records (subannual)

Daily precipitation records				
Continent	**Land**	**Location**	**Value**	**When**
Africa	La Reunion	Cilaos	1870 mm	15.03.-16.03.1952
Europe	Deutschland	Zinnwald Potsdam	312.0 mm 105.7 mm	12.08.2002 08.08.1978
Monthly precipitation records				
Asia	Indien	Cherrapunji	9300 mm	1970/71
Europe	Deutschland	Oberreute (Bodensee) Potsdam	777 mm 202.3 mm	Juli 1954 Juli 1907
Snow records				
America	USA	Paradise (Mt. Rainier)	31100 mm	1970/71
Europe	Deutschland	Zugspitze Potsdam	8300 mm 700 mm	02.04.1944 1969/70

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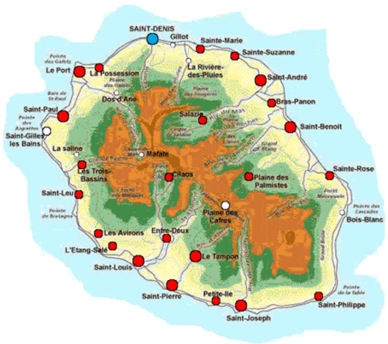
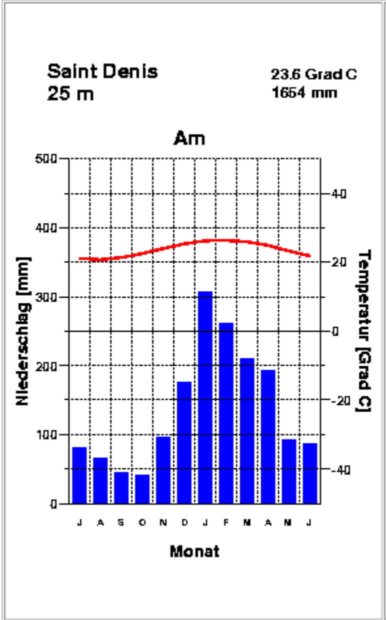
Orographic precipitation La Reunion



La Reunion

Climate diagram
Saint Denis/Reunion



Saint Denis		
Monat	[mm]	[° C]
Jan	306	26.2
Feb	262	26.3
Mar	211	26.0
Apr	193	24.9
May	93	23.3
Jun	87	21.8
Jul	81	21.1
Aug	65	20.8
Sep	45	21.4
Oct	40	22.6
Nov	96	24.0
Dec	175	25.3
Year	**1654**	**23.6**

Group work: please answer the questions!

1. How is the global share of saltwater and freshwater?
2. What are the three main components of the water balance?
3. How much water is 600 mm of precipitation?
4. How is the water balance of Brandenburg?
5. What is undercatch of observed precipitation?
6. Is the saturated water content of the air a linear or non-linear function of T?
7. What is orographic precipitation?

3. Evapotranspiration

Evapotranspiration

4.1 Definition and processes

4.2 Monitoring

4.3 Evaporation in Germany and global

3. Evapotranspiration

3.1. Definition and processes

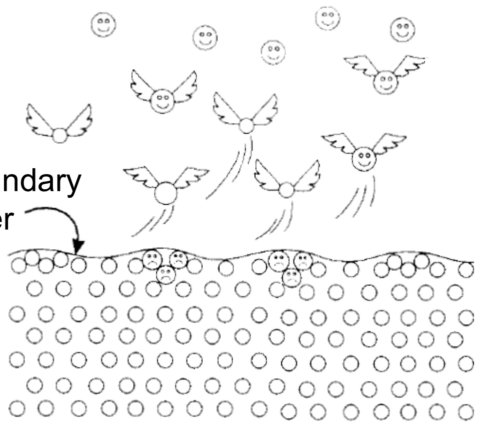
Definition

DIN 4049-3

Evaporation is a process in which water changes from the solid or liquid aggregate state to the gaseous state at temperatures below the boiling point.

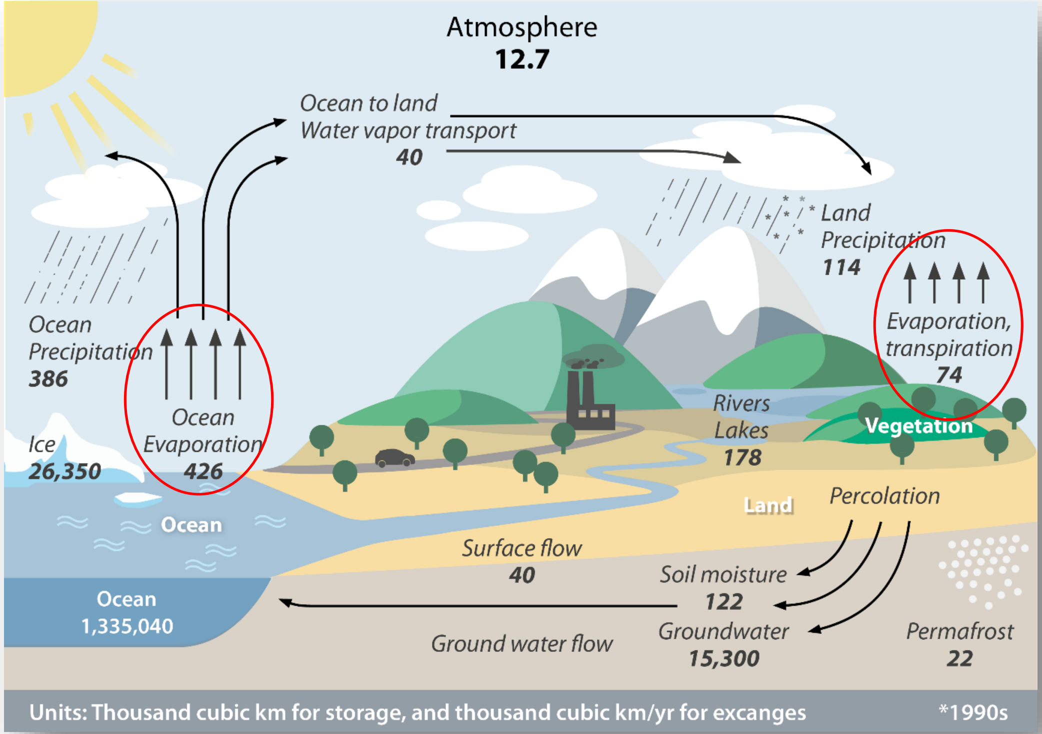
Unit of measurement: mm/unit of time

Evaporation



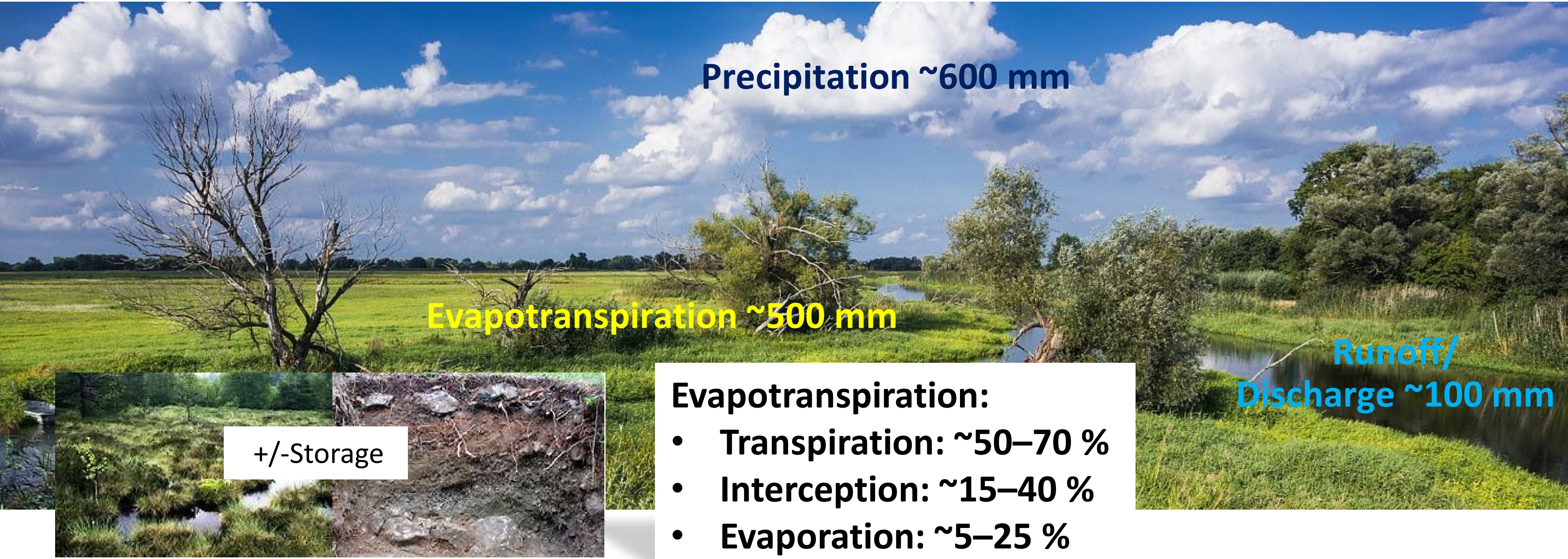
- When the molecules of a liquid collide, they transfer energy based on how they collide with each other.
- When a molecule near the surface absorbs enough energy to overcome the vapour pressure, it will escape and enter the surrounding air as a gas.

Water cycle, global



Der globale Wasserkreislauf. Darstellung: GIZ (2020) mit Daten aus Trenberth et al. (2011).

Water balance Brandenburg

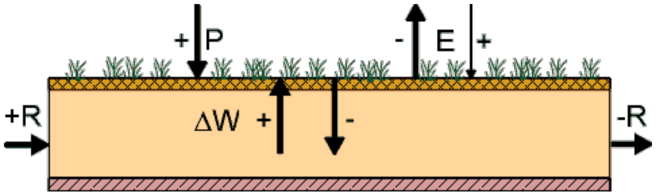


Evapotranspiration:

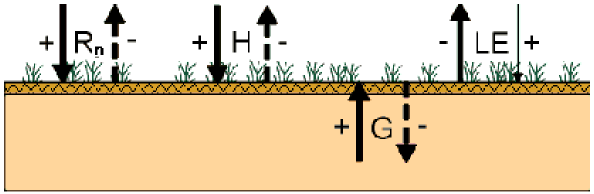
- Transpiration: ~50–70 %
- Interception: ~15–40 %
- Evaporation: ~5–25 %

Water balance and energy balance are coulpled via evaporation

Water balance	
$N + V + Q + \Delta S = 0$	
N	Precipitation
V	**Evaporation**
Q	Runoff
ΔS	Storage



Energy balance	
$R_n + H + G + LE = 0$	
R_n	Net radiation
H	Sensible heat flux
G	Ground heat flux
LE	**Latent heat flux**



Evaporation - phase transformation

The following transition heats L*, which depend on the temperature, apply to phase transitions of the water.

At 0 °C they are:

- solid fluent: L* = 333,6 kJ/kg
- fluent gas: L* = 2 500,6 kJ/kg
- solid gas: L* = 2 834,2 kJ/kg

As a comparison:

The heating of water from 0 °C to 100 °C (no change in the state of aggregation): 418 kJ/ kg.

~1/6 of the energy needed at the same initial temperature to complete the phase transition by evaporation

Evapotranspiration

Evapotranspiration = Evaporation + Transpiration

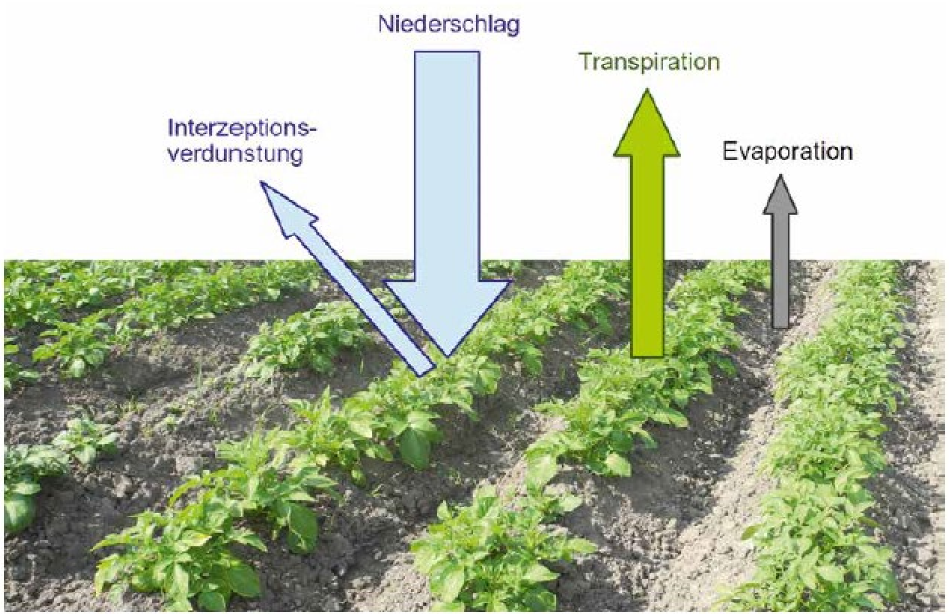


Foto: Prof. Miegel (Uni Rostock)

Evaporation

Evaporation happens from surfaces such as

- **Water surface**
- Soil without vegetation cover
- Interception (from vegetation surface)
- Snow surfaces

Evaporation

Evaporation happens from surfaces such as

- Water surface
- **Soil without vegetation cover**
- Interception (from vegetation surface)
- Snow surfaces

Evaporation

Evaporation happens from surfaces such as

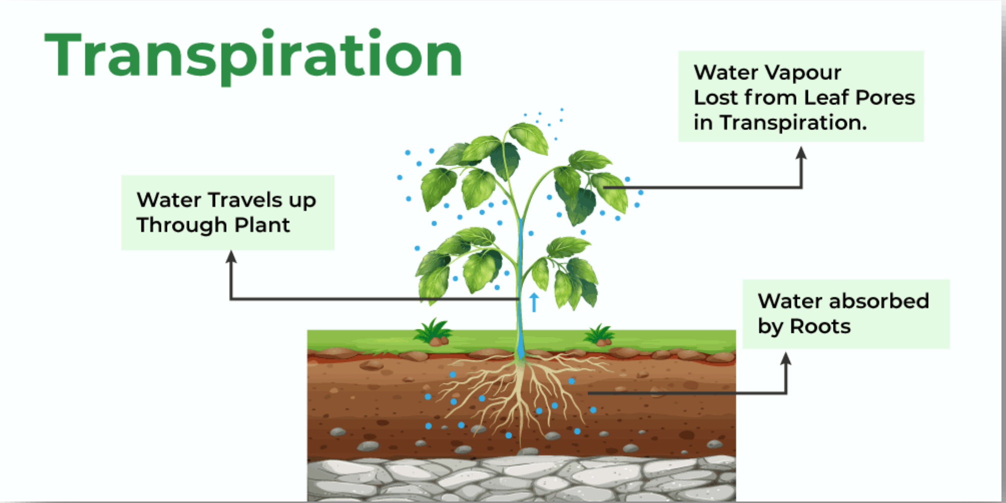
- Water surface
- Soil without vegetation cover
- **Interception (from vegetation surface)**
- Snow surfaces

Evaporation

Evaporation happens from surfaces such as

- Water surface
- Soil without vegetation cover
- Interception (from vegetation surface)
- **Snow surfaces**

Transpiration

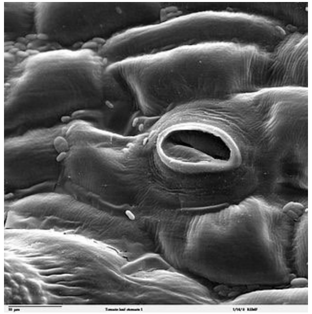


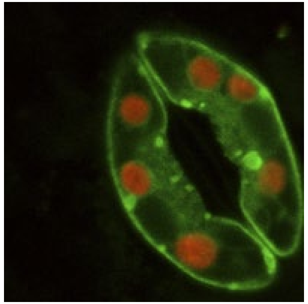
- Transpiration is the evaporation from plant surfaces due to biotic processes.
- It mainly involves the release of water through the stomata.
- Plants are able to regulate this release by closing and opening the stomata.

Plant evapotranspiration

Stomatal transpiration / stomatal resistance

- In plants, water is generally released through special adjustable door cells called stomata. CO_2 is absorbed through the same openings.
- The extent of water release in different plant species can vary by more than two orders of magnitude.
- The control of the stomata is regulated by the turgor (pressure of the cell).
- In warm regions there are special adaptations for the transpiration of plants, because there the plant is always faced with the problem that it has to absorb CO2 through the stomata on the one hand, but also loses water again as a result.
- To reduce this problem, many plants have, for example, sunken stomata with special hairs.





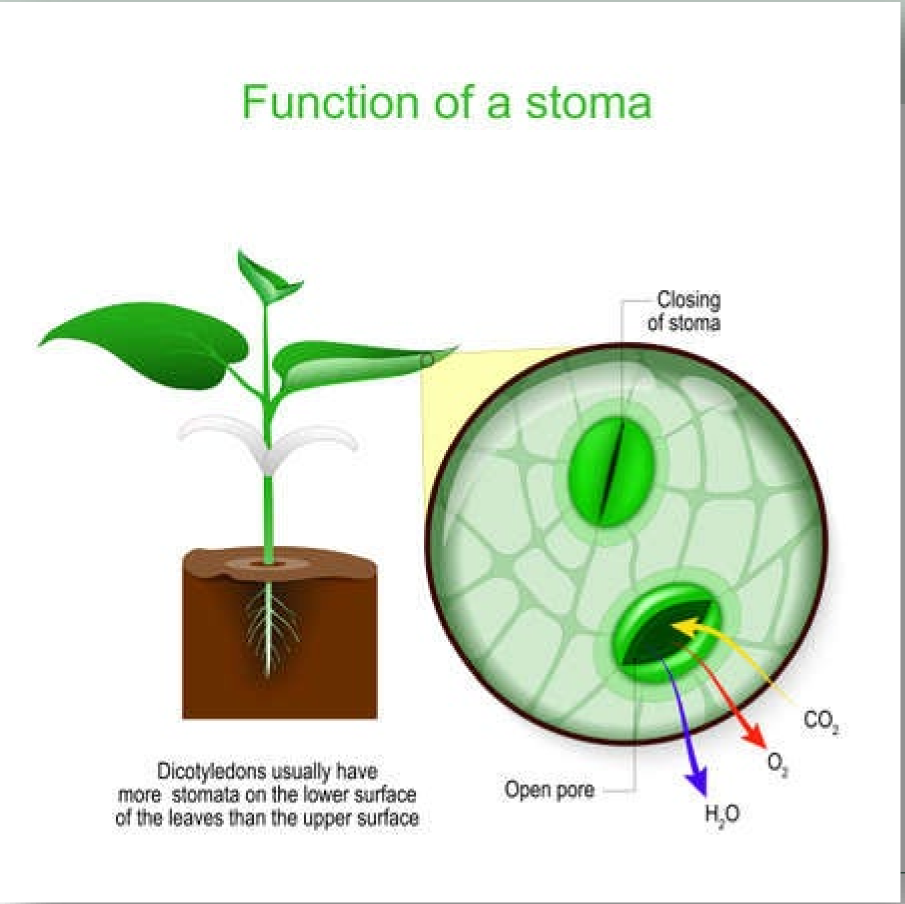
Competition CO_2 in H_2O out

Net product photosynthesis:

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

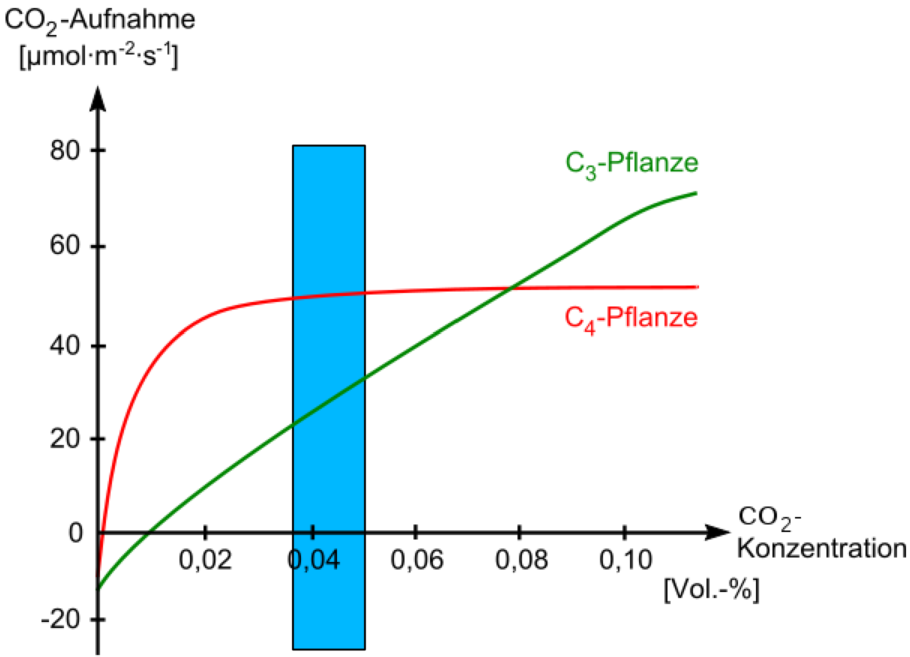
Net product respiration:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$



C3 and C4 plants

- C4 plants actively bind CO_2 using additional energy.
- This allows them to close the stomata further and consume less water per biomass produced.
- However, they have a higher temperature optimum and are less energy efficient.



Share [%] of the two components

Proportion of evaporation components on average in Central European landscapes:

- Transpiration: ~50-70 %
- Interception evaporation: ~15-40 %
- Evaporation: ~5-25 %

Effects on evaporation

Evaporation is physically dependent on the following factors:

- **Solar radiation** as a source of energy
- **Air temperature** (which in turn depends on solar radiation)
- **Air humidity** and thus the saturation deficit of the air
- **Wind movement**, especially its turbulence and thus the greater mixing of the air

Potential and actual evapotranspiration

Potential evaporation (**PE**) or **potential evapotranspiration** (**PET**) is defined as the amount of evaporation that would occur if sufficient water is available.

Actual evapotranspiration (AET) is the net result of atmospheric demand for moisture from a surface and the ability of the surface to supply moisture.

Therefore, PET is a measure of the demand side, AET is limited by the supply.

A dryland is a place where annual potential evaporation exceeds annual precipitation.

Potential evapotranspiration

Maximum possible evaporation of a site under given meteorological conditions with optimal water supply -> Conversion of the total energy supply

PET exclusively dependents on meteorological (atmospheric) variables (temperature, humidity, wind, radiation)

Examples of potentially evaporating surfaces:

- Evaporation from free water surfaces (lakes, rivers ...)
- Evaporation from moist soil (after rain events or during irrigation)
- Evaporation from snow cover

AET = PET

(e.g. over lakes)

Actual evapotranspiration AET

- Value of evaporation actually occurring at a site
- Depending on atmospheric, soil and vegetation conditions and availability of water

AET << PET

Even AET = 0

(during drought)

Equations to calculate PET

- **The Penman equation** describes evaporation (E) from an open water surface, and was developed by Howard Penman in 1948. Penman's equation requires daily mean temperature, wind speed, air pressure, and solar radiation to predict E.
- **The Penman–Monteith equation** refines weather based potential evapotranspiration (PET) estimates of vegetated land areas. It is widely regarded as one of the most accurate models, in terms of estimates.
- **The Priestley–Taylor equation** was developed as a substitute to the Penman–Monteith equation to remove dependence on observations.

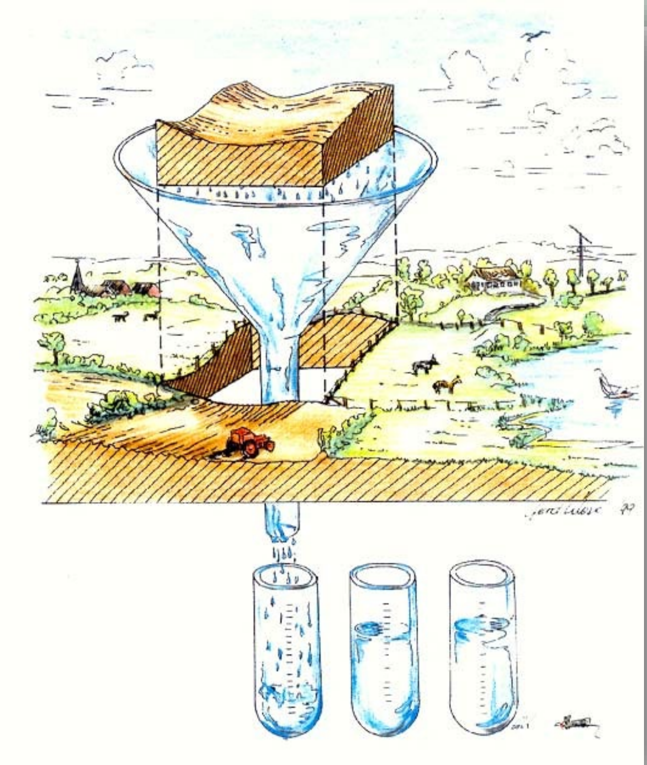
3. Evapotranspiration

3.2 Monitoring

Evaporimeter

Evaporation kettles filled with water are used to determine the evaporation by measuring the decrease of the water level.

Lysimeter



Weighing Lysimeter

- Principle: Measures changes in the weight of the lysimeter to determine water balance
- Operation: The lysimeter is placed on a scale and changes in weight are recorded over time, allowing for the calculation of evaporation, transpiration, and drainage

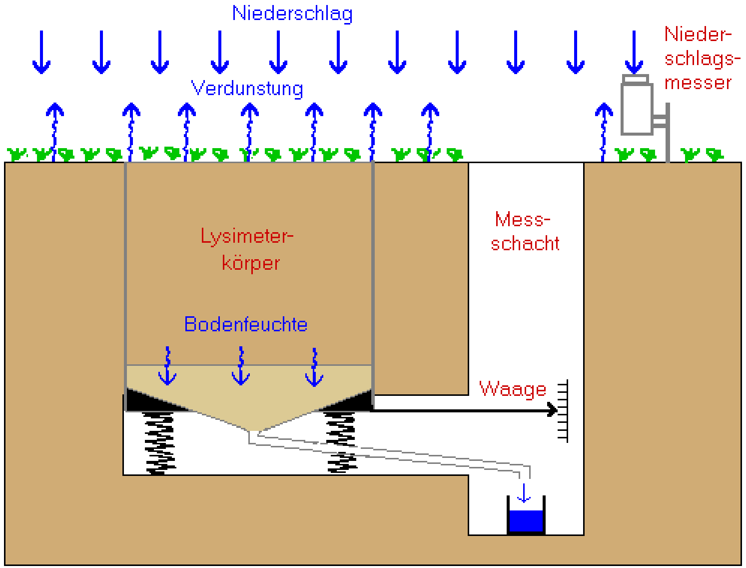
Lysimeter

Lysimeter system in Groß Lysewitz

Quelle: Fohrer, 2006

Lysimeter in Brandis (Sachsen)

Lysimeter



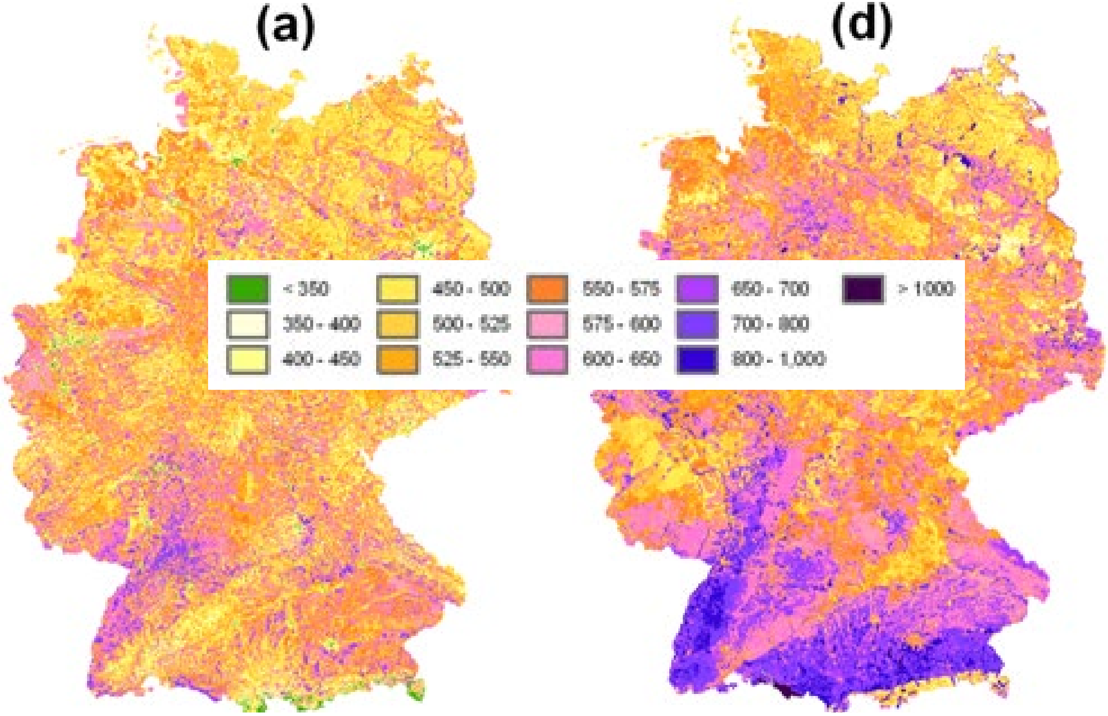
Quelle: in Anlehnung an Schröder et al. 1994

https://en.wikipedia.org/wiki/Lysimeter

3 Evapotranspiration

3.3 In Germany and global

AET 1961-90 for Germany, hyd. atlas and modelled



Hydrological atlas Modelled (Model SWIM, PIK)

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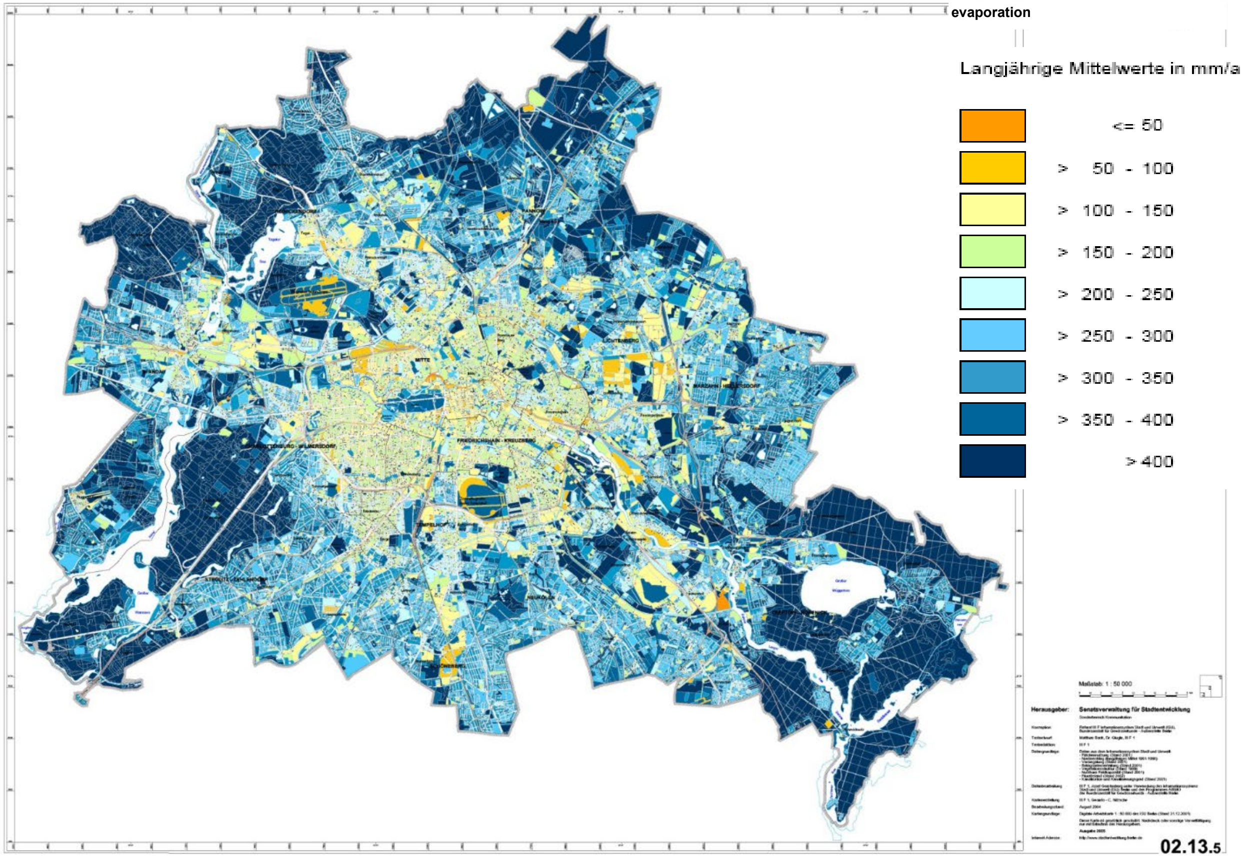
Eberswalde

P I K

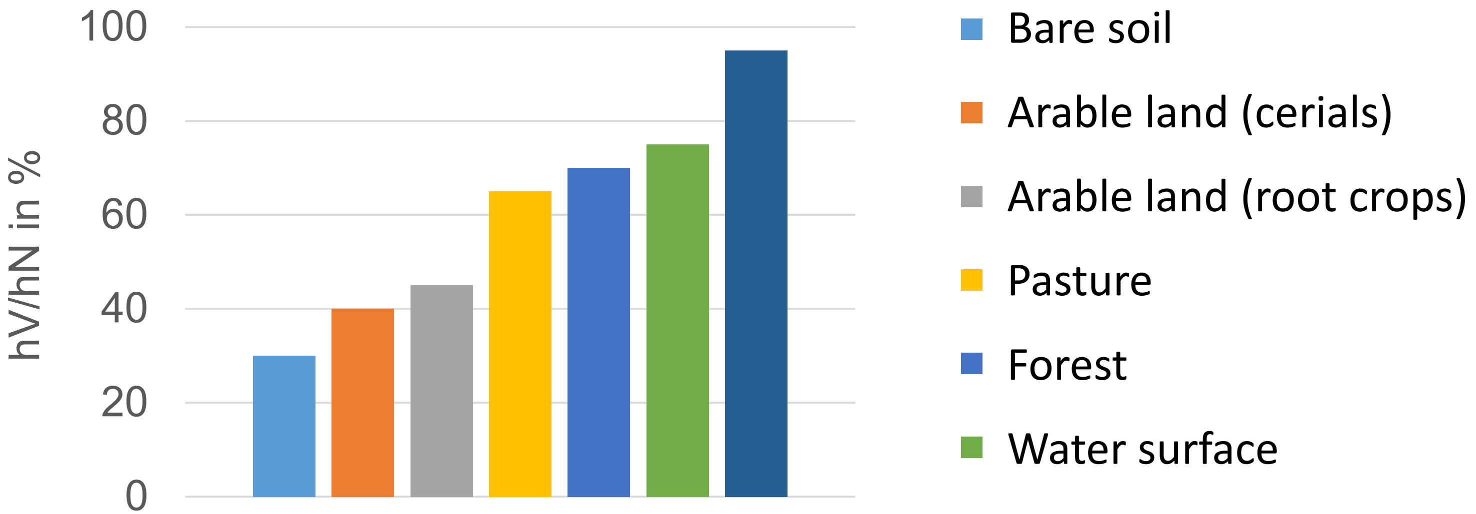
AET in Berlin



http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/

Effects of vegetation cover

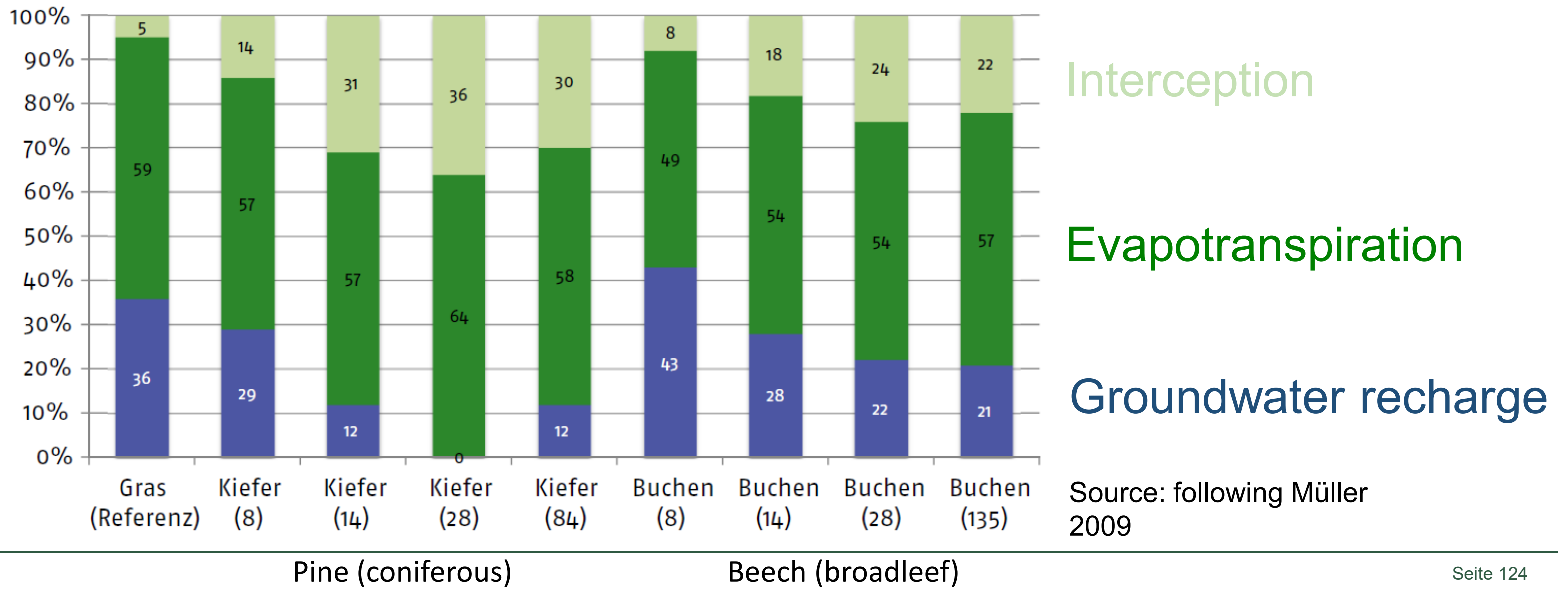
Ratio of annual evaporation to annual precipitation as a function of vegetation (exemplary)



Quelle: Nacken (RWTH Aachen)

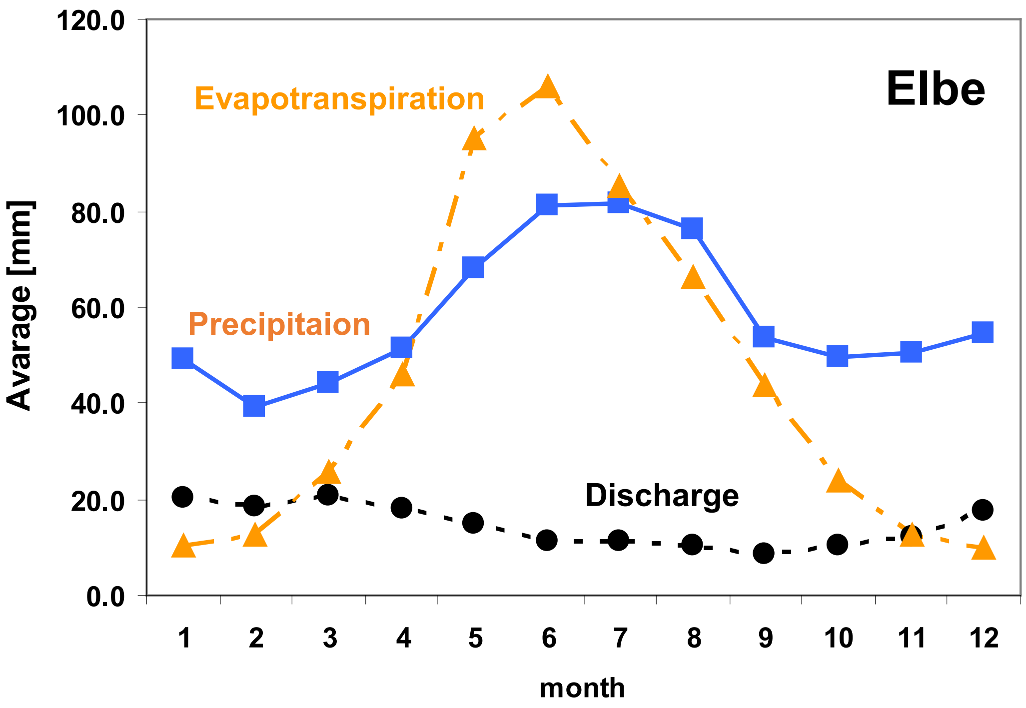
Influence of vegetation cover on water balance

Influence of vegetation cover (stand age in brackets) on the water balance of a pine and a beech forest near Eberswalde (annual precipitation 620 mm) compared to Grass.

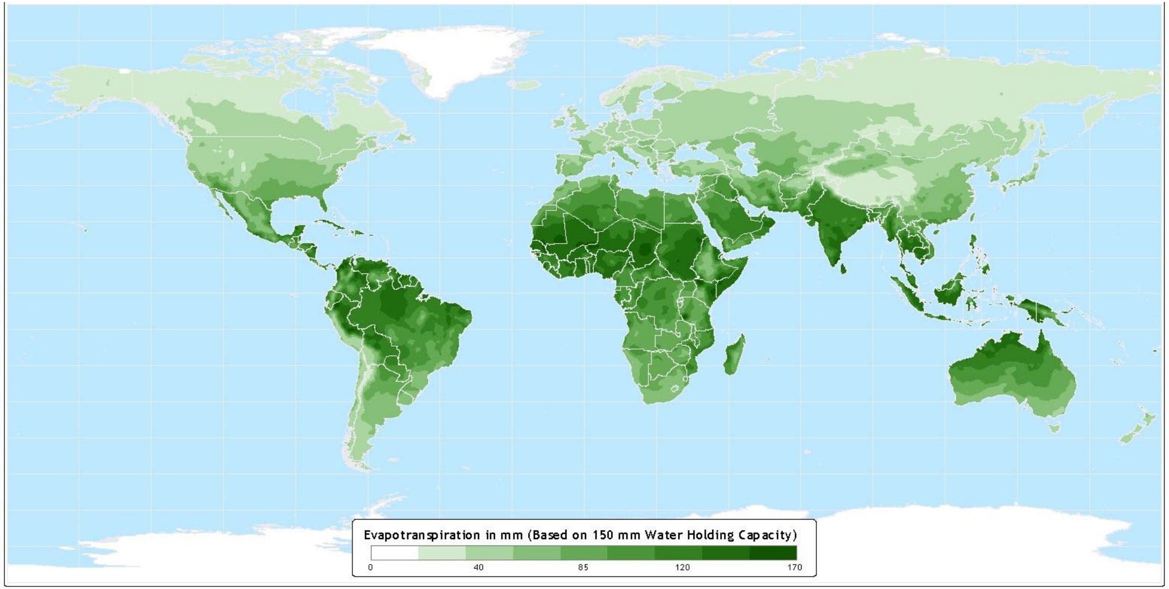


Source: following Müller 2009

Seasonal distribution of evapotranspiration



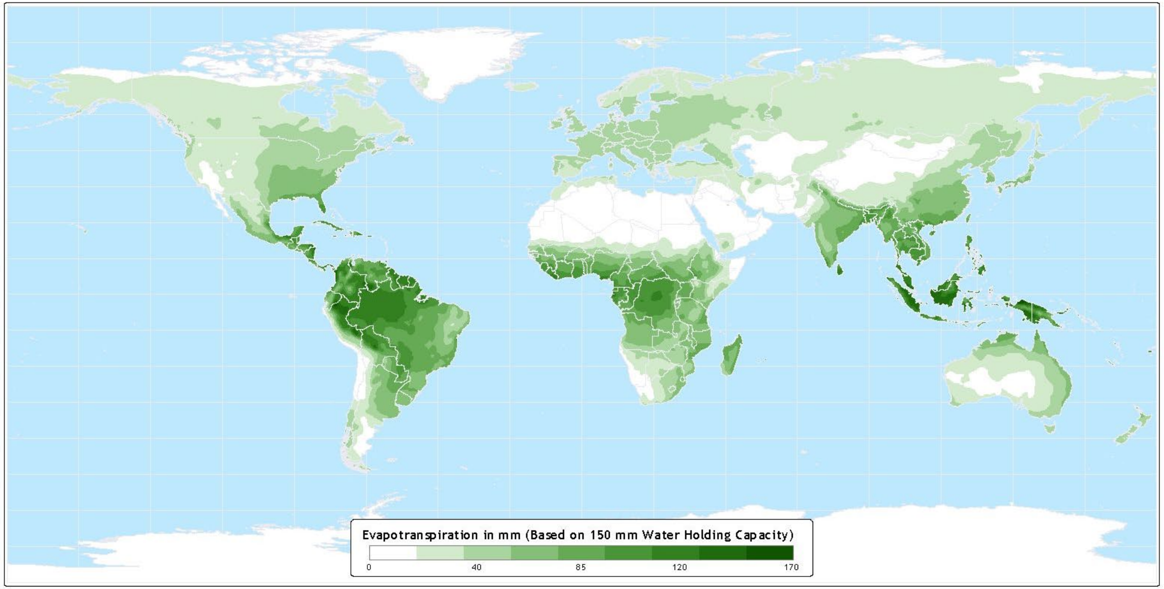
Potential evapotranspiration



Data taken from: Willmott and Matsuura (2001)

Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

Actual transpiration



Data taken from: Willmott and Matsuura (2001)

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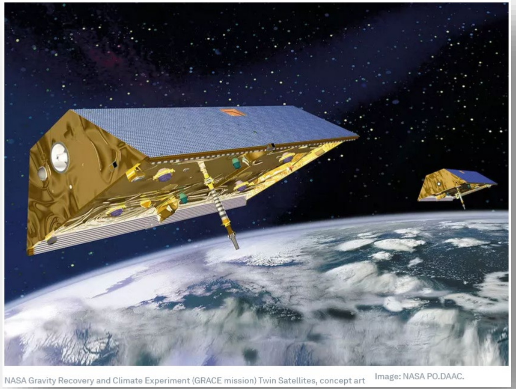
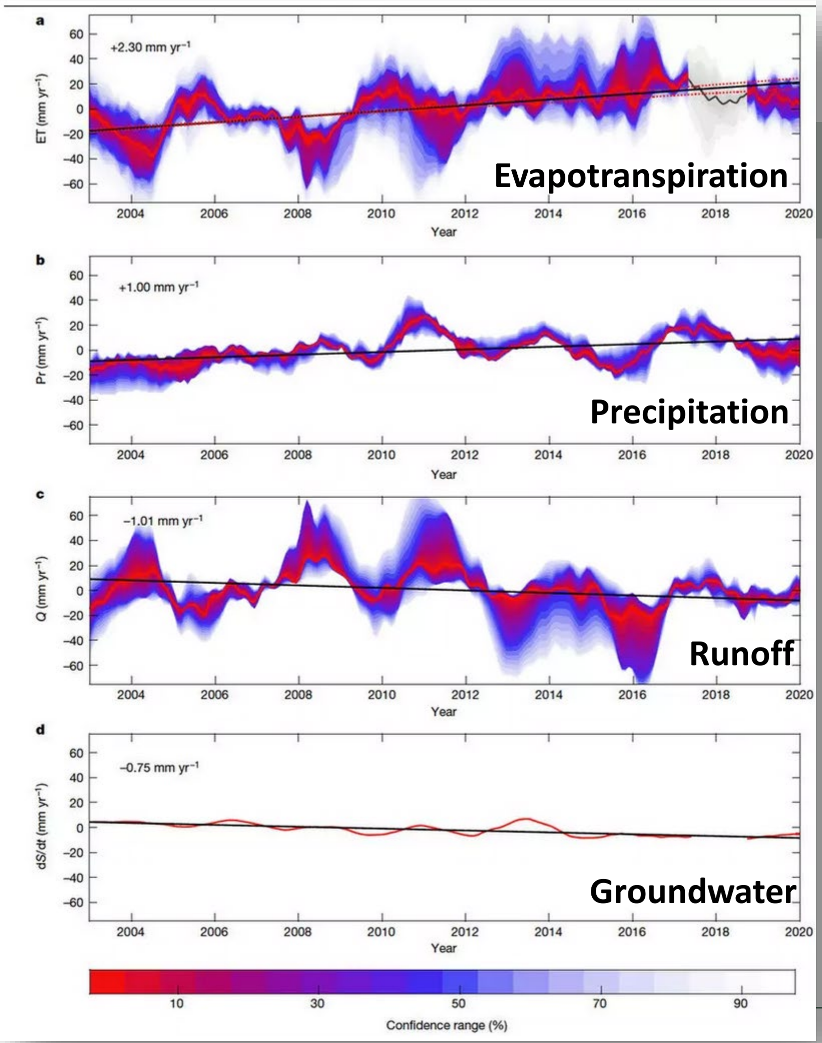
Eberswalde

Global water trends



Gravity Recovery and Climate Experiment (GRACE)



Pascolini-Campbell et al (2021)

4 Discharge

Discharge

4.1 Definition and processes

4.2 Monitoring

4.3 Discharge in Germany and global

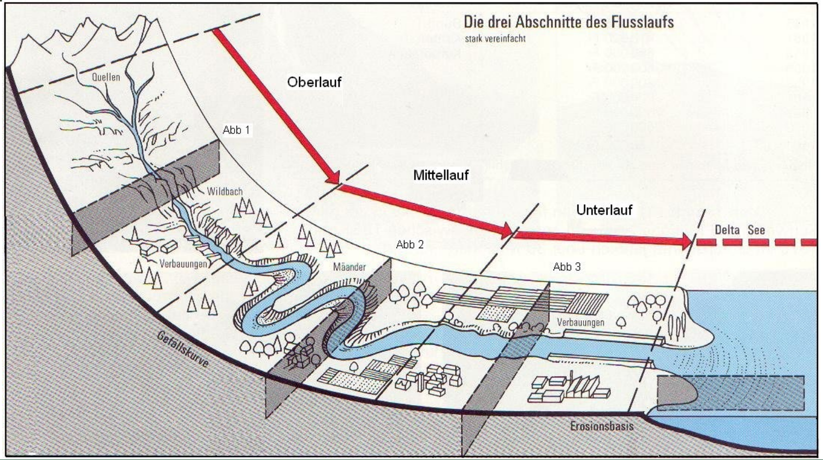
4 Discharge

4.1 Definition and processes

Definition discharge and runoff

In hydrogeology, **runoff (according to DIN 4049-1) is defined as water moving on and under the land surface** under the influence of gravity.
In hydrology, **discharge (abbreviation Q) is the volume of water leaving a catchment area** under the effect of gravity within a certain time.
If the runoff is divided (normalised) by the EZG area, it is referred to as **runoff donation**.

River types



http://homepage.hispeed.ch/heiner.brogli/Exo/omu/Geopage.htm

Flow generation: boundary conditions

Area features

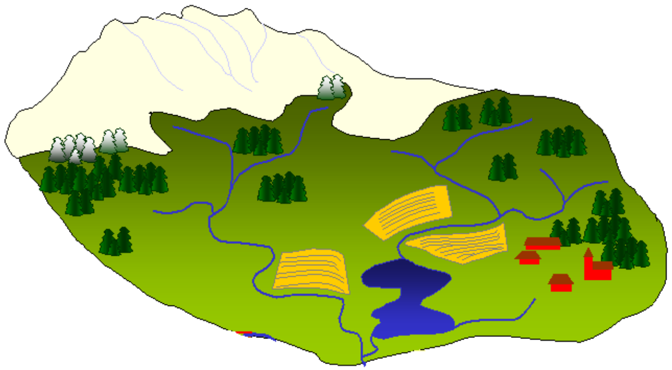
- Relief
- Soil properties
- Geology
- Groundwater conditions
- Vegetation

Hydrometeorological conditions

- Pre-humidity
- Precipitation amount and intensity
- Temperature
- Evaporation
- Proportion of snowfall
- Presence of glaciers

Anthropogenic influences

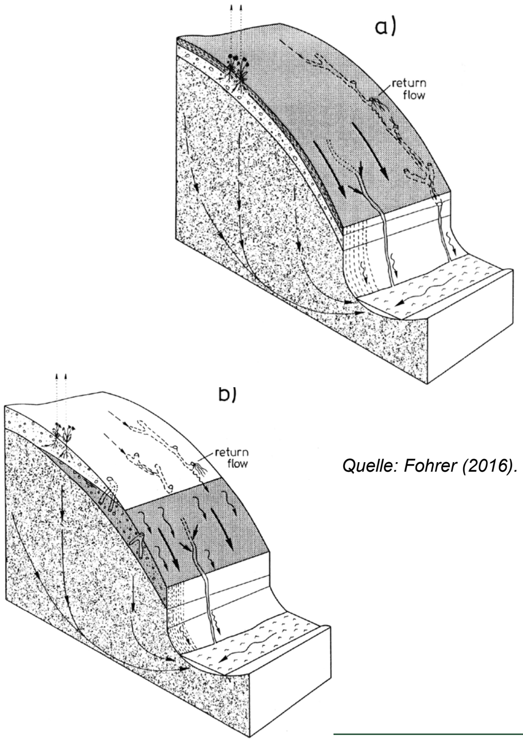
- Land use
- Degree of sealing
- Drainage system / sewerage



Surface flow

Mechanisms:

1. Due to infiltration excess
   Rainfall intensity > Infiltrability of the soil
   Also known as Hortonian runoff (after Horton, 1933).
2. Through saturation surplus
   The ground surface is saturated and can no longer absorb water.
3. Return Flow
   Runoff that has briefly infiltrated and then exfiltrated back to the surface.



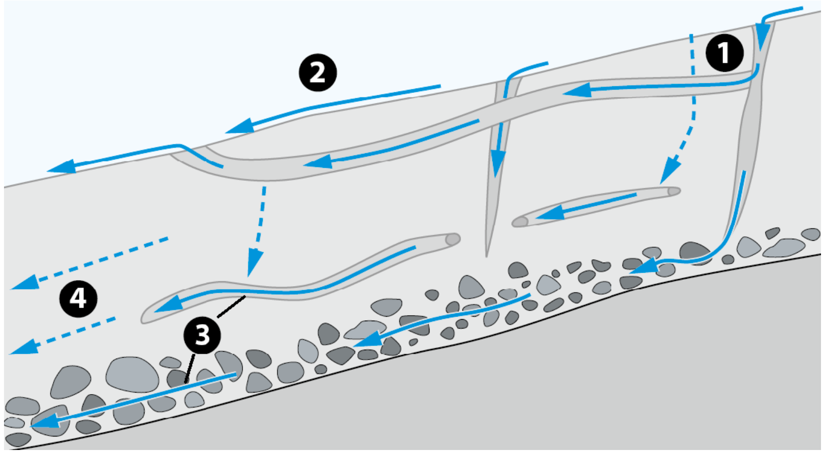
Quelle: Fohrer (2016).

Interflow

= Water that flows to the water body through near-surface, (often) unsaturated soil layers.

Important processes:

- Infiltration
- Surface runoff, possibly with return flow
- Rapid lateral runoff through preferential flow paths (macropores, root zone, gravel layer, etc.)
- Matrix flow (soil matrix)



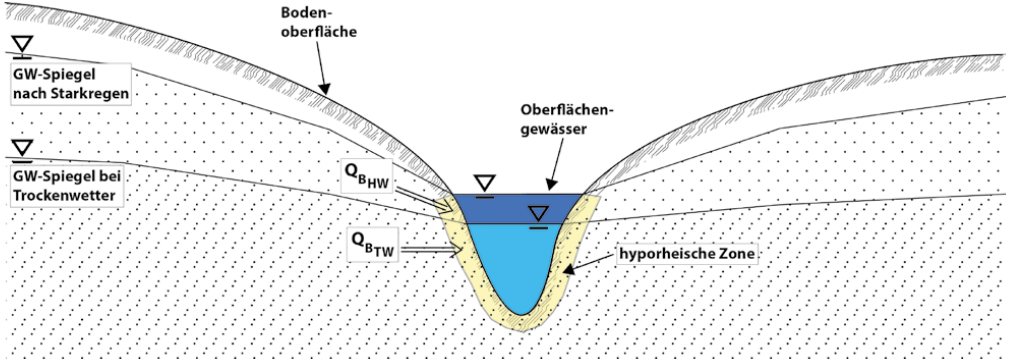
Quelle: Fohrer (2016).

Groundwater discharge

= Water that reaches the saturated zone through percolation and flows to the watercourse following the gradient.

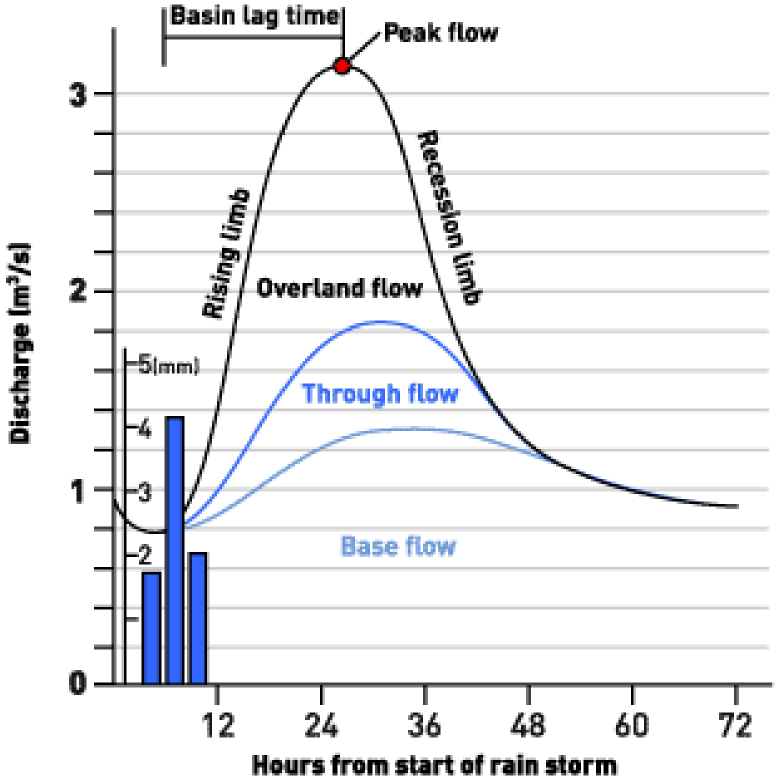
Slow process, provides most of the base flow.

Macropores (e.g. karst) can also lead to rapid groundwater recharge and thus also to the contribution of groundwater during runoff events



Q_{BHW}: Basisabfluss bei Hochwasser. Q_{BTW} : Basisabfluss bei Trockenwetter. Quelle: Fohrer (2016).

Hydrograph



Basin lag time
Peak flow
Rising limb
Recession limb
Overland flow
Through flow
Base flow
5(mm)
4
3
2
Discharge (m³/s)
0
1
2
3
12
24
36
48
60
72
Hours from start of rain storm

Discharge regime after Pardé

= Mean seasonal discharge behaviour of a river.

Pardé coefficient: ratio of mean monthly to mean annual discharge of each month: MQm_i/MQa with i = month

- **Pluvial**: influenced by rain. Maximum occurs delayed to the maximum of the raining season, depending on the residence time of the water in the EZG.
- **Nival**: influenced by snowmelt.
- **Glacial**: influenced by glacier melt.
- **Complex regime**: Has several maxima in the year, e.g. pluvio-nival regime.

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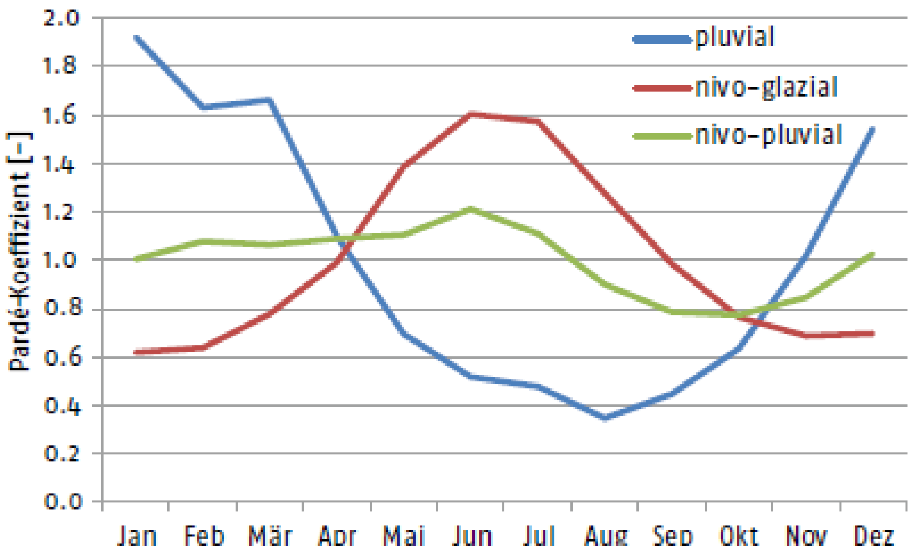
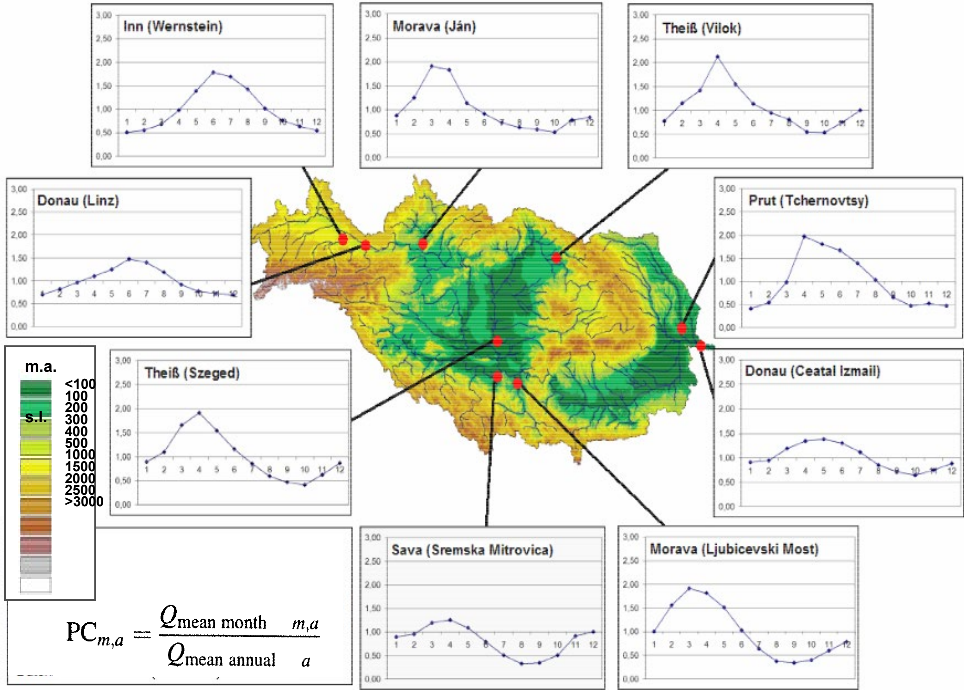
Discharge regime: examples



Blau: Ems, Pegel Greven; rot: Inn, Pegel Passau; grün: Rhein, Pegel Mainz, Quelle: Fohrer (2016).

Discharge regime along the River Danube



$$PC_{m,a} = \frac{Q_{\text{mean month}\ m,a}}{Q_{\text{mean annual}\ a}}$$

4 Discharge

4.2 Monitoring

Monitoring of discharge

The discharge (or flow) Q is defined as the quantity of water flowing through the cross-section A of a watercourse within a unit of time.

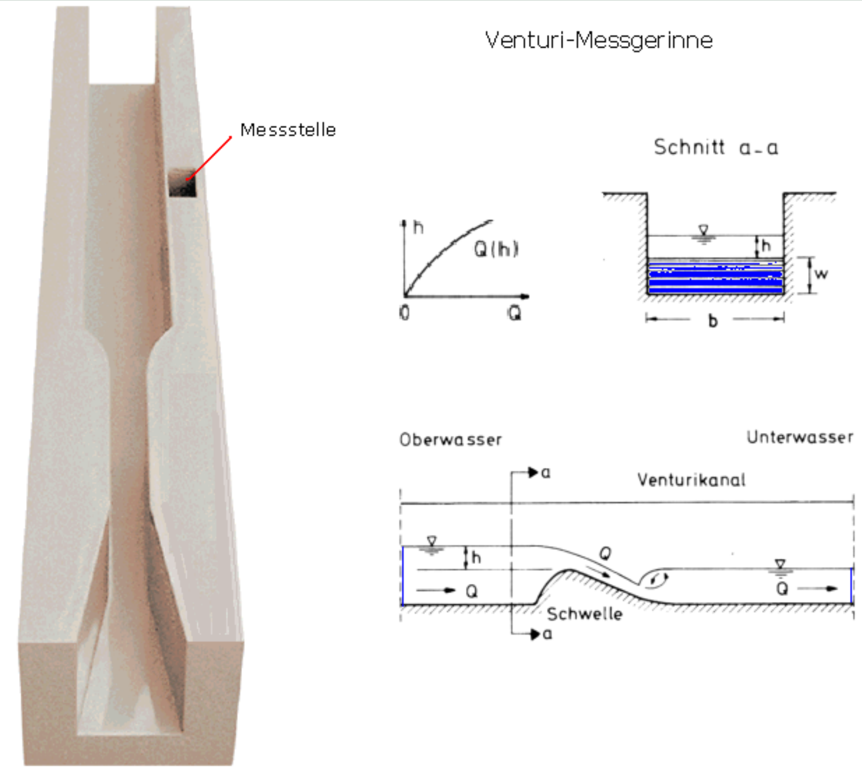
Direct measurement

- The volume of water flowing through a watercourse per unit of time is measured directly, e.g. with a bucket.
- Cumbersome and only possible for small bodies of water

Indirect measurement

- With the measurement of water level h, the discharge is determined via a discharge curve, where h = f (Q)
- Measurement of velocity v and determination of cross-section A

Venturi channel



Narrowing of the flow cross-section A

- Flow change: flowing to shooting
- Water level clear measure of flow

Quelle: Wikimedia Commons contributors, CC BY-SA.

Monitoring weir

- Weir = threshold, which is dimensioned in such a way that a shooting flow condition occurs
- The discharge can be clearly determined from the water level upstream of the weir if the weir parameters are known.

Strong intervention in the flowing water is necessary!

Thomson-/Dreieckswehr, Quelle: Fohrer (2016).

Tracer / dillution method

- **Tracer = marking substance (e.g. colour tracer or salt), which is discharged into the water at a known concentration.**
- Downstream, concentration is measured in the watercourse
- The greater the dilution, the greater the discharge

Water level gauges

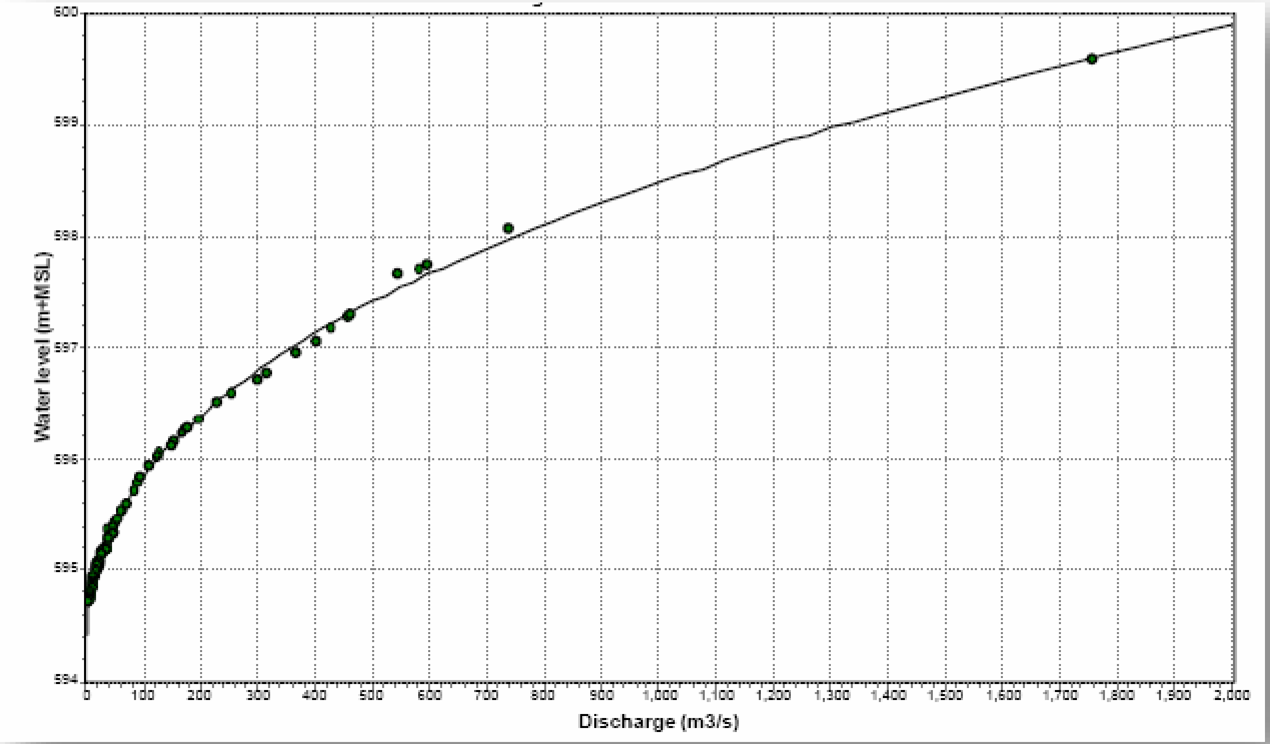
Water level gauges are measuring devices of various designs for determining the water level in bodies of water.

http://www.computerart-3d.de/projekte/pegelhaus-querschnitt/

Rating curve

In hydrology, a rating curve is a graph of discharge versus stage

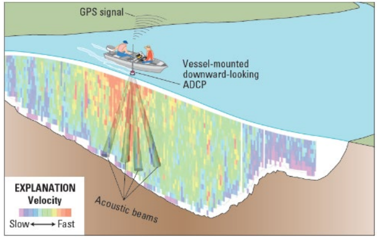
… for a given point on a stream, usually at gauging stations, where the stream discharge is measured across the stream channel with a flow meter.



Measuring and calibration via flow velocity

Mechanical measuring blade

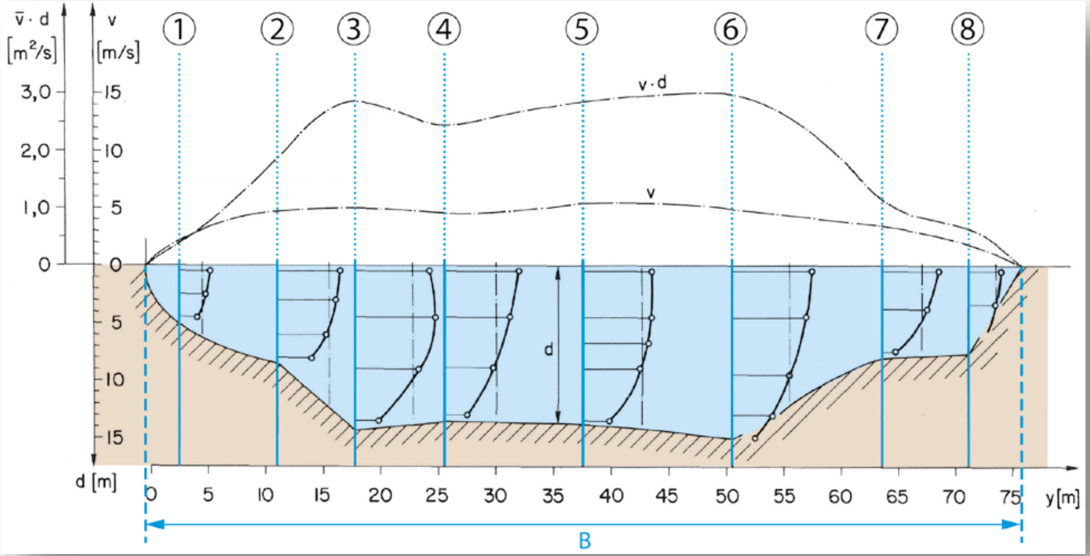
Induction probe:
Magnetic field -> Water flow with free charge carriers induces electric voltage



ADCP (Acoustic Doppler Current Profiler):
Ultrasound Doppler effect (frequency shift) on scattering bodies in water

Sources: Mueller et al. (2013) and Ott HydroMet GmbH.

Flow velocity field



Source: Fohrer (2016).

Measurement of flow velocities across the watercourse cross-section

A (vertically and horizontally) non-uniform velocity ***v*** distribution occurs in a flow cross-section ***A***. Causes: Roughness of the wetted cross-section, friction forces, turbulence.

4 Discharge

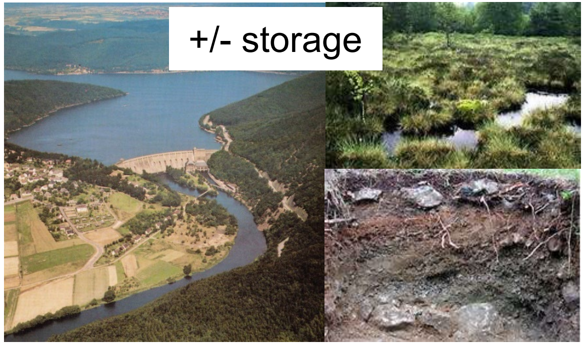
4.3 Regional and global discharge

Water balance

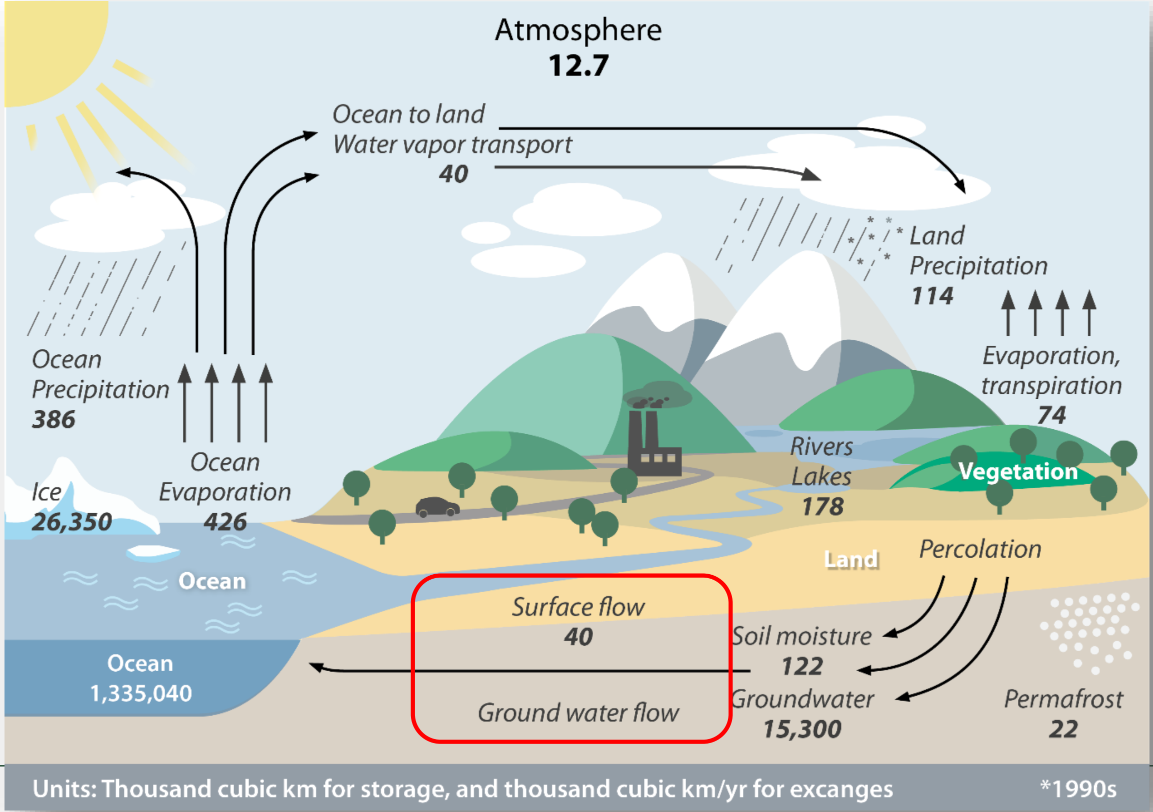
=

+

+



Water cycle, global



Water reservoirs

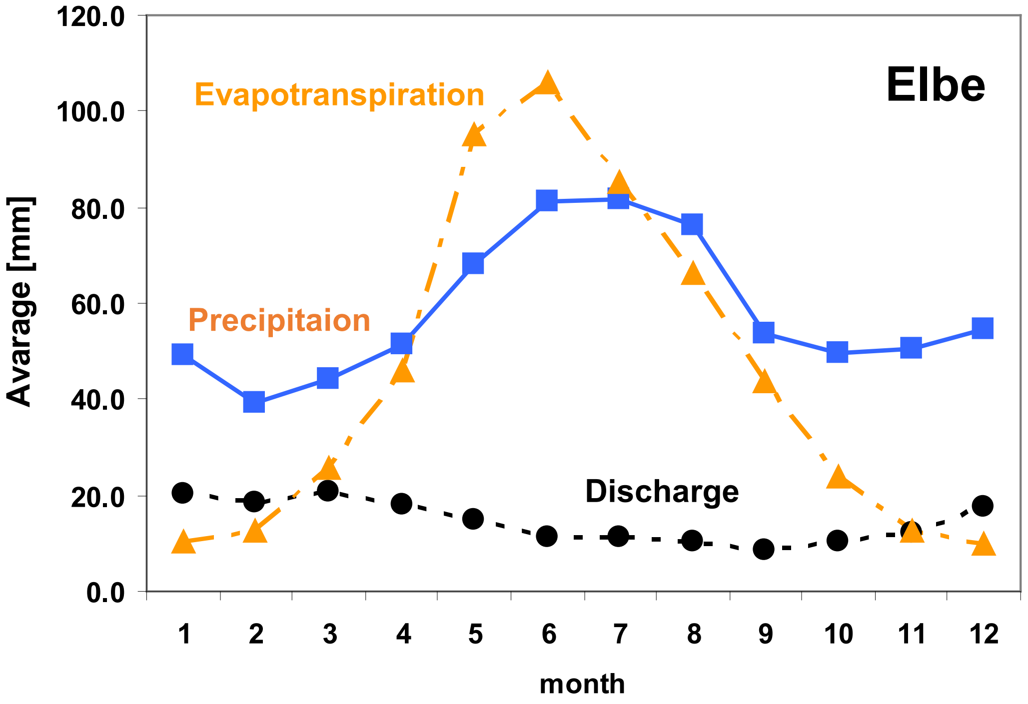
- Oceans, inland waters, glaciers, groundwater, atmosphere, soil water, organisms ...

Processes

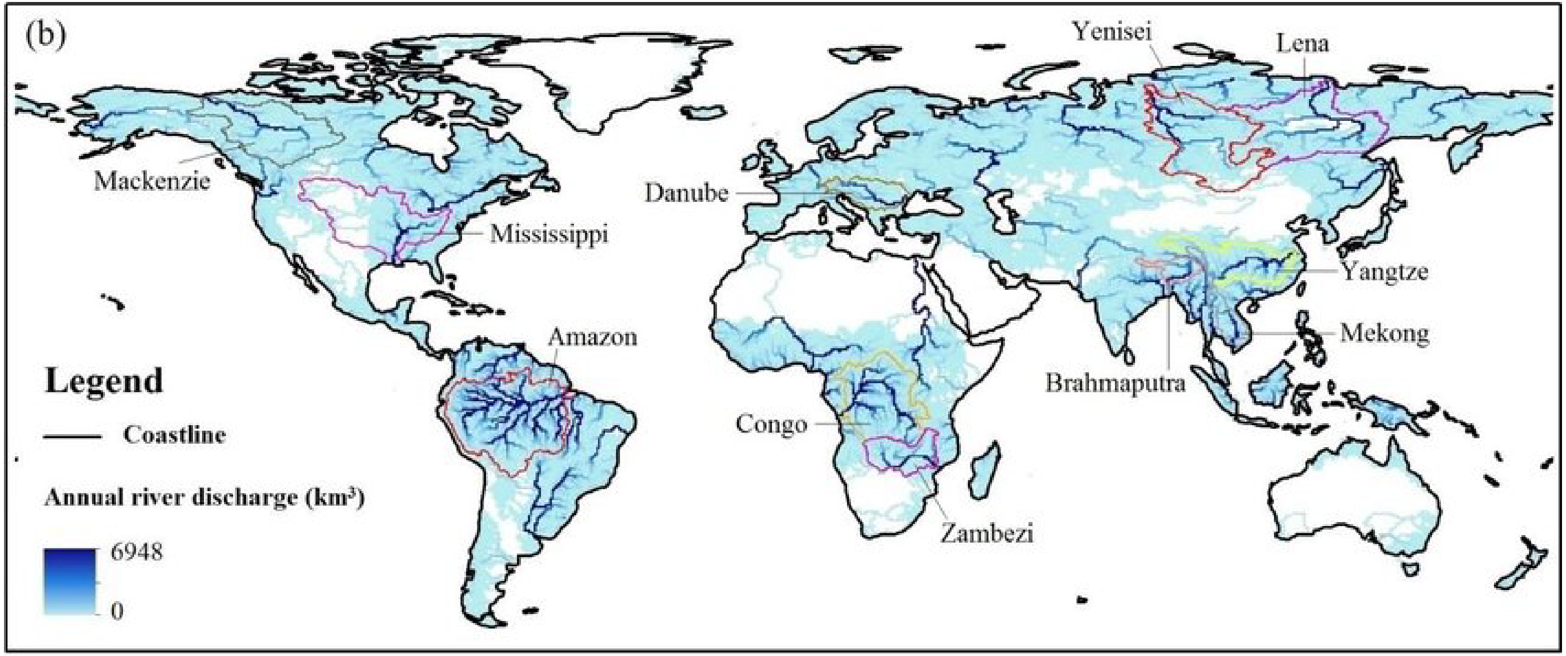
- Precipitation,
- evaporation,
- seepage,
- Runoff

The global water cycle. Illustration: GIZ (2020) with data from Trenberth et al. (2011).

Seasonal distribution of discharge



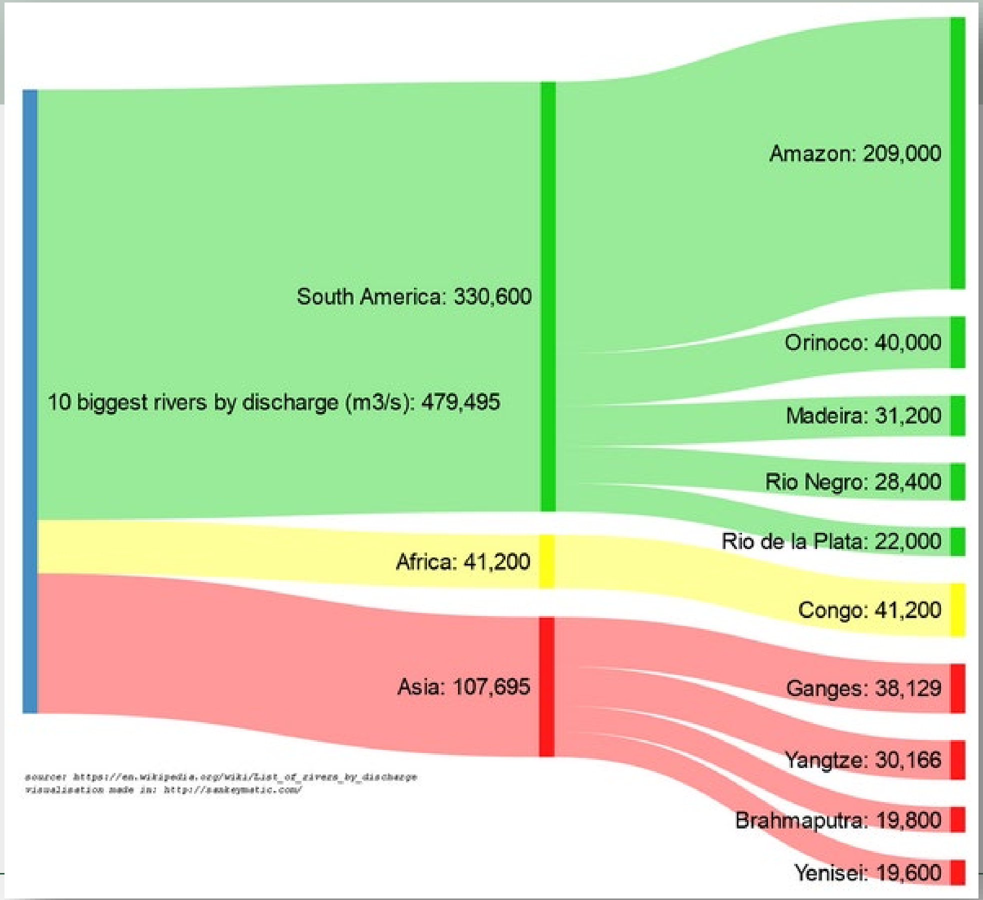
Global discharge



Li et al. 2018, Water

The largest rivers
(length)

The largest rivers
(discharge)



Please answer the questions!

1. What is potential and what actual evapotranspiration?
2. What is interception?
3. What are reanalysis data?
4. How can precipitation, evapotranspiration and runoff be measured?
5. What are discharge regimes?
6. How much water flows in a second if river if the wetted river cross-section is 5 m^2 and the flow velocity 2 ms^{-1}?
7. What is the „Water Nexus“?

Outline

Monday Nov. 18

- The water cycle: From hydrological processes to observations,
- presentation of topics, groupwork

Tuesday Nov. 19

- The nexus water – energy – food. Water as a basic need, water as a threat: health, hydrological extremes, erosion,
- Selection of topics, groupwork

Wednesday Nov. 20

- Eco-hydrological modelling,
- Groupwork

Thursday Nov. 21

- Groupwork

Friday Nov. 22

- Presentation of selected tasks, visiting PIK

Possible task for the groupwork

Adaptation in a water related sector / field:

- Cities (adaptation to flash floods, droughts, heat waves),
- Nature based solutions in river basins or landscapes,
- Re-thinking water storage (at different scales),
- Adaptation to counteract erosion,
- Integrating adaptation and mitigation,
- Water re-use
- …

Thanks!