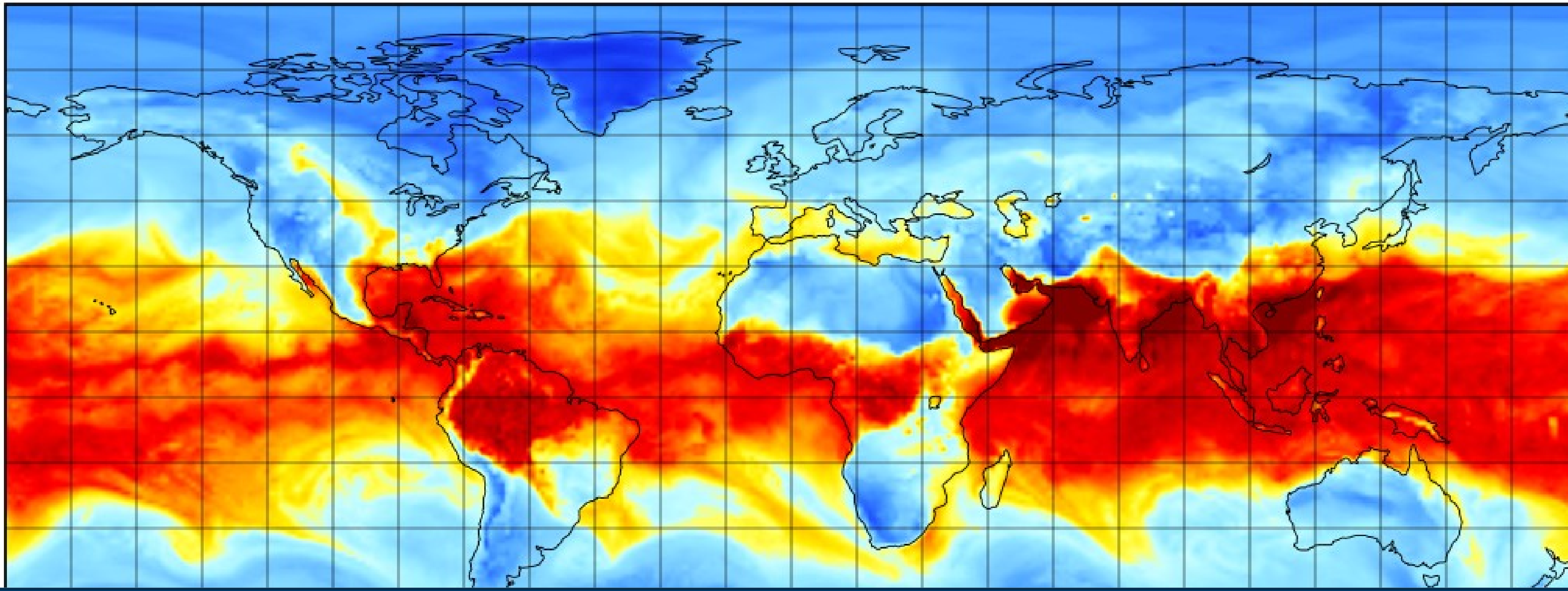

WATER IN THE ATMOSPHERE AND THE ROLE FOR CLIMATE

Part 4: Water cycle

WS 22/23 I CHRISTIAN ROLF

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TOPICS

1. Introduction into units and definitions
2. Water vapor distribution in the atmosphere
3. Cloud formation (water and ice clouds)
4. Water cycle
5. Water and climate feedback
6. Measurement of water in the atmosphere

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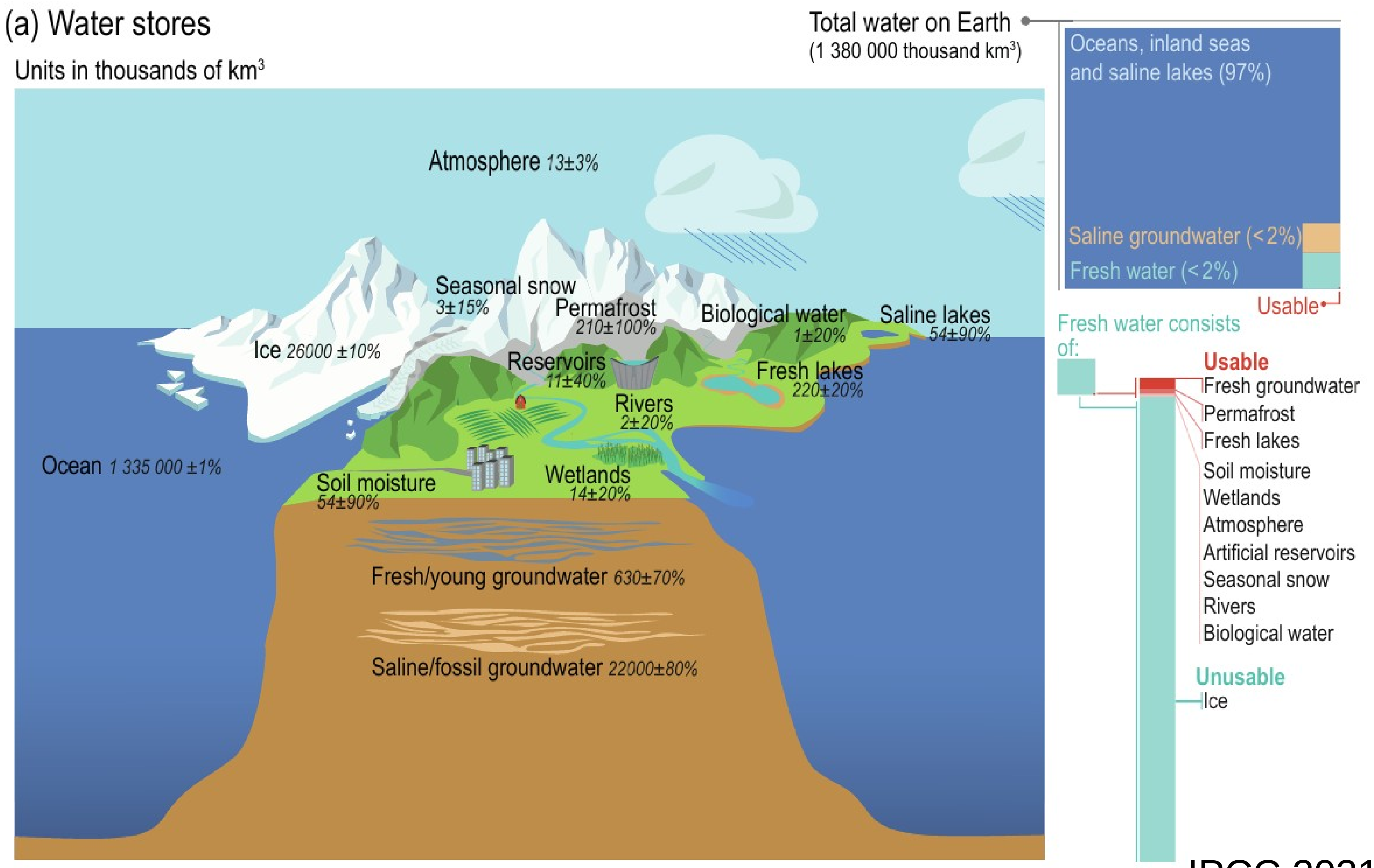
SUBTOPICS

4. Water cycle

- **Amount of water in the global water cycle**
- Schematics of the hydrological cycle
- Water balance equation
  - Precipitation
  - Soil moisture
  - Evaporation
- Annual mean mass Balance
- Transpiration of plants
- Energy balance equation
  - Bowen Ratio
  - Penman Equation
  - Net Radiation
  - Measurements of Evapotranspiration

WATER STORES



IPCC 2021

Over 70% of the planet is covered by water

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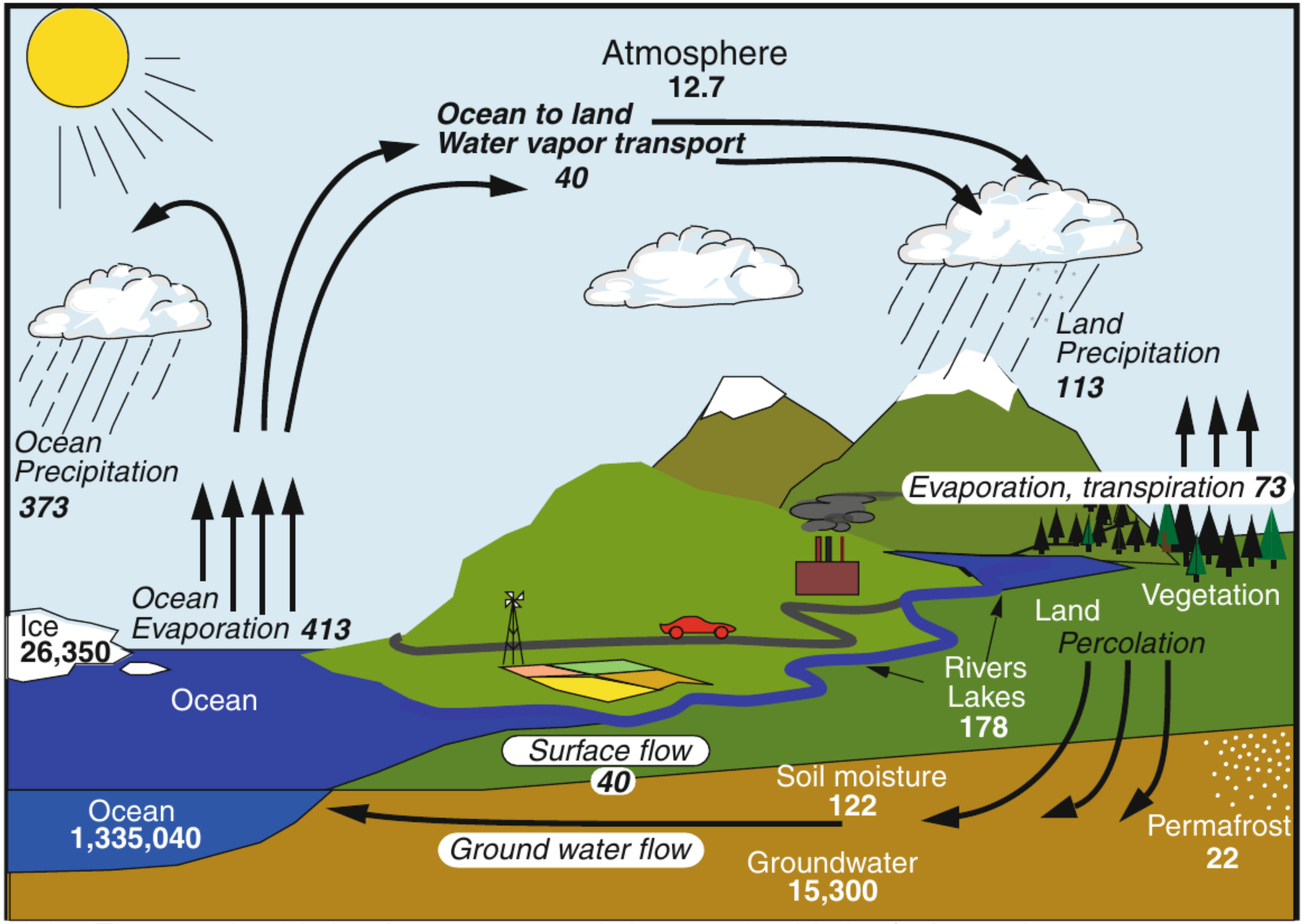
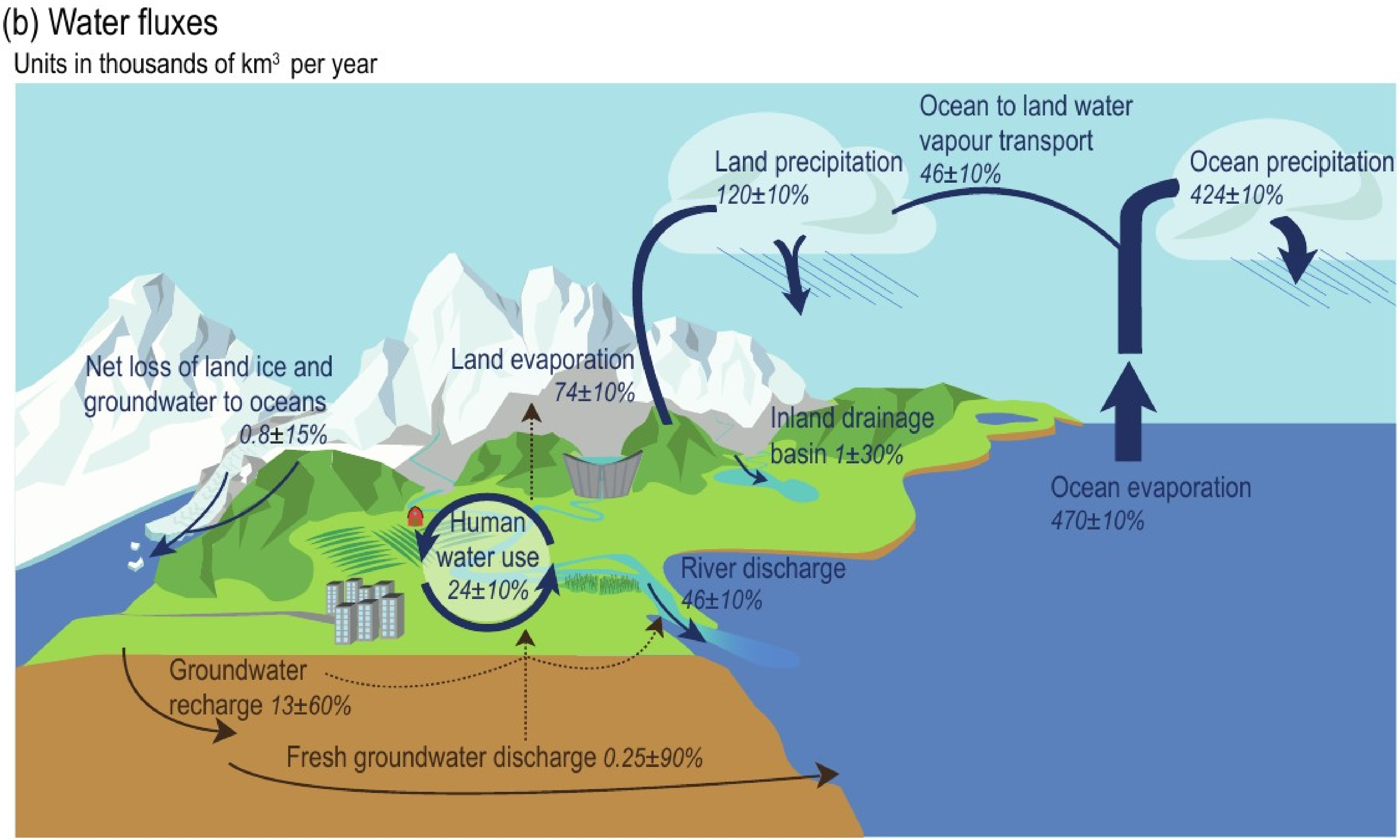
HYDROLOGICAL CYCLE - WATER FLUXES



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

Trenberth et al. (2007a, b)

HYDROLOGICAL CYCLE - WATER FLUXES



IPCC 2021

PERIODS OF WATER RESOURCES RENEWAL ON THE EARTH

Water of hydrosphere	Period of renewal
World Ocean	2500 years
Ground water	1400 years
Polar ice	9700 years
Mountain glaciers	1600 years
Ground ice of the permafrost zone	10000 years
Lakes	17 years
Bogs	5 years
Soil moisture	1 year
Channel network	16 days
Atmospheric moisture	8 days
Biological water	Several hours

Source: Shiklomanov (1999).

SUBTOPICS

4. Water cycle

- Amount of water in the global water cycle
- **Schematics of the hydrological cycle**
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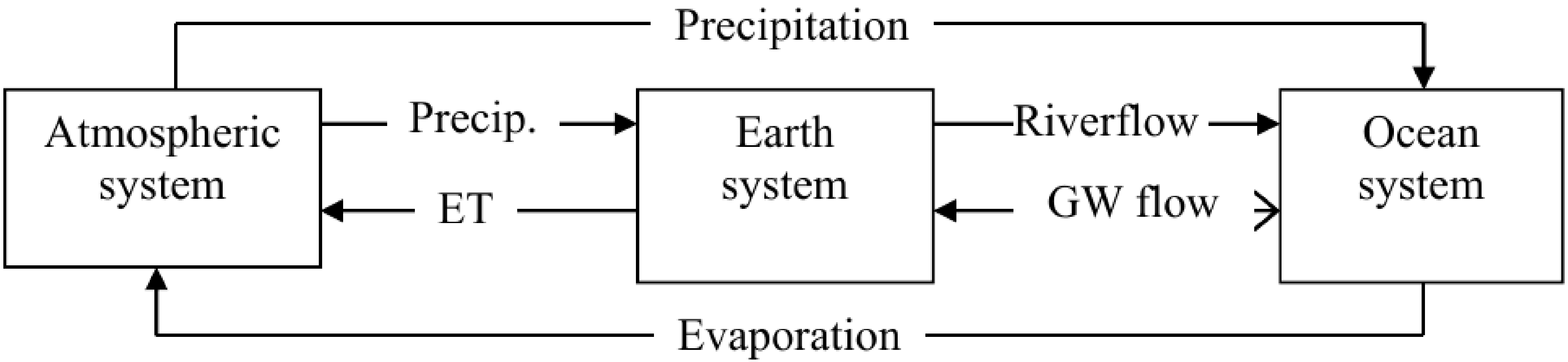
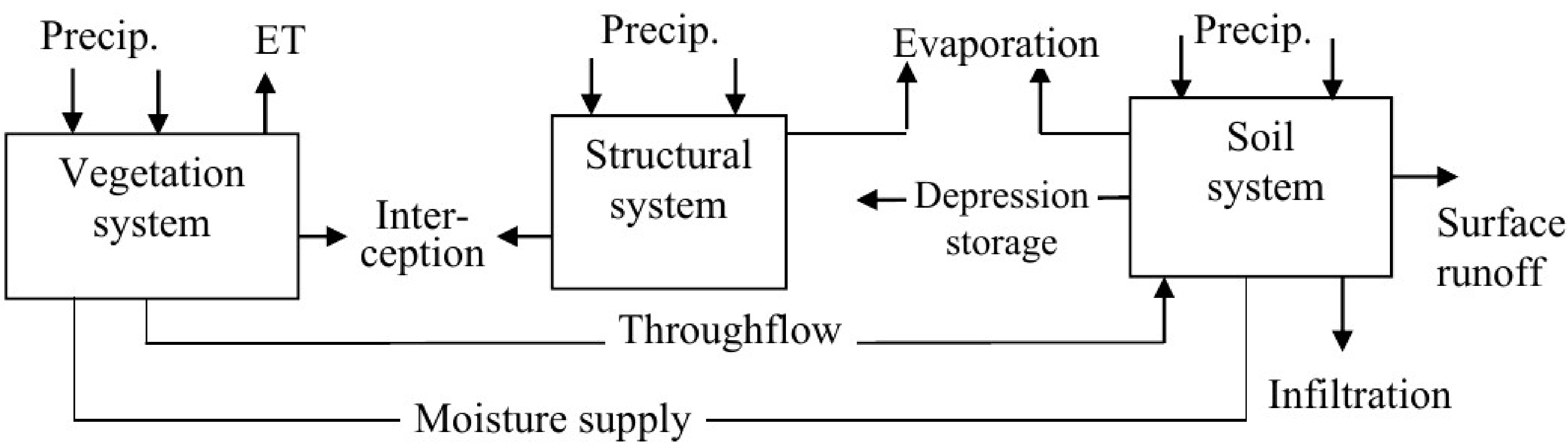
SCHEMATIC OF THE HYDROLOGICAL CYCLE GLOBAL



SCHEMATIC OF THE HYDROLOGICAL CYCLE (LAND)



SUBTOPICS

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WATER BALANCE

The water balance defines the conservation of mass across the different compartments of the hydrological cycle (atmosphere, water bodies, soil and ground, vegetation, snowpack and ice, ...)

The concept of conservation of mass implies the identification of an incoming and an outgoing flux, and of a storage variation over a given unit of time.

Water balance equation:

$$R = P - ET - IG - \Delta S$$

Where:

P = Precipitaion
R = Runoff
ET = Evapotranspiration
IG = Deep/interactive groundwater
ΔS = Change in soil storage

SUBTOPICS

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PRECIPITATION

The global averaged precipitation is also about 1 meter per year.

1) Cloud droplet growth over condensation and coalescence
2) Ice crystals sedimented from high levels and melt at warmer temperatures (mostly glaciated mixed-phase clouds)

➔ Cloud droplets further grow by collision → Rain drop is large enough to fall

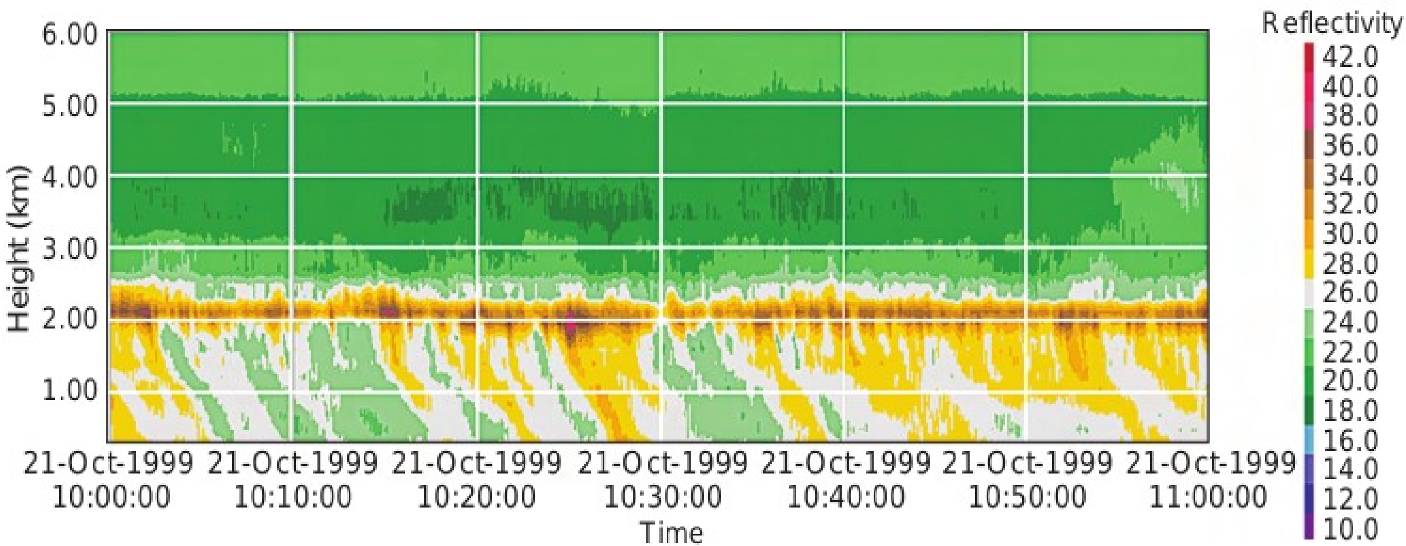


Fig. 6.45 Reflectivity (or "echo") from a vertically pointing radar. The horizontal band of high reflectivity values (in brown), located just above a height of 2 km, is the melting band. The curved trails of relatively high reflectivity (in yellow) emanating from the bright band are *fallstreaks* of precipitation, some of which reach the ground. [Courtesy of Sandra E. Yuter.]

Wallace & Hobbs

PRECIPITATION

- Ice crystals have a lower densitiy i.e. lower weight to volumne ratio compared to droplets and thus a lower fall speed

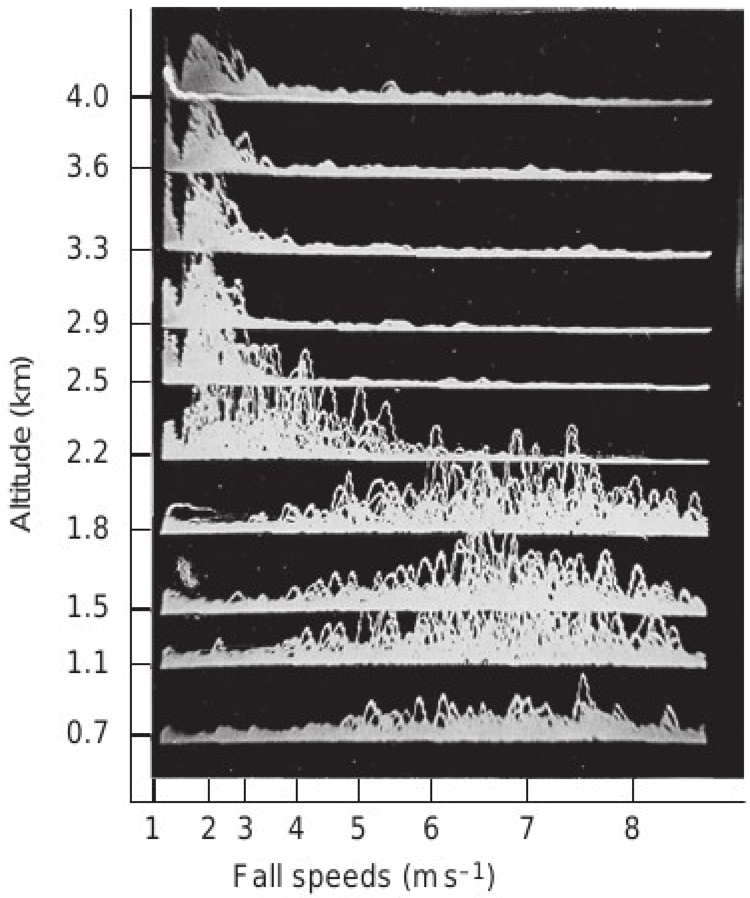
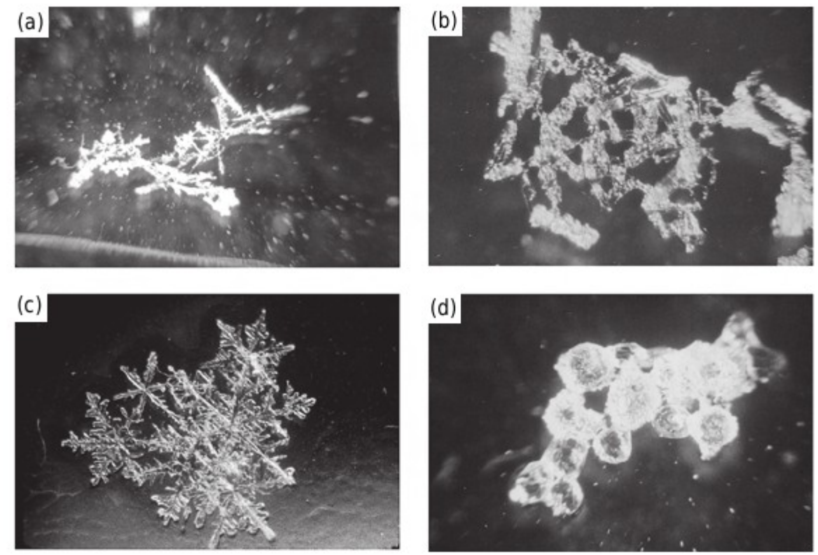


Fig. 6.46 Spectra of Doppler fall speeds for precipitation particles at ten heights in the atmosphere. The melting level is at about 2.2 km. [Courtesy of Cloud and Aerosol Research Group, University of Washington.]

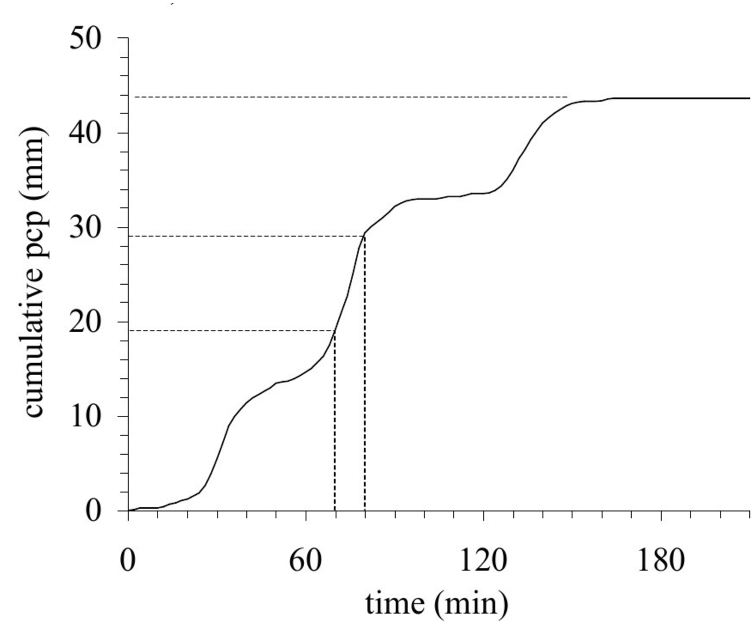
Wallace & Hobbs



Aggregates of (a) rimed needles; (b) rimed columns; (c) dendrites; and (d) rimed frozen drops. (Wallace & Hobbs)

PRECIPITATION

Important parameters
- Amount (mm)
- Intensity (mm/hr)
- Duration (minutes, hours)
- Droplet distribution (number, size)



Rain
Gauges

Rain Radar

Droplet spectrometer

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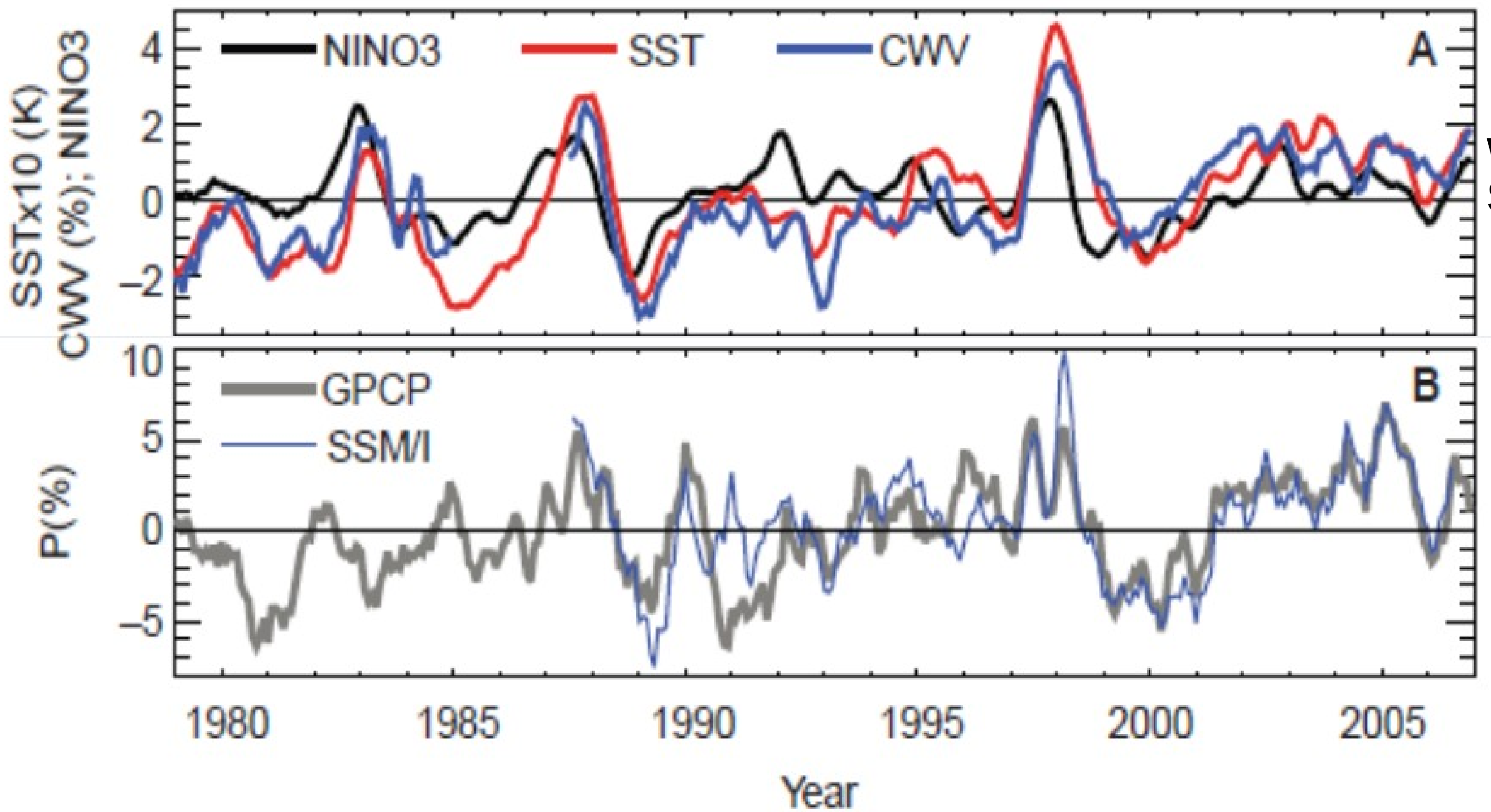
PRECIPITATION



water vapor, SST's

Precip.

Precipitation closely follows temperature and water vapor

SUBTOPICS

4. Water cycle

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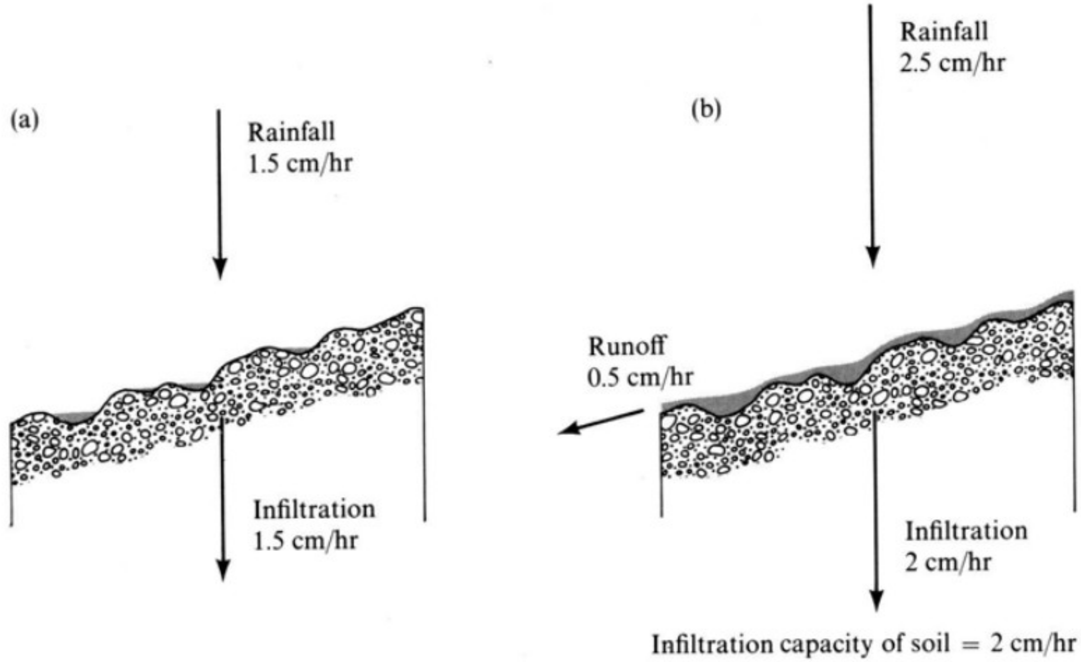
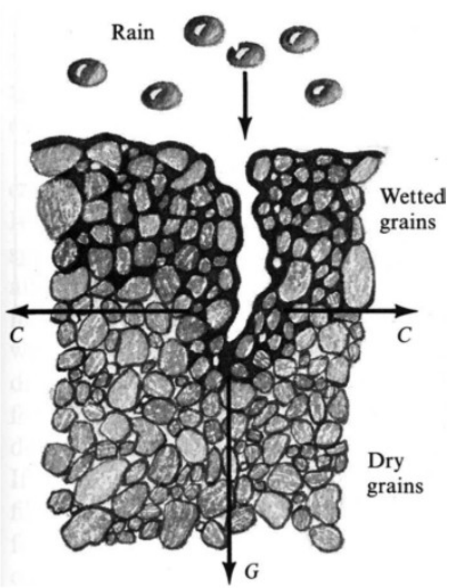
SOIL MOISTURE & INFILTRATION

- Significant overland flow occurs when infiltration capacity is exceeded by heavy rainfall.

- **Driving force**
  - gravity
  - surface tension (capillary force)





Downward Transport & Permeability
- pore sizes (Permeability)
- macro features (cracks, root holes, etc.)
- depth of the permeable soil
- vegetative cover

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SUBTOPICS

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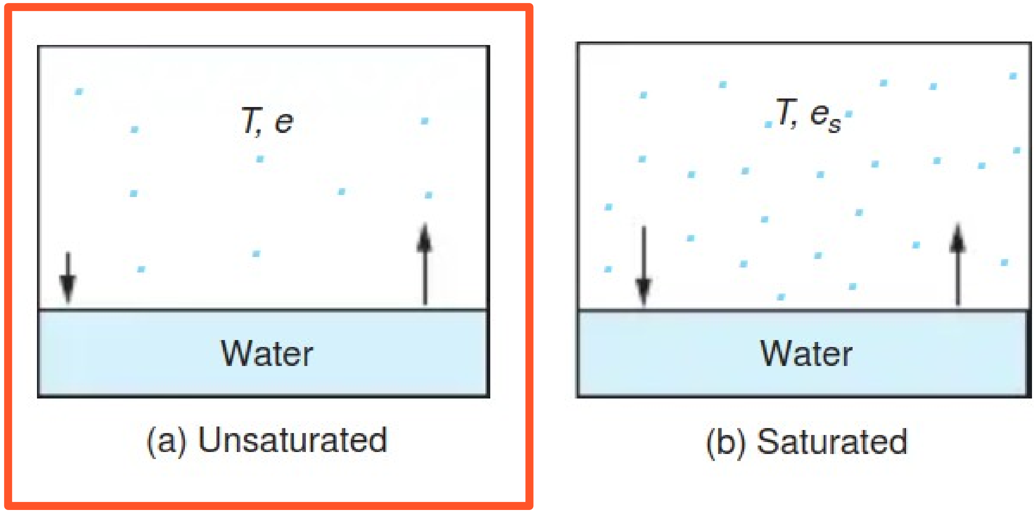
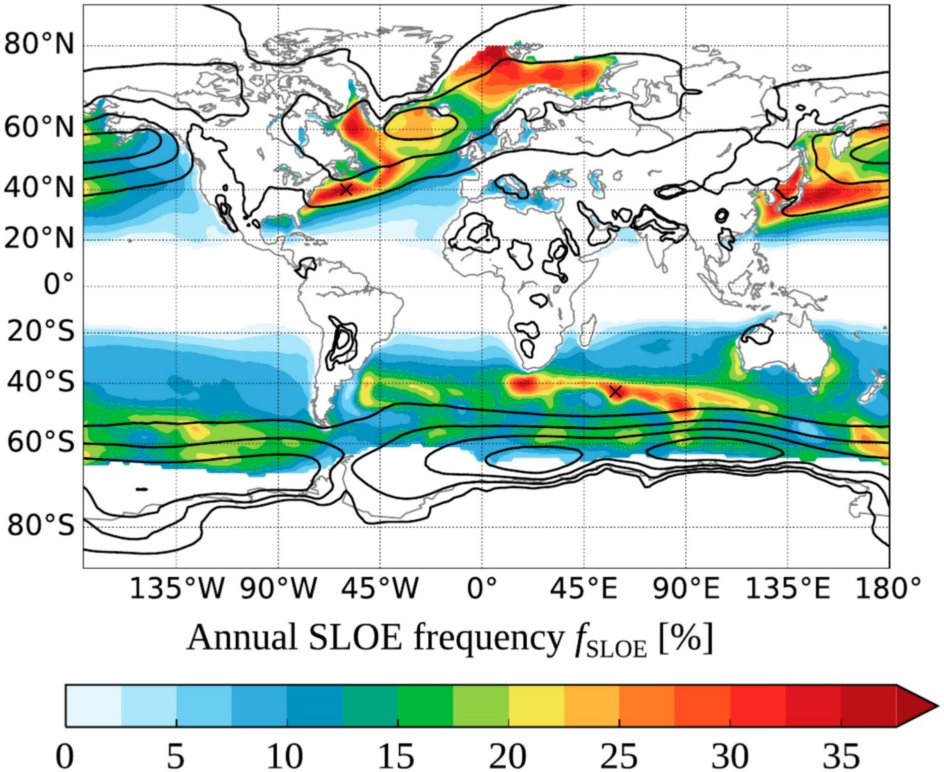
EVAPORATION

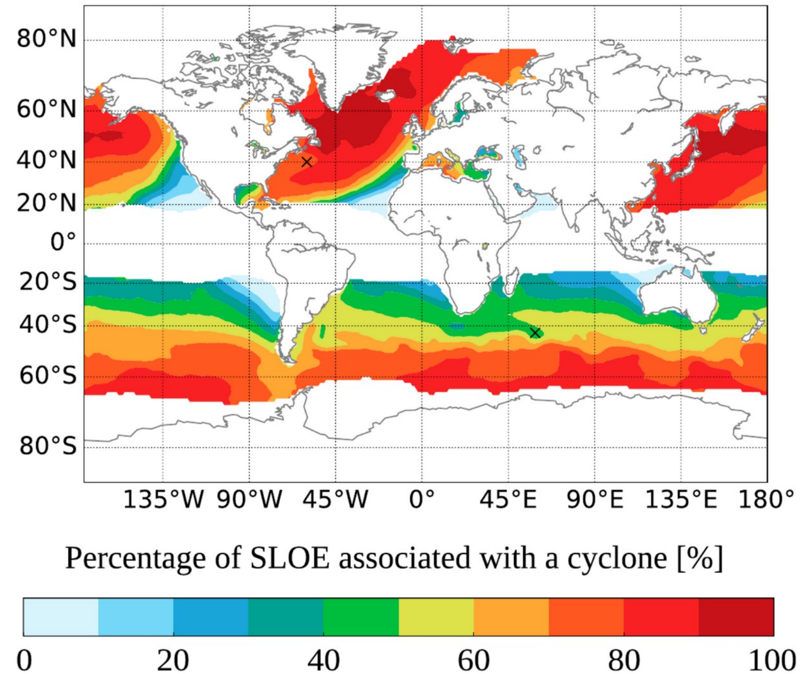


- On average, **1 meter of water is evaporated** from oceans to the atmosphere each year.
- Earth's surface lost heat to the atmosphere when water is evaporated from oceans to the atmosphere.
- The **evaporation of the 1m of water** causes Earth's surface to lost **83 watts per square meter**, almost half of the sunlight that reaches the surface.
- **Without the evaporation** process, the global surface **temperature would be 67 ℃** instead of the actual 15 ℃.

EVAPORATION

- Large scale ocean evaporation mainly caused by cyclonic weather systems





SLOE: strong large-scale ocean evaporation

Aemisegger, F., and L. Papritz, 2018:
A climatological analysis of strong large-scale ocean evaporation. Part I: Identification, global distribution, and associated climate conditions.
J. Climate, 31, 7287–7312,
https://doi.org/10.1175/JCLI-D-17-0591.1.

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ANNUAL MEAN MASS BALANCE

Averaged over the globe, the rate of precipitation P equals the rate of evaporation E.

Steady state conditions:

Water vapor over in a column of area A, extending from the Earth's surface to the top of the atmosphere.

$$\overline{Tr} = \overline{E} - \overline{P}$$

Tr: Horizontal transport (water flux)

Time dependent hydrological mass balance over land:

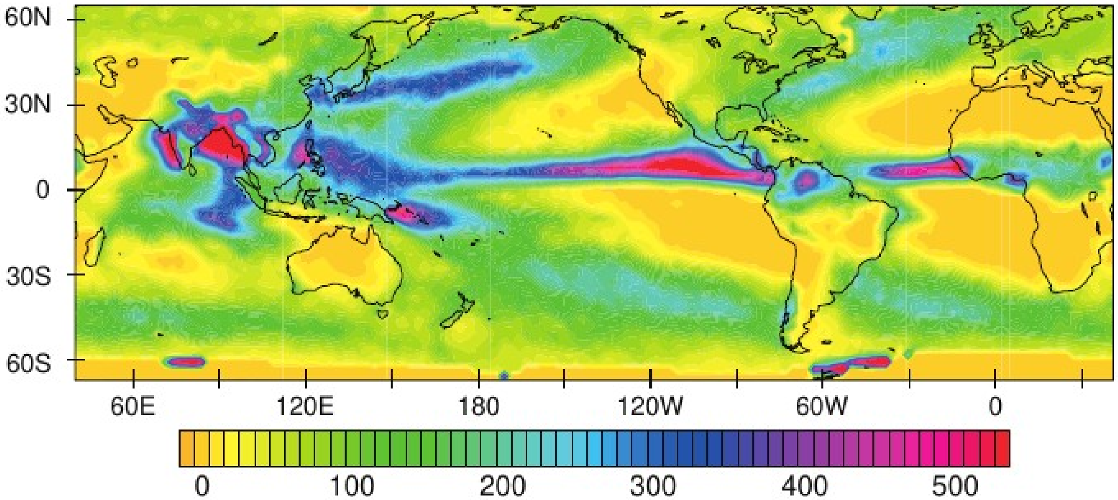
$$\frac{d\,\overline{St}}{dt} = \overline{P} - \overline{E} - \overline{T}$$

St: area averaged water storage

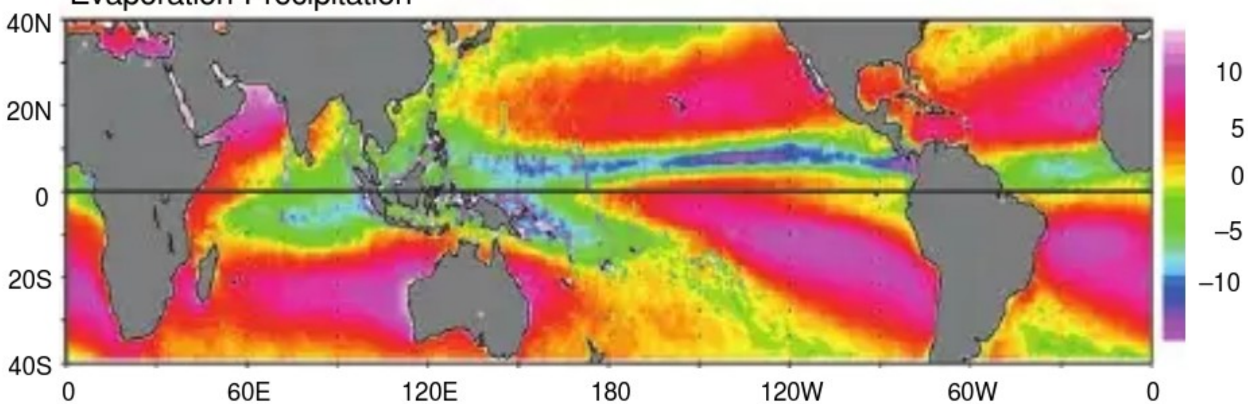
T: Transport term (in- and outflow, i.e. rivers)

ANNUAL MEAN MASS BALANCE

Precipitation July climatology (satellite & in-situ)



Evaporation-Precipitation

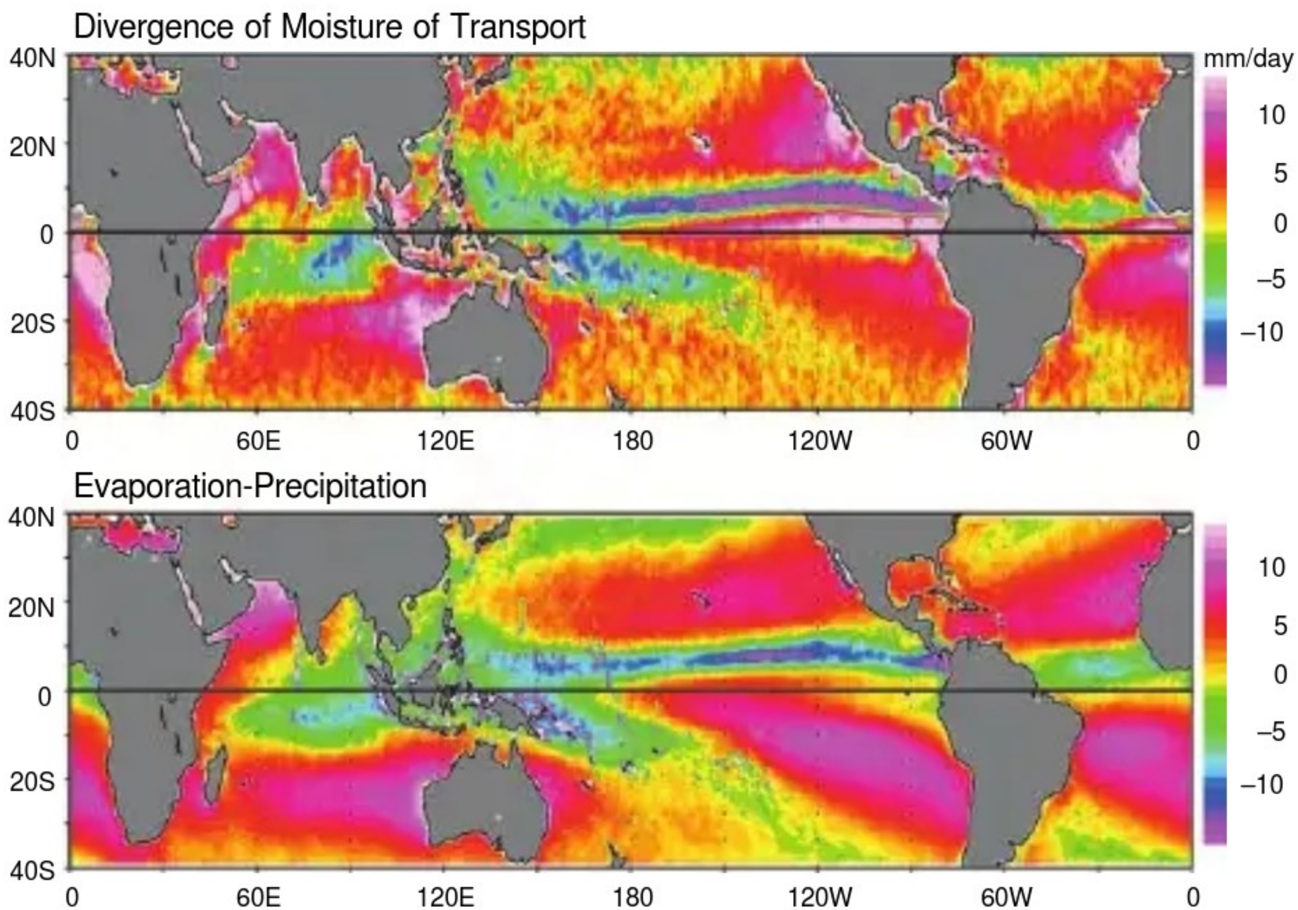


Wallace and Hobbs

P and E - P
exhibit similar distributions indicates that the horizontal gradients of P must be much stronger than those in E.

Gradient in P are due to wind patterns

ANNUAL MEAN MASS BALANCE



Wallace and Hobbs

Terms in the annual mean mass balance of atmospheric water vapor in units of mm day^{-1} of liquid water.

(Top) The local rate of change of vertically integrated water vapor due to horizontal transport by the winds.

(Bottom) Difference between local evaporation and local precipitation. If the estimates were perfect, the maps would be identical.

Consistent picture from measurement data of P, E, and Tr

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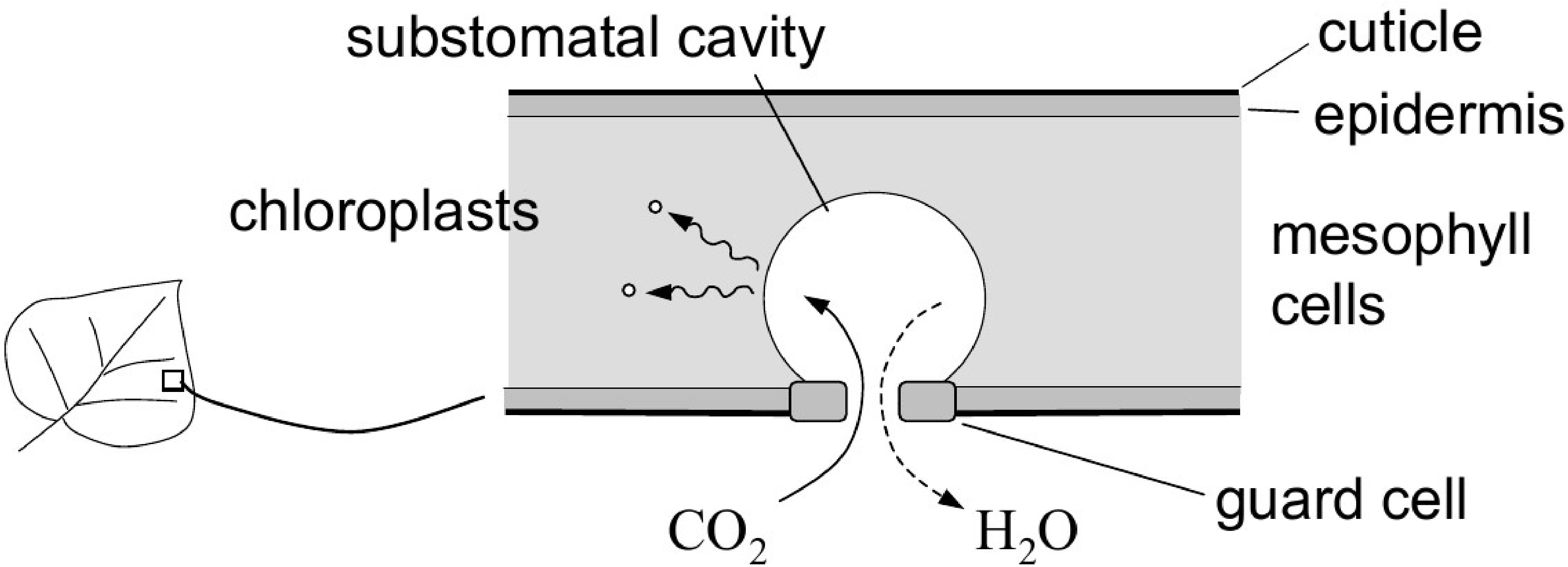
TRANSPIRATION OF PLANTS

Transpiration – loss of water from stomatal opening



Plants control their temperatures by evapo-transpiration
(i.e., by giving off water vapor through their leaves or needles).

Evaporation + Transpiration = Evapotranspiration (ET)

SUBTOPICS

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ENERGY BALANCE EQUATION

$$Q_G = Q_N - Q_H - Q_e + Q_V - Q_{VE}$$

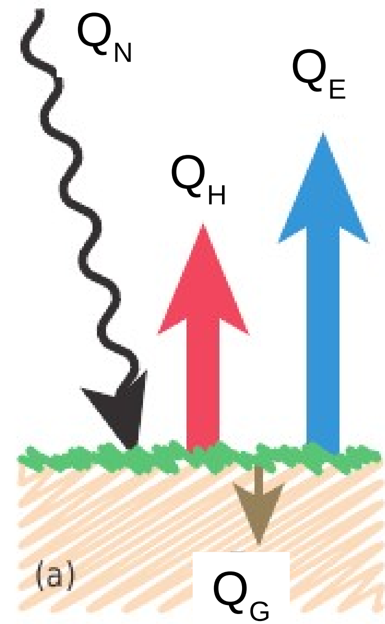
neglectable

Q_G: Energy conduction to ground
Q_N: net radiation
Q_H: sensible heat
Q_E: latent heat
Q_V: net energy advection (in)
Q_{VE}: net energy advection (out)

Aim:
Estimate evaporation E_0 from Q_e with the help of L_v (latent heat)

$$Q_H = \rho c_p \frac{T_z - T_0}{r_a}$$

$$Q_E = L_v E_0 = \rho L_v \frac{q(z) - q_s(0)}{r_a + r_s}$$



r_s: Surface resistance (stomata of plants)
r_a: aerodynamical resistance (turbulance)
L_v: latent heat of vaporization

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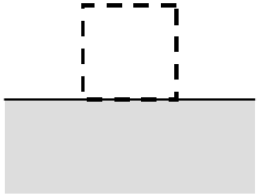
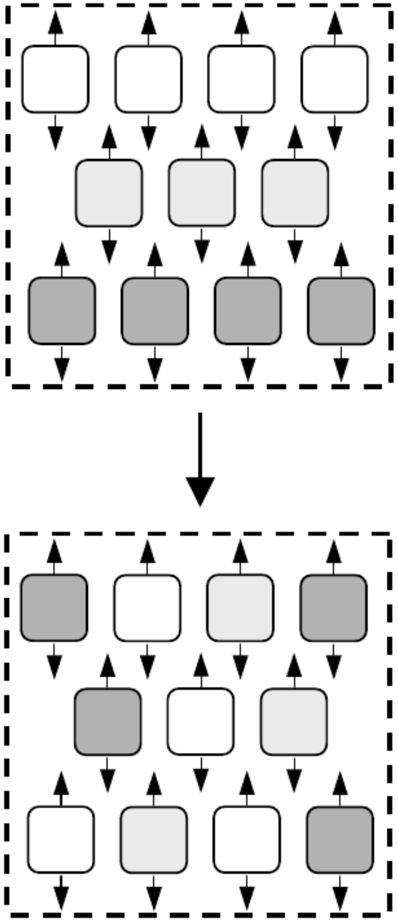
BOWEN RATIO

It is difficult to measure Q_E and Q_H separately, but reasonably easy to measure the ratio Q_H/Q_E . Why?





1) Each parcel contains numerous molecules. Parcels near the water surface contain more water vapor than the ones far from the surface.

2) Random motion of the parcels lead to the net upward transfer of water vapor.

$$R = \frac{Q_H}{Q_E}$$

Typical values:
R< 0.1 tropical oceans
(warm sea surface → dominate latent heat flux)
R= 0.5-1.5 ice surfaces
R ≈ 0.5 over grasland
R≈10 for deserts)

BOWEN RATIO

$$R = \frac{Q_H}{Q_E} = \frac{c_p p}{L_v \epsilon} \frac{T_z - T_0}{e_z - e_0} \left(1 + \frac{r_s}{r_a}\right) \qquad \gamma = \frac{c_p p}{L_v \epsilon}$$

γ: psychrometric constant (hPa °C^{-1})
L_v: latent heat of vaporization

r_s: Surface resistance (stomata of plants)
r_a: aerodynamical resistance (turbulance)

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BOWEN RATIO & PENMAN EQUATION (1)

BOWEN RATIO & PENMAN EQUATION (2)

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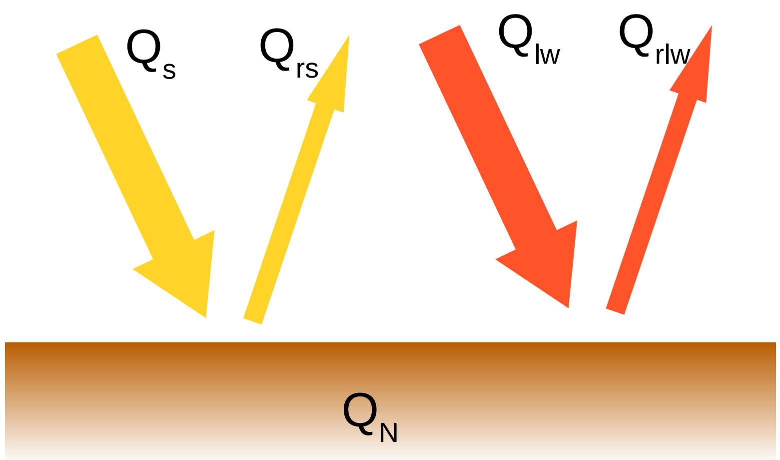
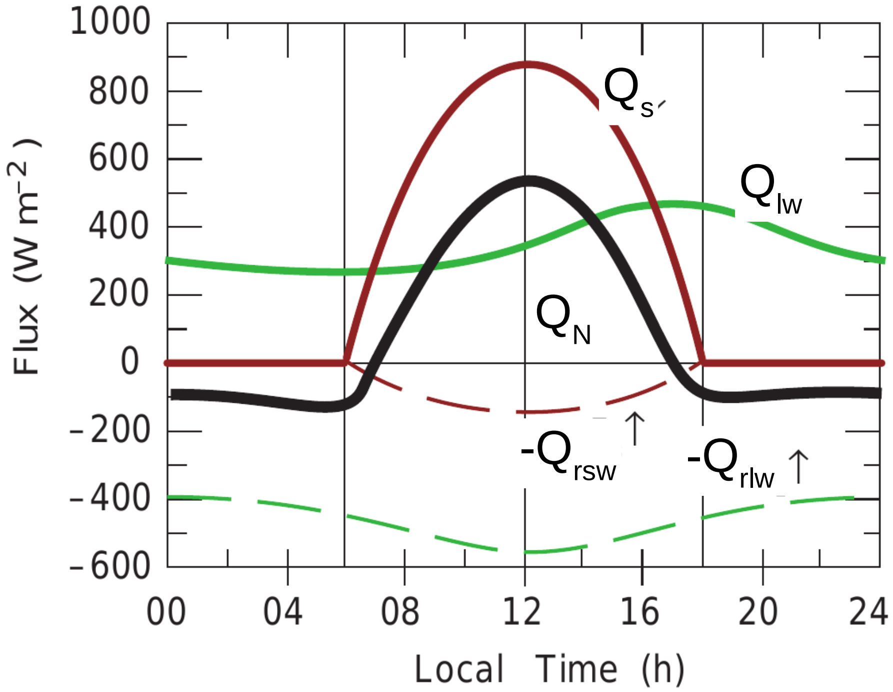
NET RADIATION

Approximate estimates of Q_N:

$$Q_N = Q_s - Q_{rs} + Q_{lw} - Q_{rlw} = Q_s(1-\alpha) + \Delta Q_{lw}$$

Q_s : incoming shortwave (solar) radiation
Q_{rs}: reflected shortwave radiation
ΔQ_{lw}: net longwave radiation
α: albedo (assumed 0.06 for water)





Wallace and Hobbs

SUBTOPICS

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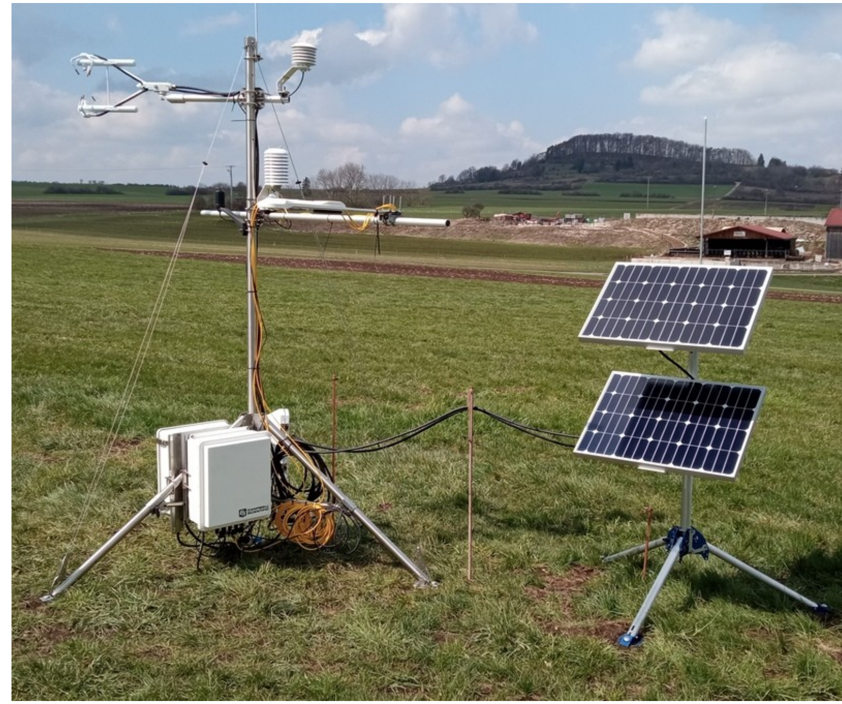
  - **Measurements of Evapotranspiration**

EVAPOTRANSPIRATION MEASUREMENT

- **Temperature, Pressure, Precipitation**
- **Ultrasonic anemometers:**
  three-dimensional wind direction and velocity,
- **Pyranometer:**
  short-wave solar irradiation (global radiation) as well as the solar radiation reflected at the earth's surface
- **Pyrgeometer:**
  same as Pyranometer
  long-wave terrestrial radiation
- **Ground heat flux plates:**
  Measurement of the heat transport from the ground into the atmosphere and vice versa at a depth of 5 centimetres.
- **Radiation thermometer:**
  Determination of surface temperature.
- **Inclinometer:**
  Electrical measurement of the instrument's inclination.
- **SISOMOP:**
  Soil temperature and moisture at three depths.
- **Moisture and carbon dioxide sensor:** CO_2 and H_2O (CO_2 and latent heat fluxes)



Energy balance station

EVAPOTRANSPIRATION MEASUREMENT