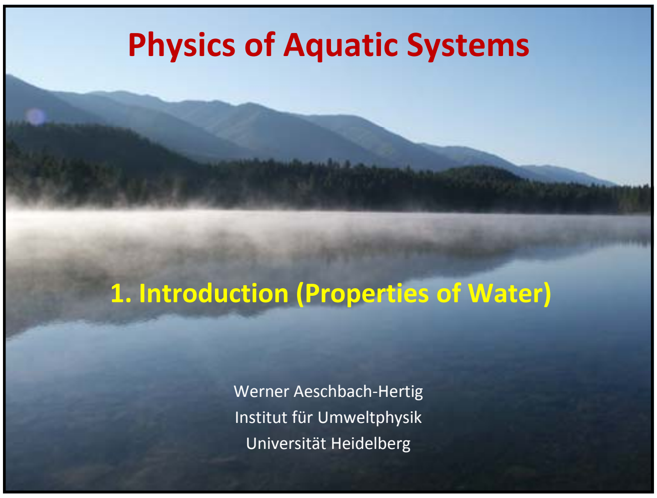


MVEnv3

Physics of Aquatic Systems

One of four main lectures in Environmental Physics:
Atmosphere, climate, terrestrial and aquatic systems

Main focus: Lakes, groundwater, isotope hydrology

This lecture builds on fundamental environmental physics (e.g., fluid dynamics) of the lecture MKEP4

For details, updates and lecture notes see
http://www.iup.uni-heidelberg.de/institut/studium/lehre/AquaPhys/MVEnv3.html

Overall Contents I

Part I: Aquatic Physics

1. Introduction (role and physical properties of water)
2. Density stratification and flow in lakes and oceans
3. Turbulent flow in surface waters
4. Ocean circulation
5. Turbulent transport in surface waters
6. Heat and gas exchange
7. Flow and transport in groundwater

Overall Contents II

Part II: Isotope Hydrology

1. Introduction to Isotope Hydrology
2. Stable Isotopes I
3. Stable Isotopes II
4. Tritium and ^{3}He
5. Dating of Young Groundwater and Modeling
6. Dating of old Groundwater
7. Noble Gases and Paleoclimate

Contents of Session 1: Introduction

- Definition of "Physics of Aquatic Systems"
  - Compartments of the hydrosphere
- 1.1 The global hydrological cycle
  - Water problems as a motivation for water research
- 1.2 The role of water in the environment
- Physical properties of water
  - 1.3 Specific and latent heat, vapour pressure

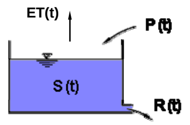
What is "Physics of Aquatic Systems"?

- Study of physical conditions and processes (e.g. stratification, flow, transport, mixing, heat/gas exchange) in natural systems containing liquid water (e.g. lakes, ocean, groundwater)
- Related Disciplines, Subdisciplines:
  - Physical Oceanography and Limnology
  - Hydro(geo)logy and soil physics
  - Meteorology and (paleo)climatology

For comparison: What is **Hydrology**?

- Study of the global water (hydrological) cycle, especially water on the **continents**, above, on, and below the surface
- Classical hydrological systems: Catchments of rivers/aquifers
- Physical aspects: Water balance, water fluxes
- Chemical, biological, and technical/sociological aspects
- Engineering aspects: water supply, flood protection, etc.

Hydrologic Water Balance



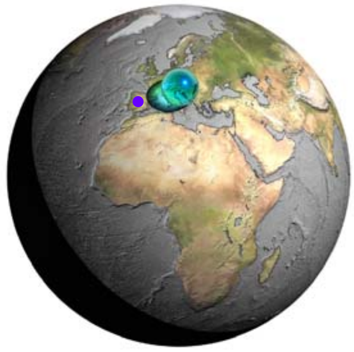
Hydrological system: reservoir with
- input P (precipitation)
- output R (runoff)
- output ET (evapotranspiration)

Continuity/Mass conservation: Input – Output = Change in storage

$$P - R - ET = \frac{dS}{dt}$$

- Simple equation, but …
  … individual terms are difficult to quantify
- Isotopes may help → Part 2 of this lecture

Water on Earth



All water on Earth:

$1.37 \cdot 10^9$ km³

Sphere with R ≈ 700 km

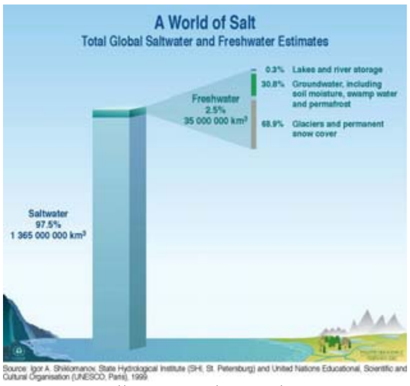
thereof 3 % fresh water:

~ $40 \cdot 10^6$ km³

Sphere with R ≈ 200 km

http://www.adamnieman.co.uk/vos/index.html

Saltwater and Freshwater



http://www.unep.org/vitalwater/index.htm

Water in env. compartments (blue: Hydrosphere)
volumes in 10^3 km³

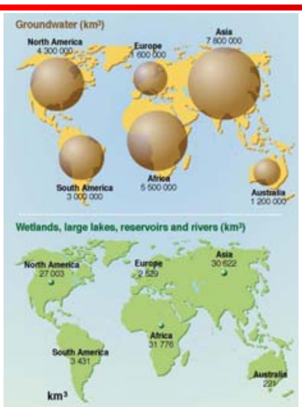
Saltwater:	1'365'000
thereof	
Oceans:	1'365'000
Salt lakes (Casp. Sea):	80
Freshwater:	35'000
thereof	
Ice:	24'000
Groundwater:	10'800
Soil water:	70
Lakes:	110
(Lake Baikal	23)
Atmosphere:	16
Rivers:	2
Biosphere:	2

Compartments of the Hydrosphere

	Volume in 10^3 km³	% of total freshwater	flux 10^3 km³/year	turn-over time year
Salt water				
Oceans	1 350 000		425	3000 ¹)
Freshwater				
Ice	27 800	69.3	2.4	12 000 ²)
Groundwater	8 000*	29.9	15	500 ³)
Lakes	220**	0.55		
Soil moisture	70	0.18	90	0.8 ⁴)
Atmosphere	15.5	0.038	496	0.03 ⁵)
Reservoirs	5	0.013		
Rivers	2	0.005	40	0.05 ⁶)
Biomass	2	0.005		
Total	40 114	100		

from Mook, 2001

Groundwater and Surface Water

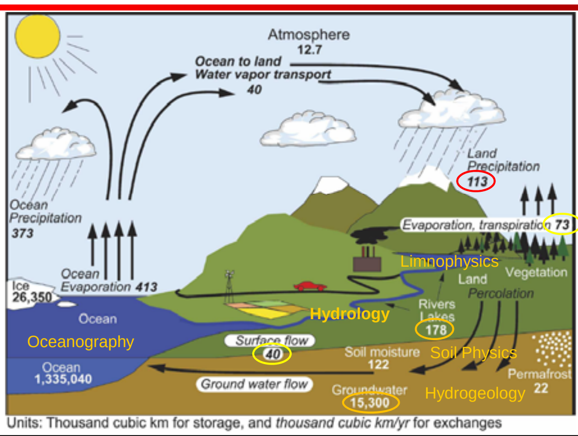


Groundwater:
- By far largest freshwater reservoir
- partly difficult to access
- Usually clean (drinking water)
- slow renewal

Surface water:
- Rather limited Resource, esp. in arid regions
- Easily accessible
- Frequently polluted
- fast recycling

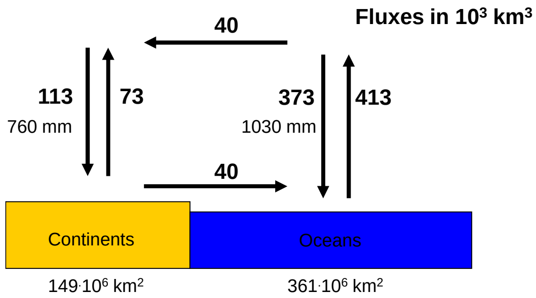
http://www.unep.org/vitalwater/index.htm

1.1 The Global Hydrological Cycle



Trenberth et al., 2007, J. Hydrometeor. 8: 758 - 769

Global Water Budget and Cycle



Whole Earth evaporation/precipitation flux: $486 \cdot 10^3$ km³ ≈ 950 mm

Water Balance of the Continents

Component	Volume flux [km³/a]
Input	
Precipitation	113.000
Output	
Evapotranspiration	73.000
- Ecosystems	51.000
- Grassland	14.400
- Cropland	7.600
Runoff	40.000
- Withdrawals	3.800
Sum Output	113.000

"Blue" and "green" water

green water
30 % utilised

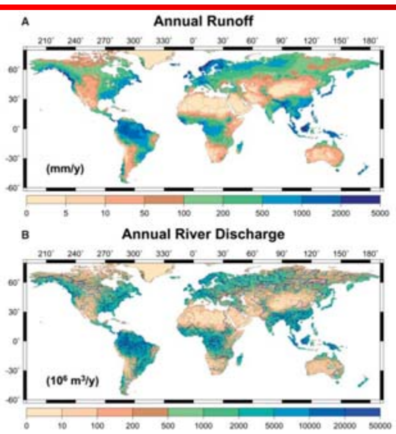
blue water
10 % utilised

renewable water resource: 40.000 km³/a

realistically accessible: 13.000 km³/a

present utilisation: ≈ 30 %

Distribution of the Water Resources

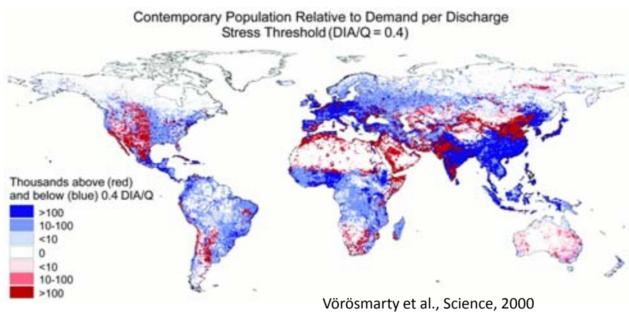


Water scarcity is regional, not global.

Oki and Kanae, 2006.
Science 313: 1068-1072

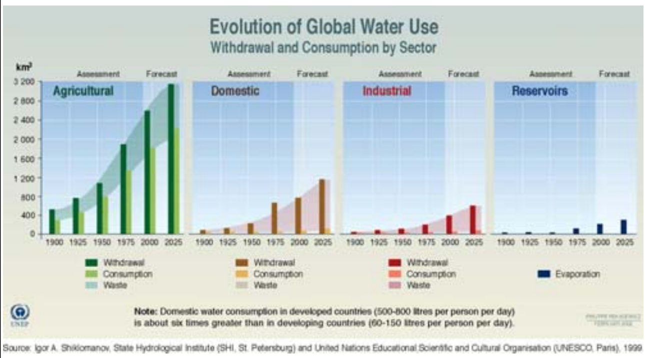
Global Distribution of Water Resource Stress

DIA/Q = Ratio of total (Domestic, Industrial, Agricultural) water demand to total sustainable water supply (river discharge Q)



Vörösmarty et al., Science, 2000

Global Water Use



http://www.unep.org/vitalwater/index.htm

Irrigation

Irrigated agriculture

- produces 40 % of the world's food on 20% of the agricultural area
- accounts for 70% of the water withdrawals (3.000 of the available 13.000 km³/a)
- regionally overutilises surface and ground water

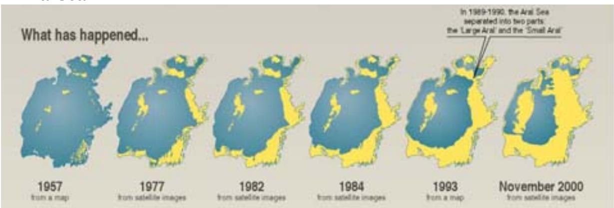
Hidden problem:

non-sustainability

Unsustainable Water Use: Drying Lakes

Aral Sea

http://www.unep.org/vitalwater/index.htm

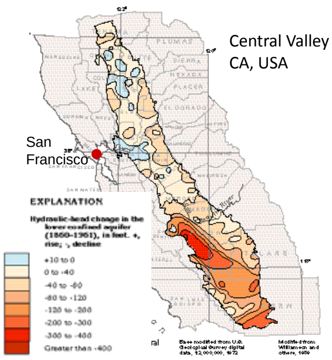


Lake Chad

Unsustainable Water Use: Drying Rivers

The Yellow River (Huang He) nowadays falls dry for about 4 months each year.

Unsustainable Water Use: Falling Water Tables



Central Valley CA, USA

Groundwater Atlas of the US

http://capp.water.usgs.gov/gwa/

Unsustainable Water Use: Falling Water Tables

North China Plain

Foster et al., 2004. Hydrogeol. J. 12: 81-93

1.2 The Role of Water in the Environment

- Water permeates all spheres of the environment
  - important medium for transport (heat, substances)
- Basis of life
  - most abundant molecule in the biosphere
- Role of water in the climate system
  - Ocean: Heat storage and transport
  - Water vapour: greenhouse gas, clouds, latent heat
  - Snow, ice: high albedo

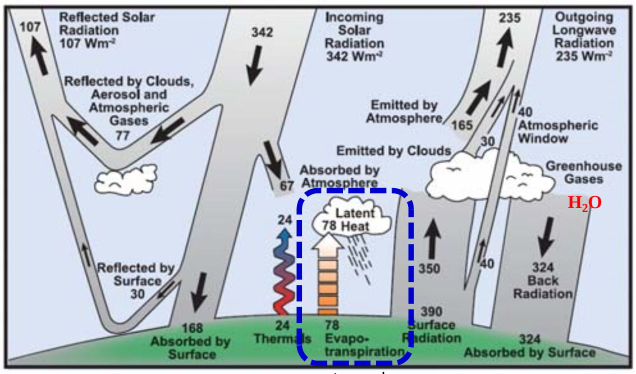
Role of the Ocean in the Climate System

Facts on the ocean:

- Area: $361 \cdot 10^6$ km² (70 % of Earth's surface)
- Volume: $1.365 \cdot 10^9$ km³ ⇒ mean depth 3800 m
- Mass: $1.4 \cdot 10^{21}$ kg (≈ 280x m_{atm})

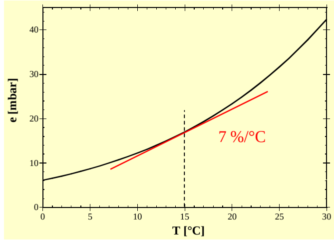
- largest heat reservoir
- largest mobile CO_2 reservoir
- large surface with low albedo

The Hydrologic Cycle in the Climate System



IPCC, AR4, 2007 water cycle

Warming Accelerates the Water Cycle

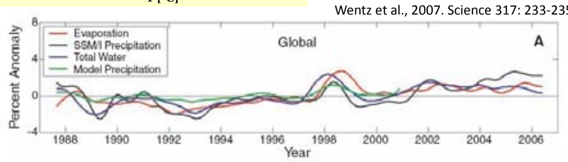


Water vapour saturation pressure depends strongly on temperature

Theoretical increase of water fluxes by about 7% per °C

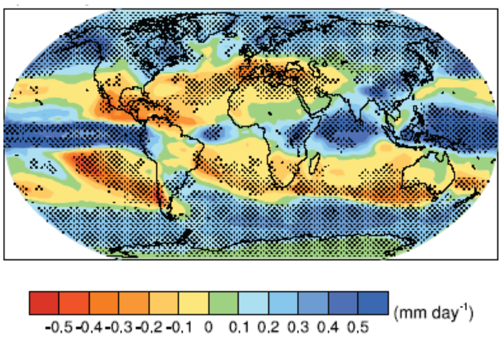
Actual changes:
Climate models: < 3%/°C
Data: ≈ 6 %/°C

Wentz et al., 2007. Science 317: 233-235.



Predictions for Precipitation

Precipitation 2080-99 compared to 1980-99



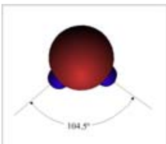
IPCC, AR4, 2007 (http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm)

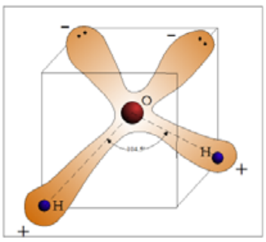
Physical Properties of Water

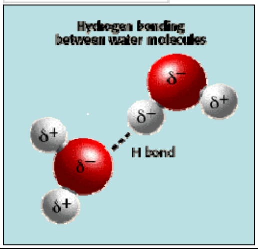
Property	Comparison	Importance, consequences
Specific heat 4180 J kg^{-1} K^{-1}	Highest of all solids and liquids except liquid NH_3	Heat transport by water movement, heat buffering
Heat of fusion 3.34·10^5 J kg^{-1}	Highest except NH_3	Thermostatic effect at freezing point
Heat of evaporation 2.25·10^6 J kg^{-1}	Highest of all substances	Heat and water transfer in the atmosphere
ρ_{max} at T > $T_{freezing}$ (~4 °C at 0%, 1 atm)	anomalous	Density stratification of lakes, facilitates freezing
$\rho_{solid} < \rho_{liquid}$	anomalous	Ice floats on water, freezing only at surface, weathering
Surface tension	Highest of all liquids	Drop formation, capillary forces, soil water retention, cell physiology
Dissolving power	Very high	Transport of dissolved substances
Dielectric constant	Highest of all liquids except H_2O_2 and HCN	High dissociation of dissolved salts

Molecular Origins of the Properties

H_2O-Molecule:
- H-O-H with 104.5° binding angle
- polar
- hydrogen bonds!







1.3 Specific and Latent Heat, Vapour Pressure

Tab. 1.3: Spezifische Wärme c_p und Umwandlungswärme von Wasser im Vergleich zu anderen Stoffen (siehe auch Tab. 1.4)

Eigenschaft			Wasser	Andere Substanzen	
Spez. Wärme	c_p, 25°C	[J·kg^{-1}K^{-1}]	4.18·10^3 a)	Al: Fe: H_2-Gas: He:	0.90·10^3 0.44·10^3 14.3 10^3 5.18·10^3
	Eis, 0°C	[J kg^{-1}K^{-1}]	2.11·10^3		
Verdampfungswärme 25°C		[J kg^{-1}]	2.44·10^6	CO_2 (0°C): NH_3 (0°C):	2.32·10^5 1.26·10^6
Schmelzwärme	0°C	[J kg^{-1}]	3.34·10^5		

a) Zwischen 0 und 100°C variiert c_p nur um ungefähr 1% (s. Tab. 1.4).

Temperature Dependence of some Properties

Tab. 1.4: Einige physikalische Eigenschaften von Wasser bei Atmosphärendruck

Temp. T [°C]	Dampfdruck e_w [mbar]	Spez. Wärme c_p [J kg^{-1} K^{-1}]	Verdampfungs-wärme [10^6 J kg^{-1}]	Molek. Diff. für Wärme D_T [10^{-6} m^{2}s^{-1}]	Kinemat. Viskosität ν [10^{-6} m^{2}s^{-1}]
0	6.1	4217.4	2.501	0.134	1.787
5	8.7		2.489		1.519
10	12.3	4191.9	2.477	0.138	1.307
15	17		2.465		1.14
20	23.3	4181.6	2.454	0.142	1.004
25	31.6		2.442		0.893
30	42.3	4178.2	2.43	0.146	0.801
35	56.2		2.415		0.724
40	73.8	4178.3	2.406	0.152	0.658
45	95.8		2.391		0.602
50	123	4180.4	2.382		0.553
60	199	4184.1	2.357	0.158	0.475
70	311	4189.3	2.333		0.413
80	473	4196.1	2.308	0.164	0.365
90	701	4204.8	2.283		0.326
100	1013	4215.7	2.257	0.166	0.294

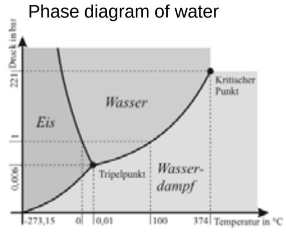
Saturation Vapour Pressure

Description of a phase transition
1 ↔ 2 by the
Clausius-Clapeyron equation:

$$\frac{dp}{dT} = \frac{L_{12}}{T(v_1 - v_2)}$$

L: Latent Heat
$v_i = 1/\rho_i$ = specific volumes

Phase diagram of water



For vapour ↔ water: $v_2 = v_w << v_v$ and $v_v = \frac{RT}{p}$

Thus: $\frac{dp}{dT} = \frac{Lp}{RT^2}$ mit $R_D = R/M_W$ = 461.5 J kg^{-1} K^{-1}

Saturation Vapour Pressure

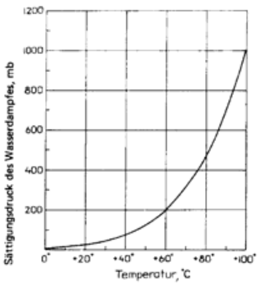
From Clausius-Clapeyron:

$$\frac{dp_s}{p_s} = \frac{L}{R}\frac{dT}{T^2}$$

Integration gives

$$\ln\frac{p_s(T)}{p_s(T_0)} = -\frac{L}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)$$

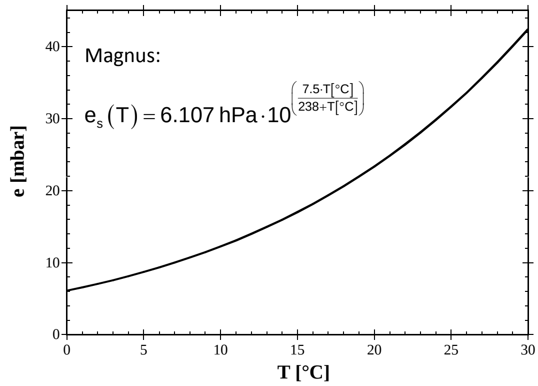
$$p_s(T) = p_0 \cdot \exp\left[-\frac{L}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$



e.g.: T_0 = 0°C, p_0 = 6.11 mbar, L = 2.5·10^6 J kg^{-1}

In practice: Magnus equation $p_s(T) = 6.107\ \text{hPa} \cdot 10^{\left(\frac{7.5T[°C]}{238+T[°C]}\right)}$

Saturation Vapour Pressure



Summary

- Aquatic Physics looks at physical processes in aquatic systems
- The hydrological cycle is a central process in the environment
- The hydrosphere is an essential part of the climate system
- Humanity's use of water is about 30 % of the available resource
- In arid regions, over-exploitation occurs (drying lakes, rivers, etc.)
- Physical properties of water are quite extraordinary
- High specific and latent heat are important for the climate
- Vapour pressure strongly increases with temperature