Terrestrial Energy and Water Balance

CHESS Land Surface Modelling Course

2-6 10 2017 - Bergen

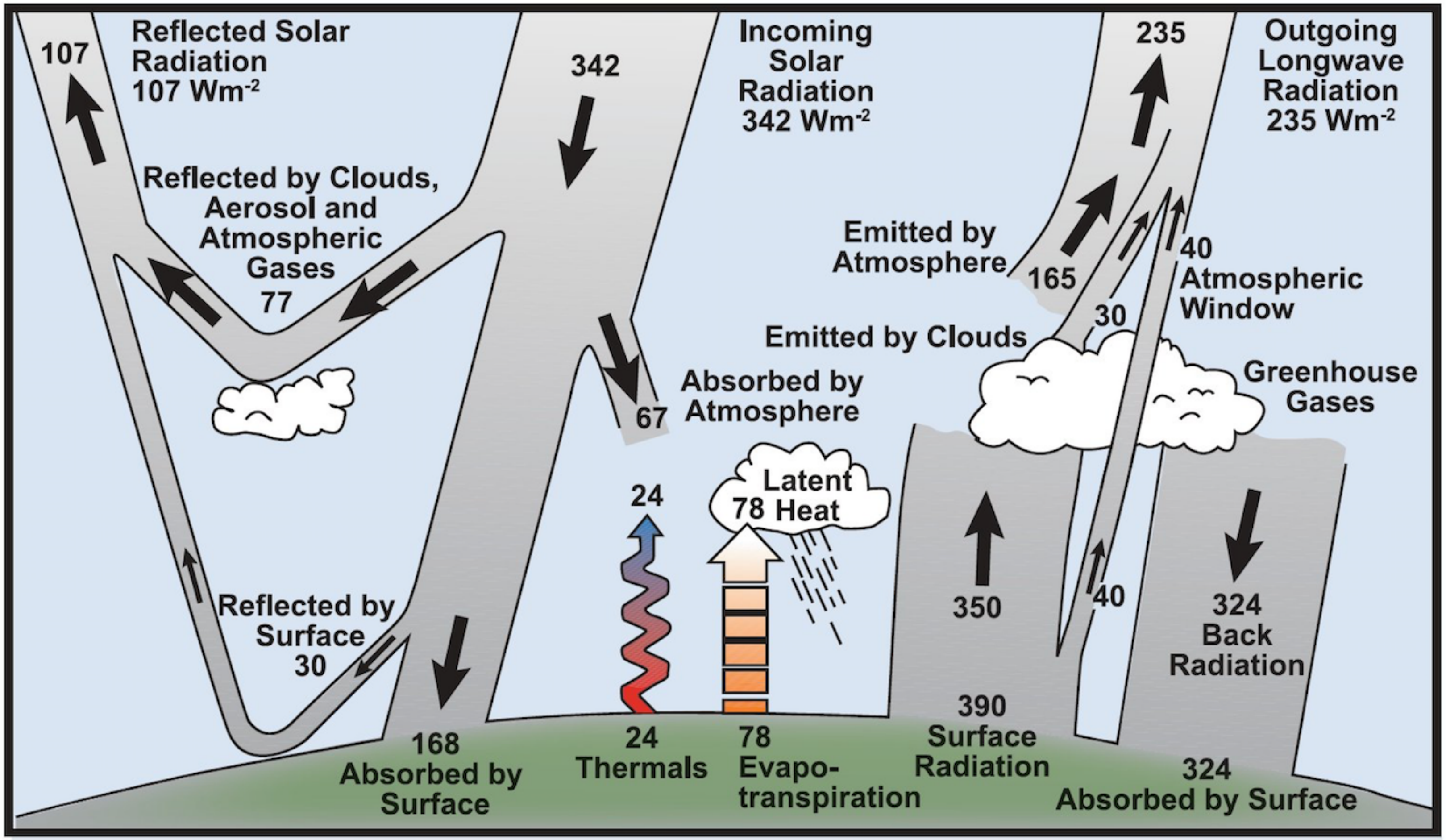
by

Altug Ekici

Energy Balance

Surface energy balance

Radiation budget



IPCC, 2007

Surface energy balance

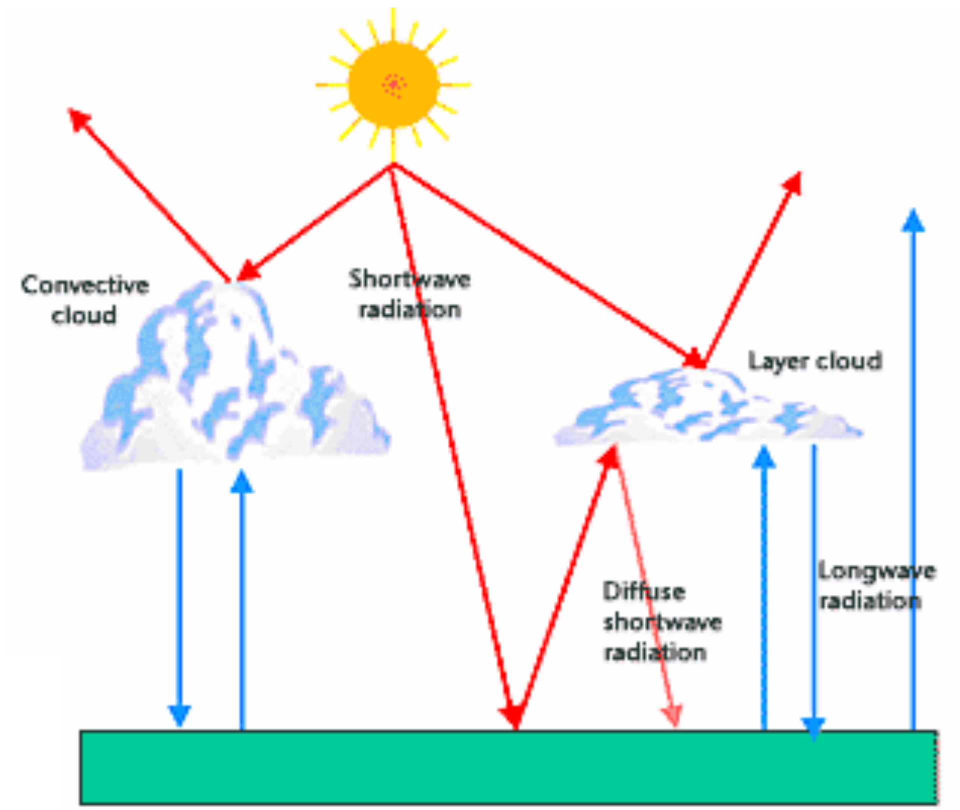
Radiation budget

- Shortwave / Longwave radiation

- Incoming / outgoing radiation

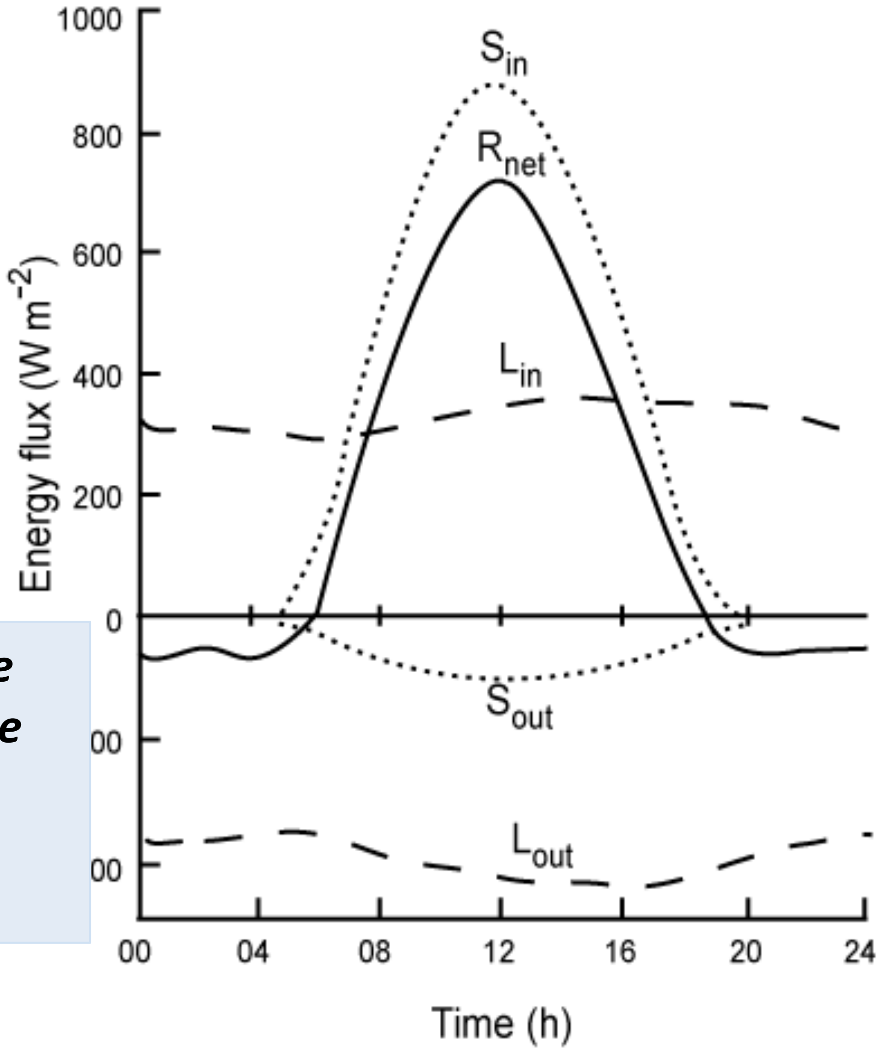
- Direct / diffuse radiation

$$R_{net} = (K_{in} - K_{out}) + (L_{in} - L_{out})$$



Surface energy balance

Radiation budget



"shortwave radiation input, albedo, surface roughness, and surface temperature are the parameters that most strongly influence radiation balance and therefore net radiation"

Surface energy balance

Radiation budget

α **Albedo**

Depends on:
- Wetness
- Colour
- Leaf nitrogen
- Ecosystem structure
  - deep canopy
  - smooth canopy

Snow-albedo feedback?

Table 4.1 Typical values of albedo for the major surface types on Earth.

Surface type	Albedo
Ocean and lakes	0.03-0.10[a]
Bare soil	
Wet, dark	0.05
Dry, dark	0.13
Dry, light	0.40
Evergreen conifer	0.08-0.11
Deciduous conifer	0.13-0.15
Evergreen broadleaf	0.11-0.13
Deciduous broadleaf	0.14-0.15
Arctic tundra	0.15-0.20
Grassland	0.18-0.21
Savanna	0.18-0.21
Agricultural crops	0.18-0.19
Desert	0.20-0.45
Sea ice	0.30-0.45
Snow	
Old	0.40-0.70
Fresh	0.75-0.95

Surface energy balance

Radiation budget

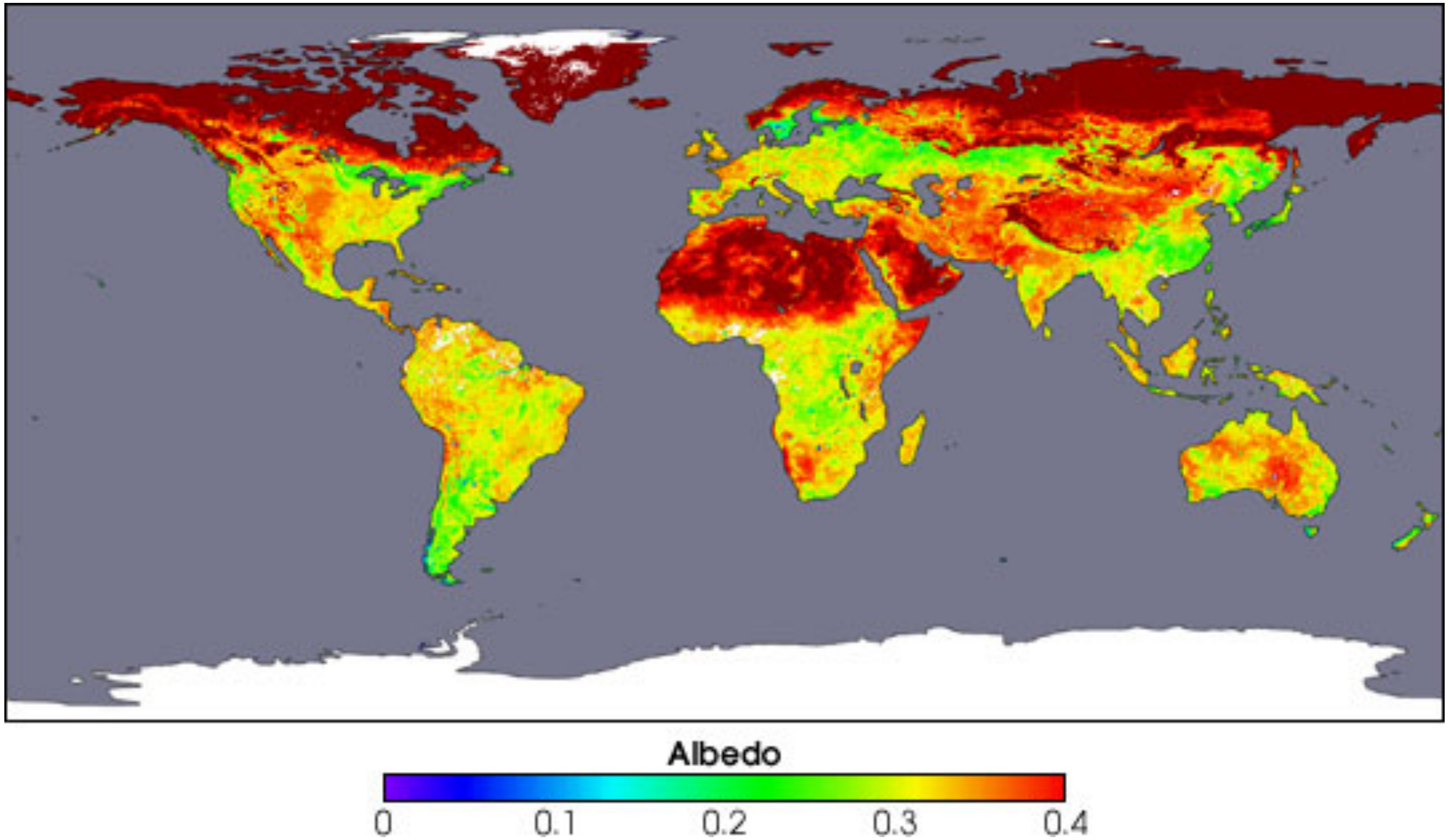
Snow-albedo feedback

α **Albedo**

Surface energy balance

Radiation budget

α **Albedo**



visibleearth.nasa.gov

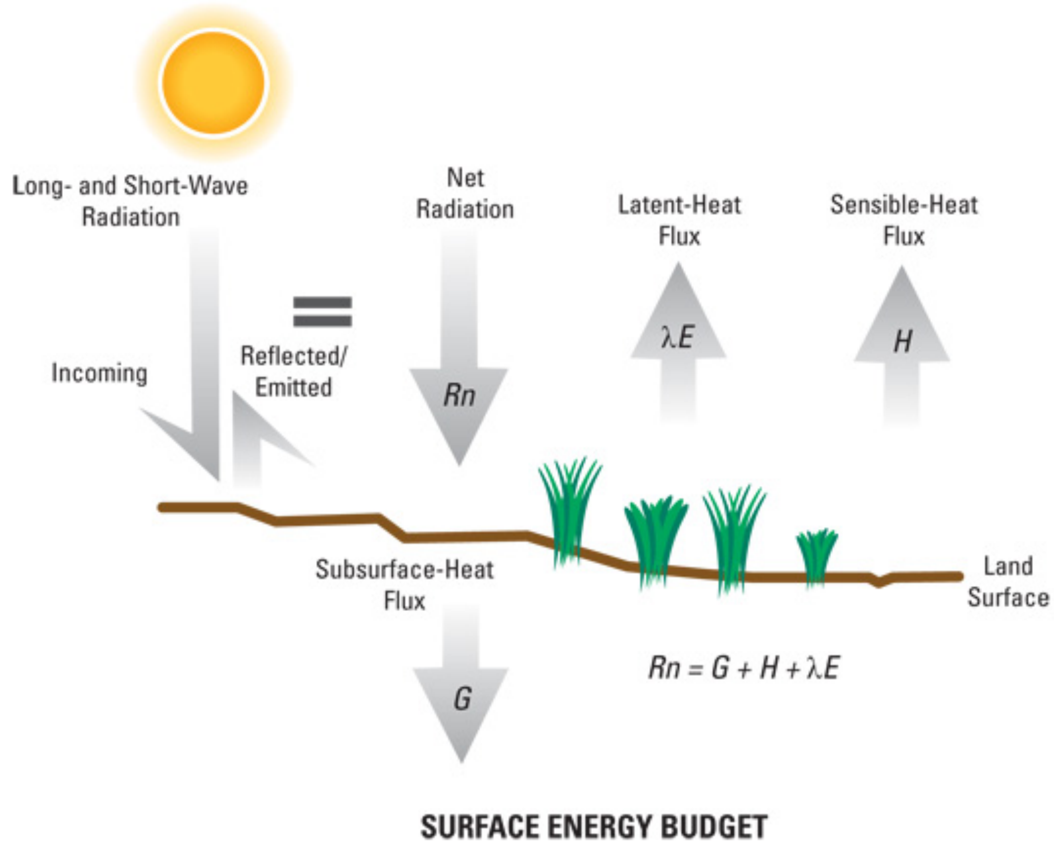
Surface energy balance

Partitioning of absorbed radiation

- Sensible heat flux
- Latent heat flux
- Ground heat flux

$$R_{net} = H + LE + G + \Delta S$$

H Sensible heat flux
L Latent heat of vaporization
E Evapotranspiration
G Ground heat flux
ΔS Storage



Surface energy balance

Partitioning of absorbed radiation

Stored heat
- usually small
- accounts for ecosystem growth

Ground heat flux
- usually balances day/night
- higher in frozen soils
- higher over water bodies

Turbulent fluxes (Sensible/Latent heat flux)
- convective turbulence
- mechanical turbulence

  surface roughness

  coupling to bulk air

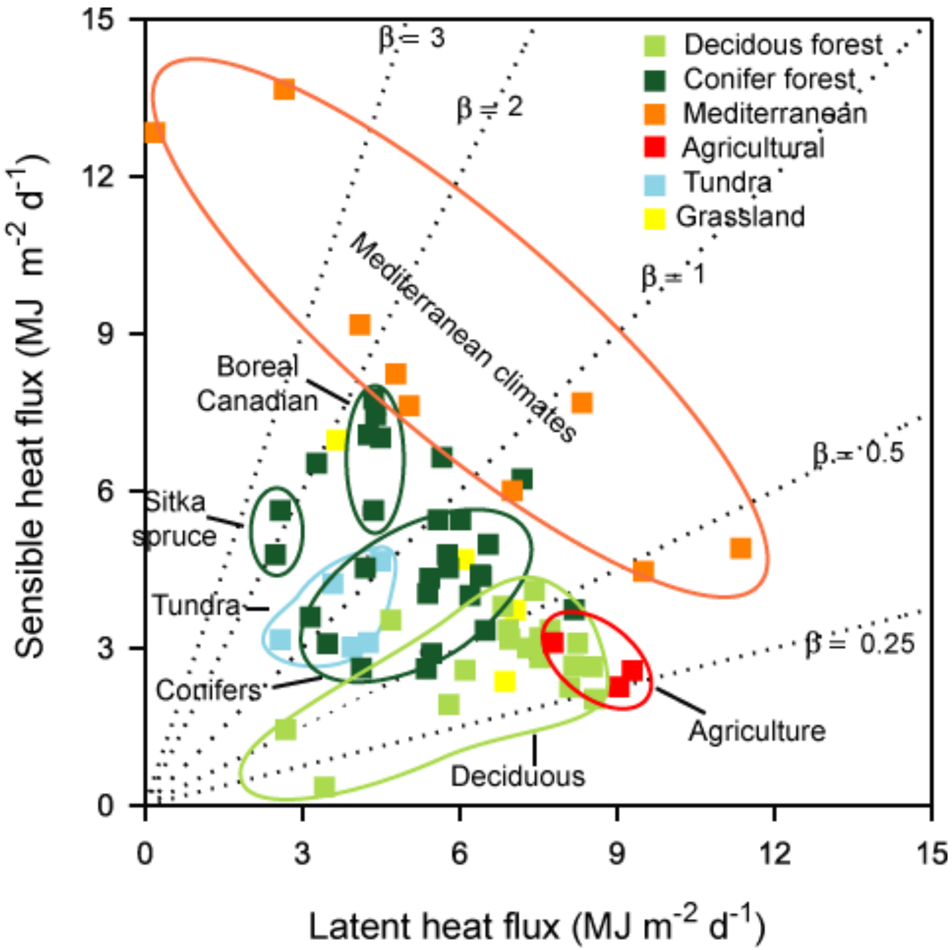
Surface energy balance

Partitioning of absorbed radiation

Bowen ratio: *H / LE*

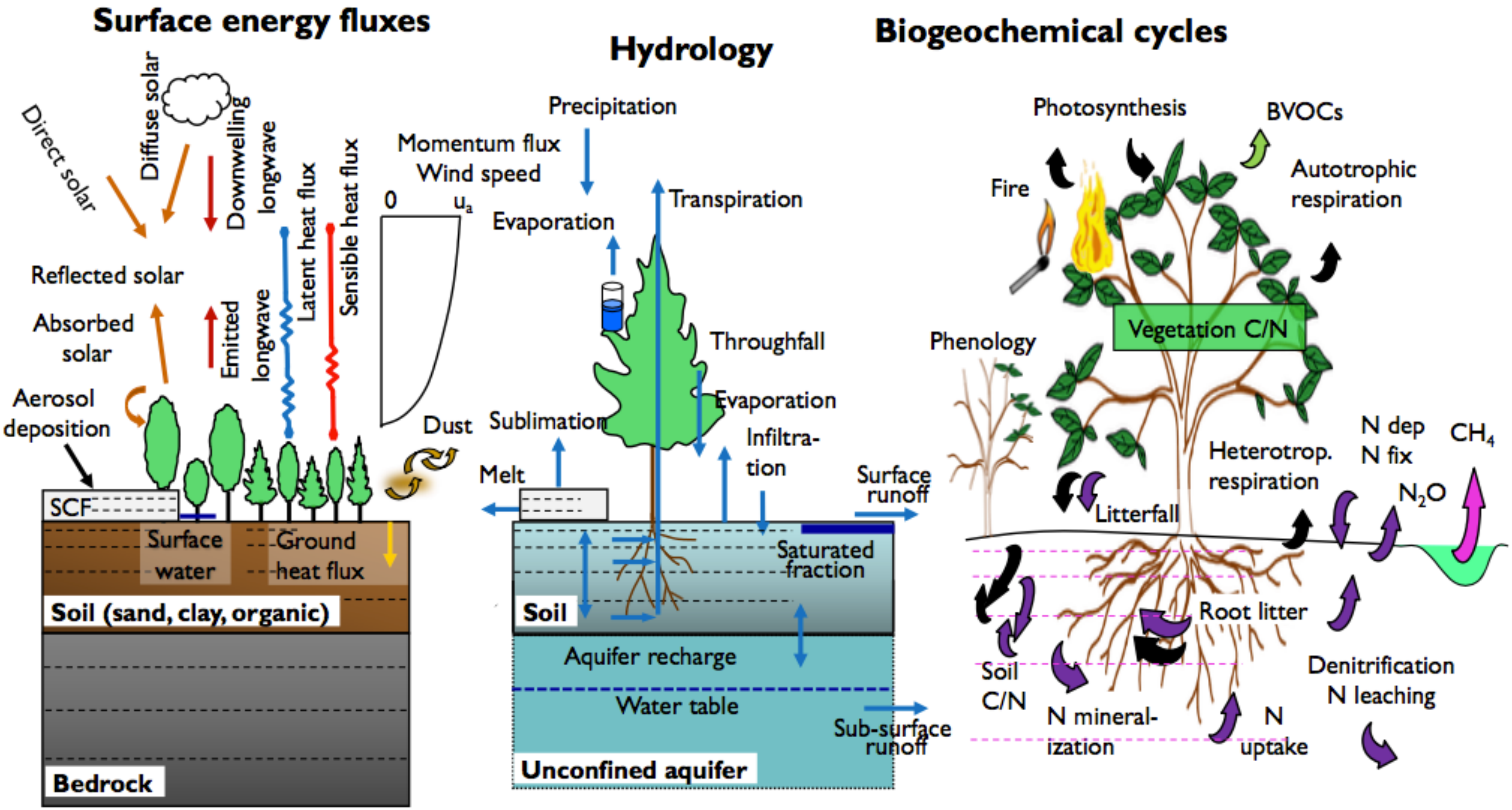
Depends on:

- wet/dry system
- species characteristics
- atm. turbulence (wind/roughness)

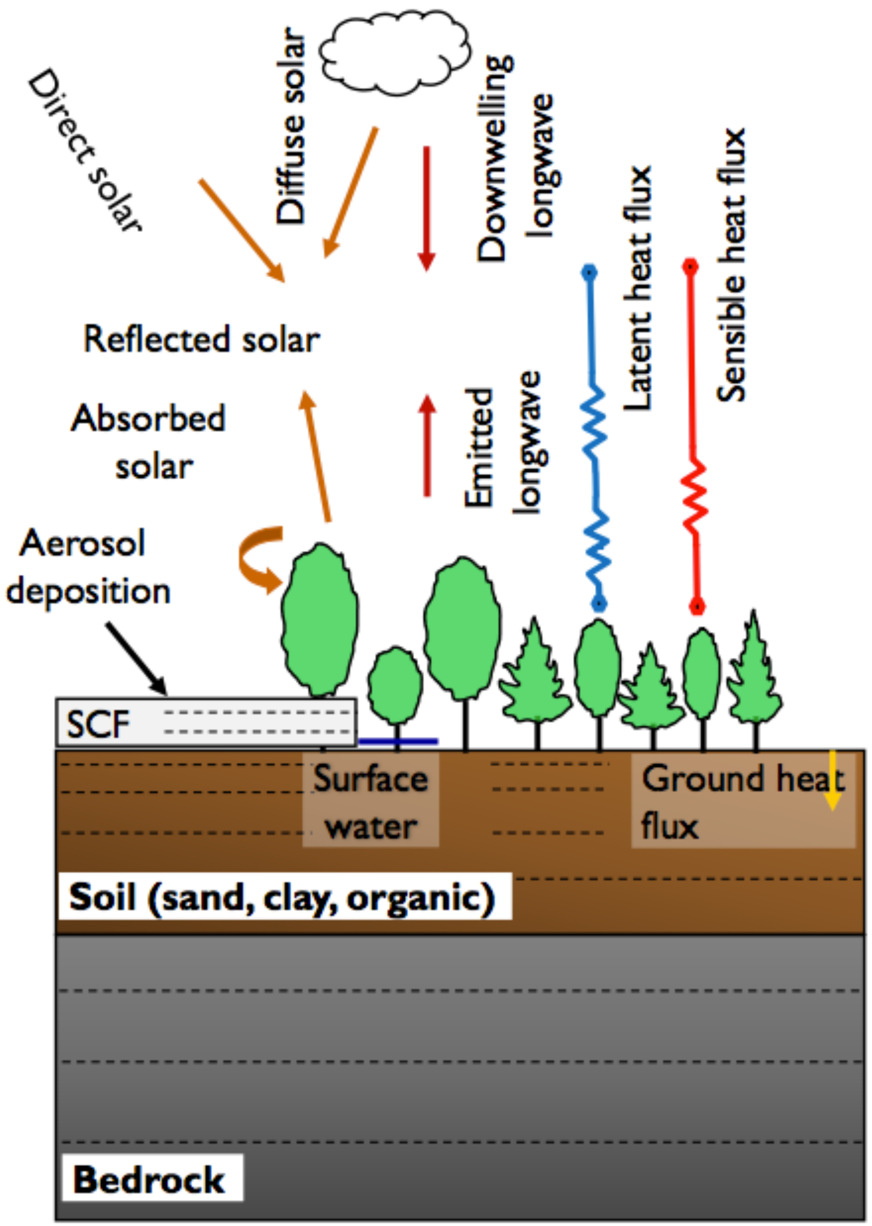


Surface energy balance

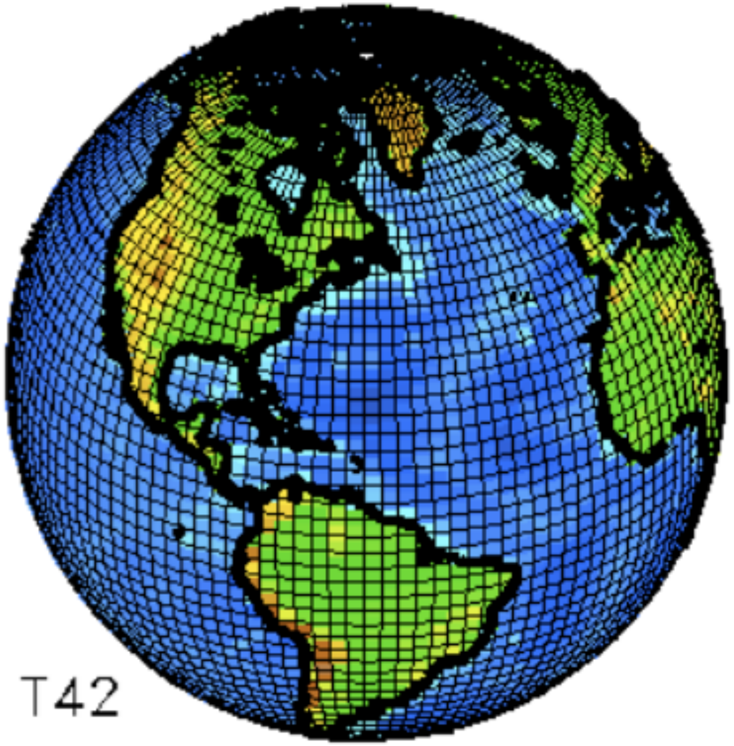
Model representation (CLM)



At each time step the land model solves Surface Energy Balance



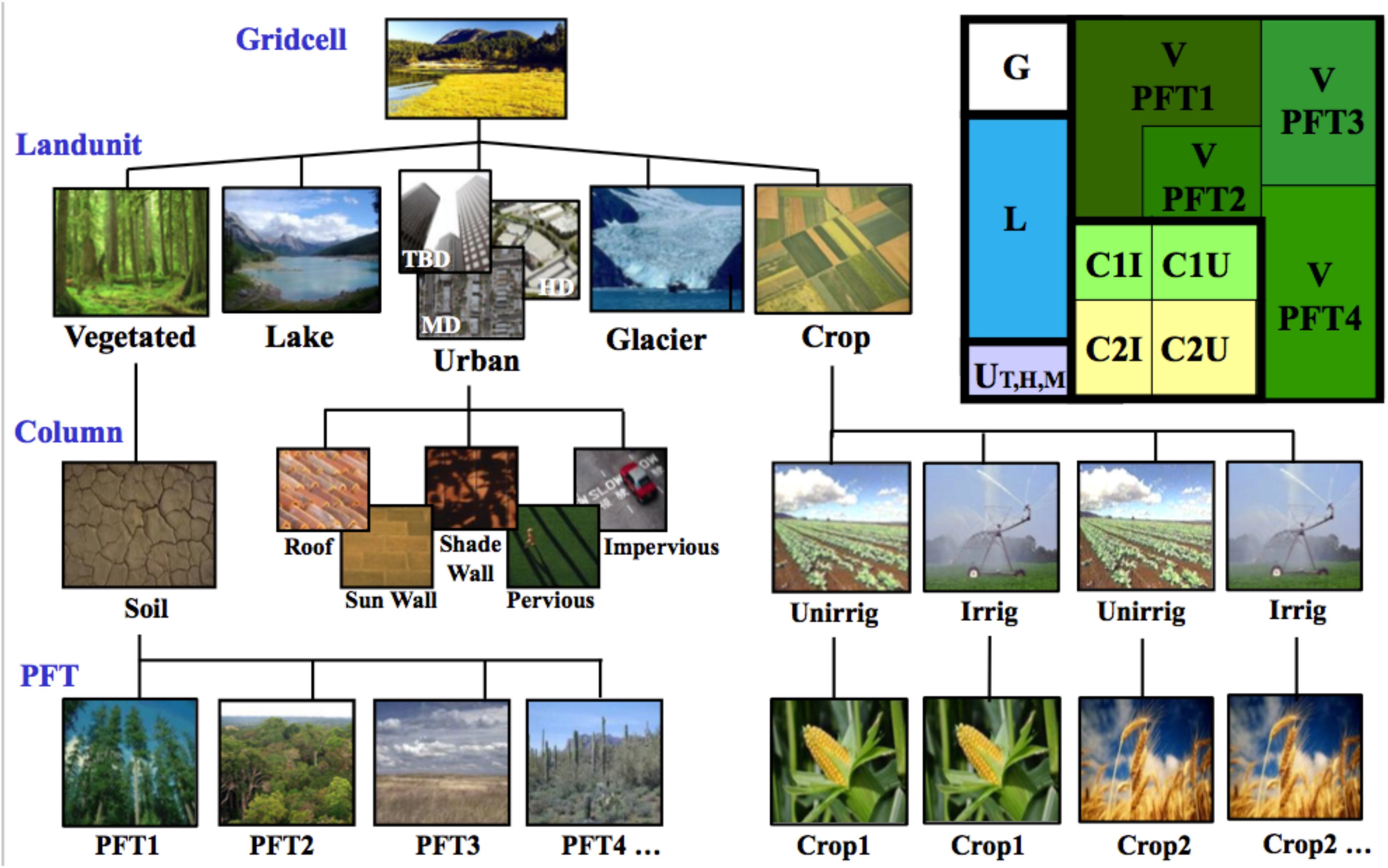
Community Earth System Model (CESM1)



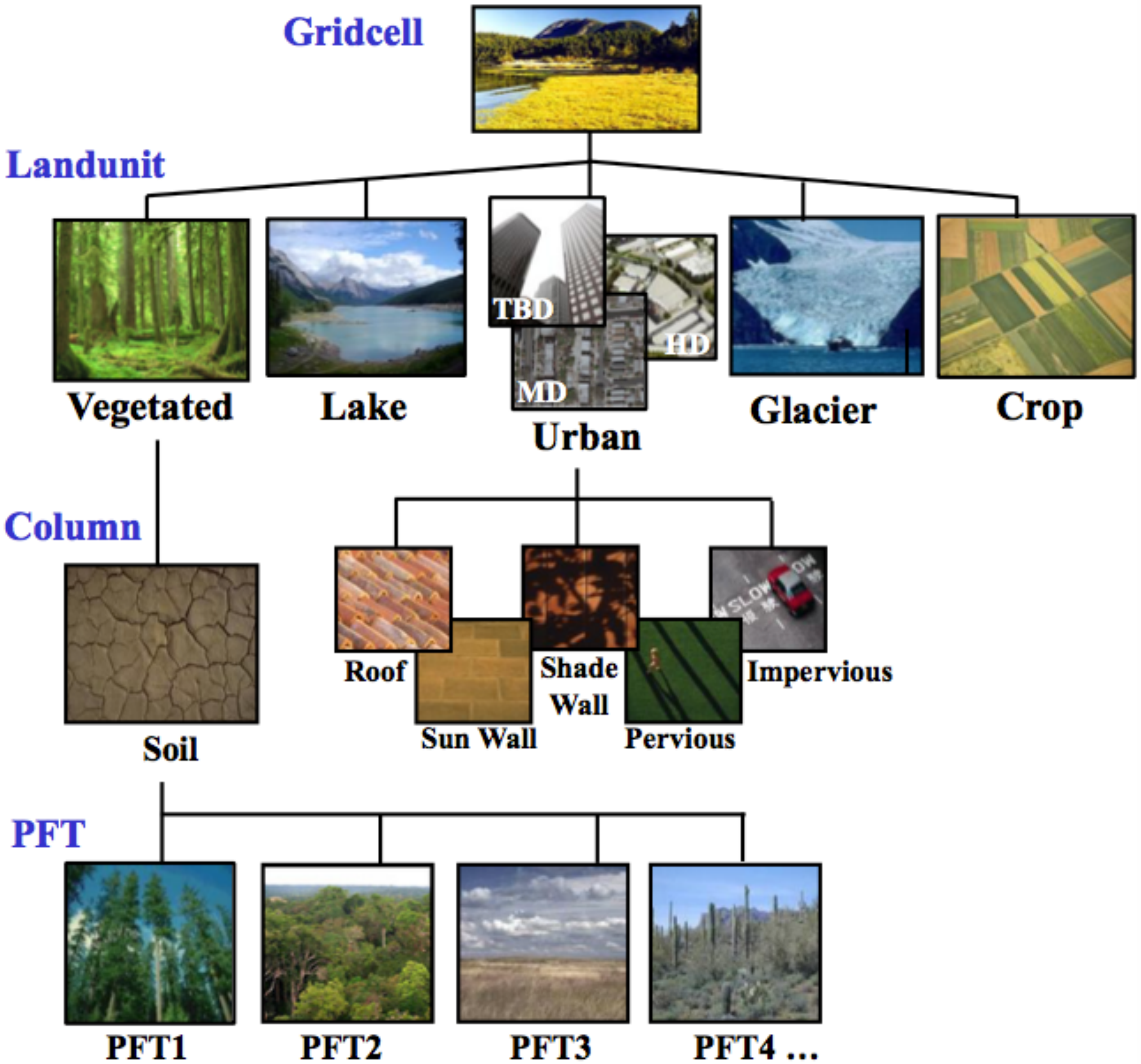
Core is a Coupled Ocean-Atmosphere-Land- Sea Ice model (CCSM4)

- 0.25°, 0.5°, 1° , 2°, T31 resolutions
- 30 minute time step
- 26 atmosphere levels
- 60 ocean levels
- 15 ground layers
- ~5 million grid boxes at 1°
- ~1.5 million lines of computer code
- Archive data (monthly, daily, hourly) for hundreds of geophysical fields (over 250 in land model alone)

CLM surface types and tiling



CLM surface types and tiling



Plant Functional Types:

0. Bare

Tree:

1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

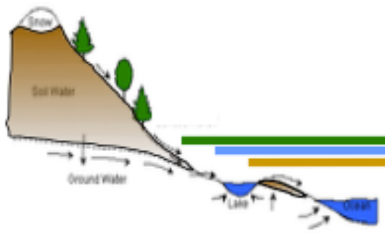
Herbaceous / Understorey:

9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. C3 Arctic Grass
13. C3 non-Arctic Grass
14. C4 Grass
15. Crop

CLM PFT parameters

- Optical properties (visible and near-infrared):
  - Leaf angle
  - Leaf reflectance
  - Stem reflectance
  - Leaf transmittance
  - Stem transmittance
- Fire:
  - Combustion completeness
  - Fire mortality
- Land models are parameter heavy!!!

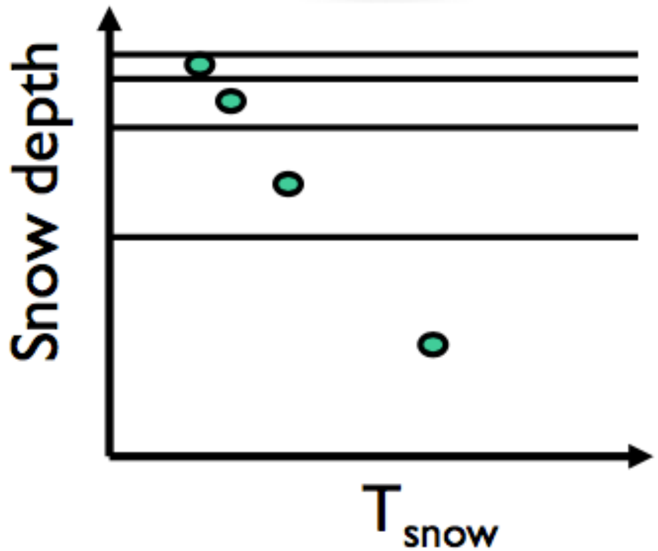
- Morphological properties:
  - Leaf area index (annual cycle)
  - Stem area index (annual cycle)
  - Leaf dimension
  - Roughness length/displacement height
  - Canopy top and bottom height
  - Root depth and distribution
- Photosynthetic parameters:
  - Specific leaf area
  - m (slope of conductance-photosynthesis relationship)
  - Vcmax (maximum rate of carboxylation)
  - Leaf carbon to nitrogen ratio
  - Fraction of leaf nitrogen in Rubisco
  - Soil water potential at stomatal open/closure



Land model complexity: Snow model example

State Variables

$$N, w_{liq,i}, w_{ice,i}, \Delta z_i, T_i$$



- Up to 10-layers of varying thickness
- Represented processes
  - Accumulation and fresh snow density f (T, wind)
  - Snow melt and refreezing
  - Snow aging
  - Water and energy transfer across snow layers
  - Snow compaction
    - destructive metamorphism due to temperature and wind
    - overburden
    - melt-freeze cycles
  - Sublimation
  - Aerosol (black carbon, dust) deposition
  - Canopy snow storage and unloading
  - Canopy snow radiation
  - Snow burial of vegetation
  - Snow cover fraction
- Missing processes
  - Blowing snow
  - Subgrid variations in snow depths
  - Depth hoar

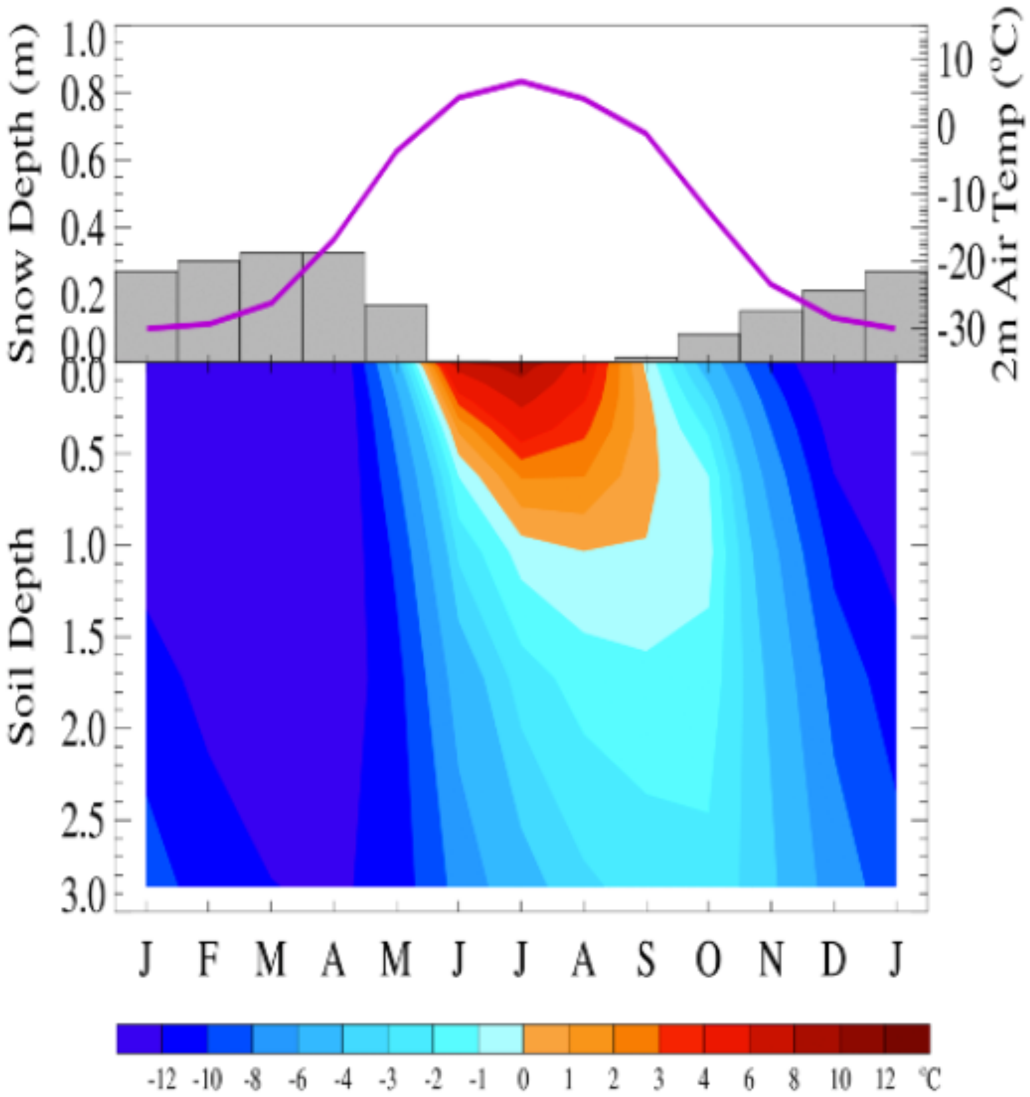
Snow/Soil thermodynamics

–Solve the heat diffusion equation for multi-layer snow and soil model

$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z} \right)$$

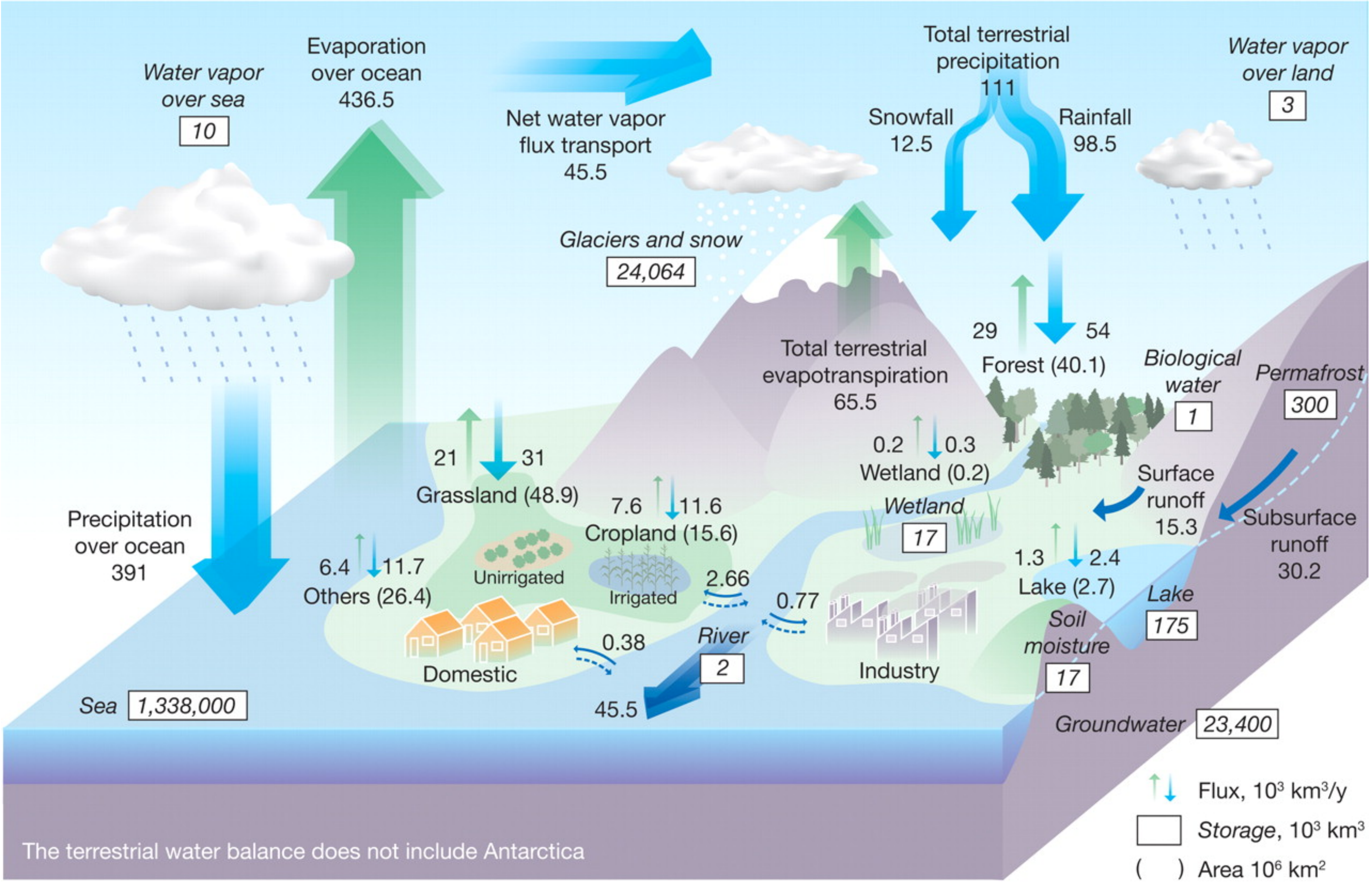
where C_p (heat capacity) and K (thermal conductivity) are functions of:

- **temperature**
- **total soil moisture**
- **soil texture**
- **ice/liquid content**



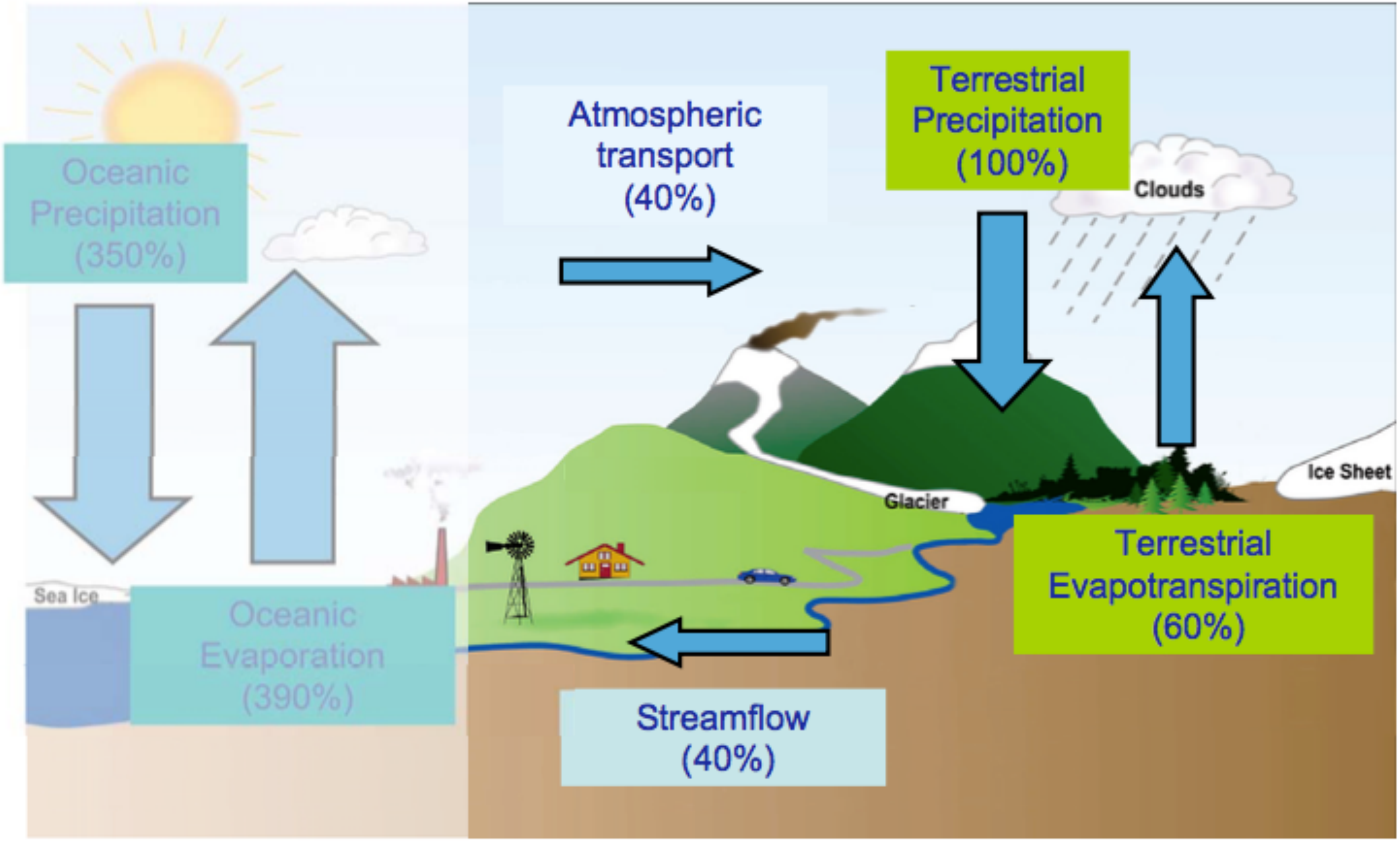
Water Balance

Global water balance



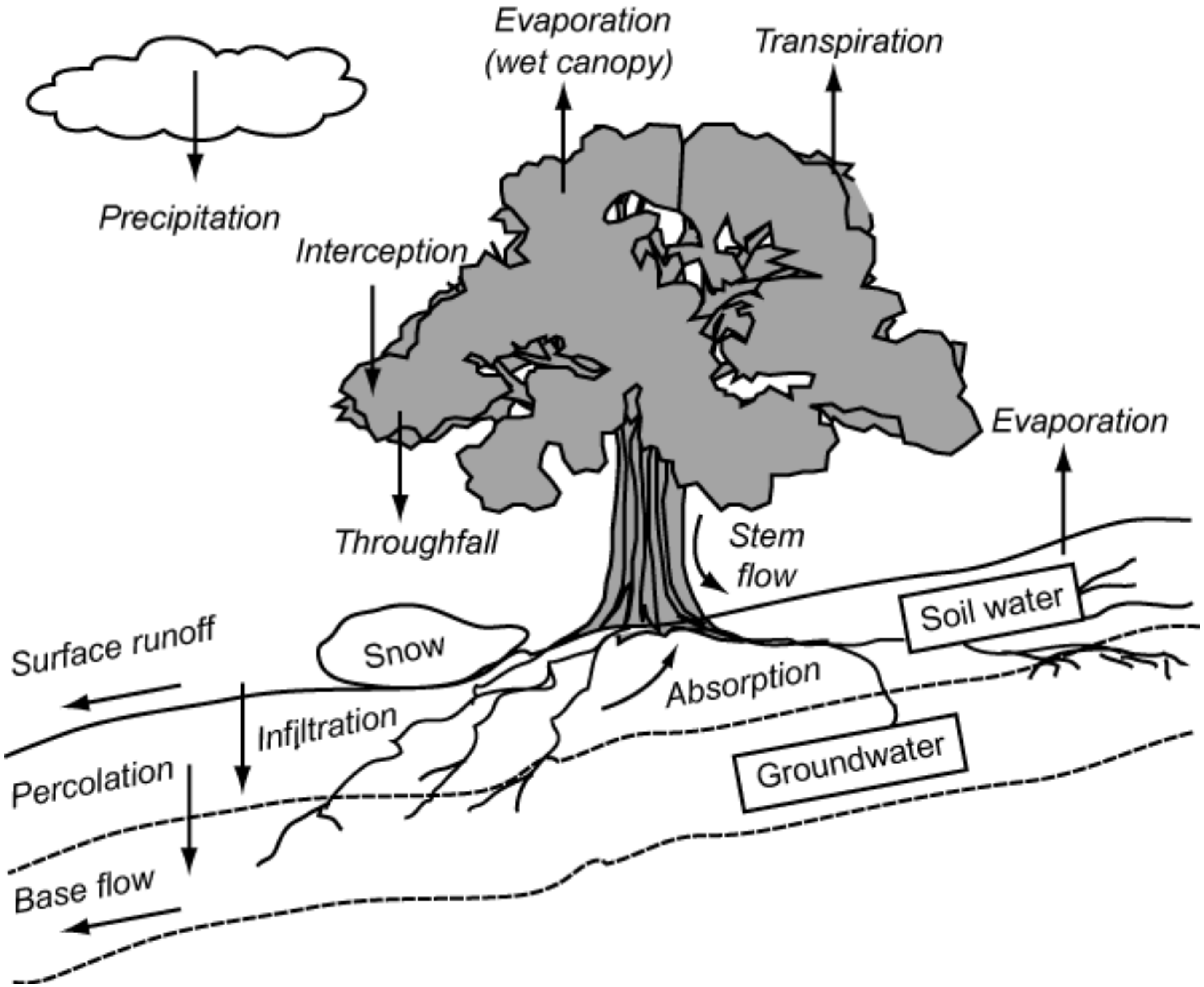
Oki and Kanae, 2006

Terrestrial water balance



(Flux estimates: Oki and Kanae, Science 2006)

Overview of surface water budget

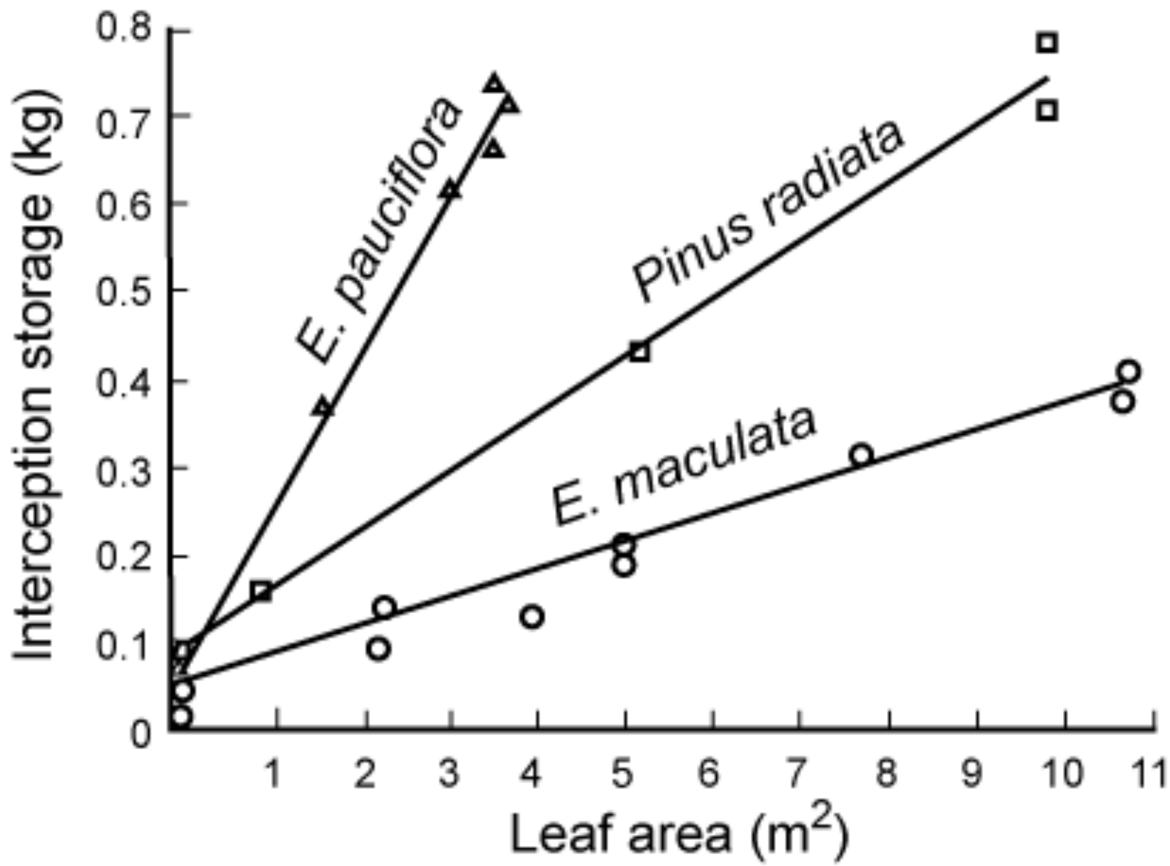


Water inputs

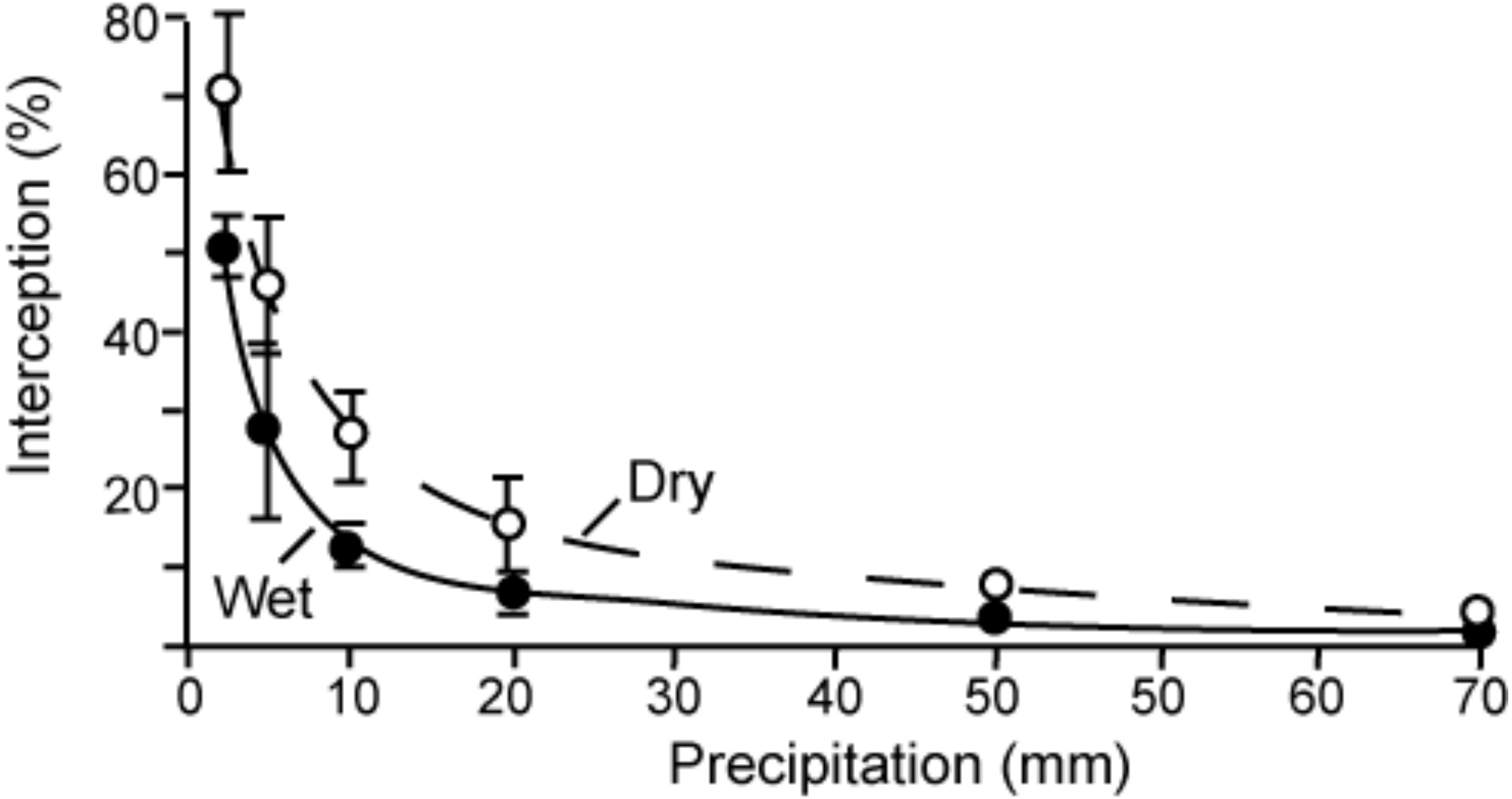
Precipitation is the main water input
- Rain
- Snow

Groundwater

Canopy interception
(fog)



Water inputs



Water movements within Ecosystems

Water movement from canopy to soil

- Canopy interception
    - canopy area/LAI
    - dry/wet systems
    - land use change

" In general, canopy interception reduces water input to soils, especially from light rains. Only in the presence of fog does canopy interception augment water inputs to soils."

- Throughfall

- Stemflow

- Fog dew formation

Water movements within soils

Water storage and movement in soil

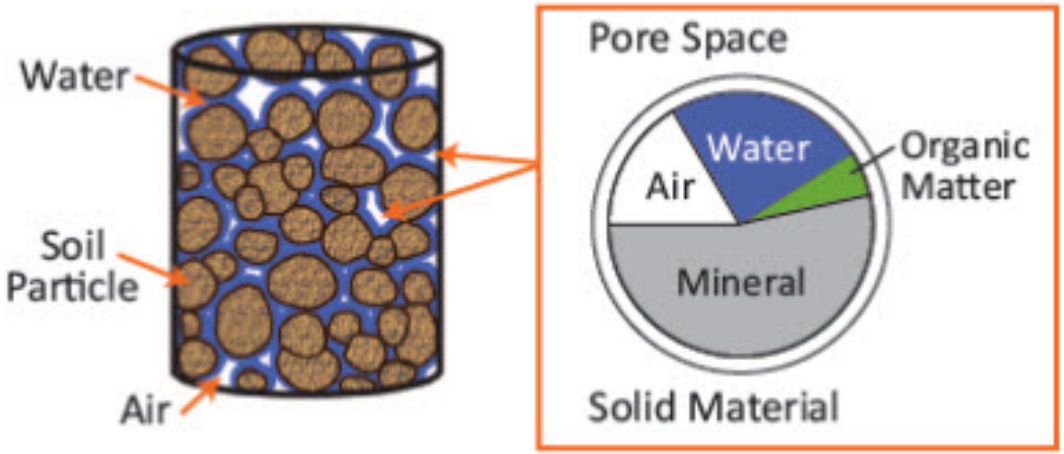
Soil water stored in thin water films

Movement along a potential gradient

$$\Psi_t = \Psi_p + \Psi_o + \Psi_m$$

Ψ_t **water potential**
Ψ_p **pressure potential**
Ψ_o **osmotic potential**
Ψ_m **matric potential**

Composition of an Unsaturated Soil Sample



Water movements within soils

Water storage and movement in soil

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Movement along a potential gradient

$$\Psi_t = \Psi_p + \Psi_o + \Psi_m$$

Ψ_t **water potential**
Ψ_p **pressure potential**
Ψ_o **osmotic potential**
Ψ_m **matric potential**

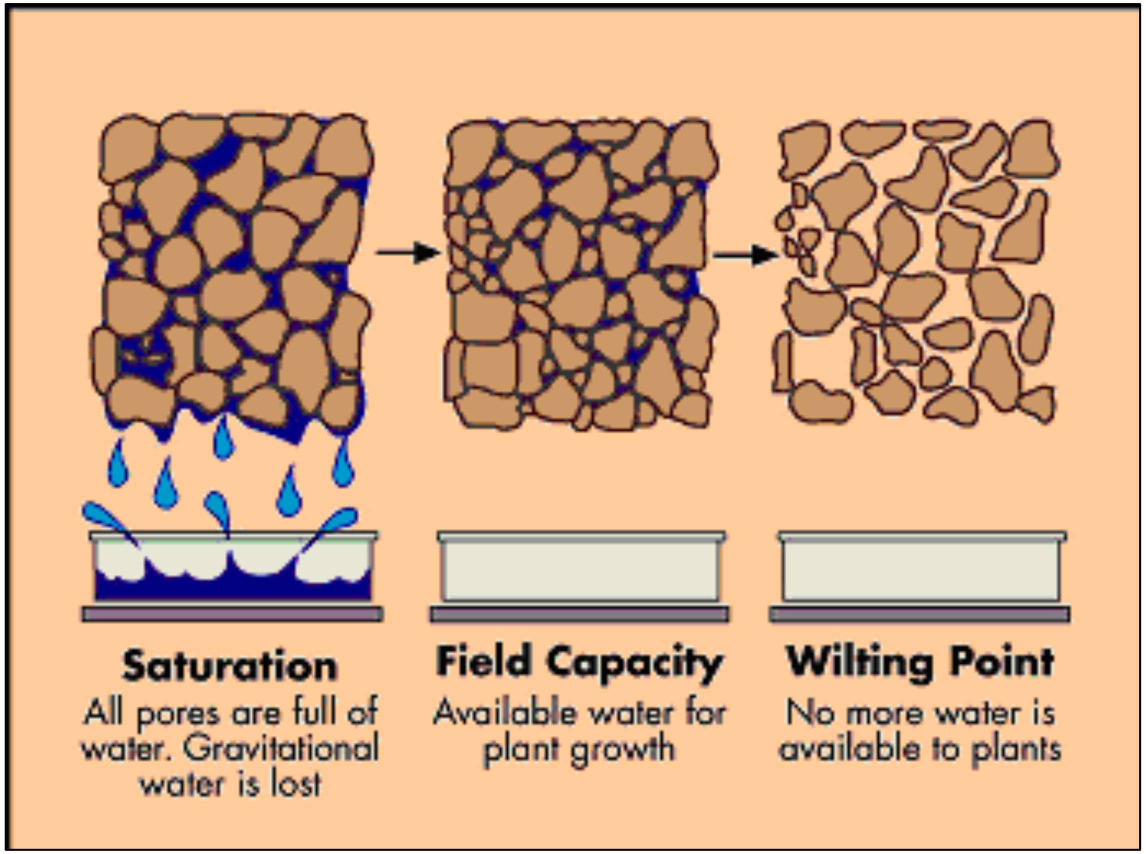
"Pressure gradients associated with gravity and matric forces control most water movement through soils."

Water movements within soils

Water storage and movement in soil

Infiltration of:
- Rainwater
- Snowmelt

into **macropores**



Water movements within soils

Water storage and movement in soil

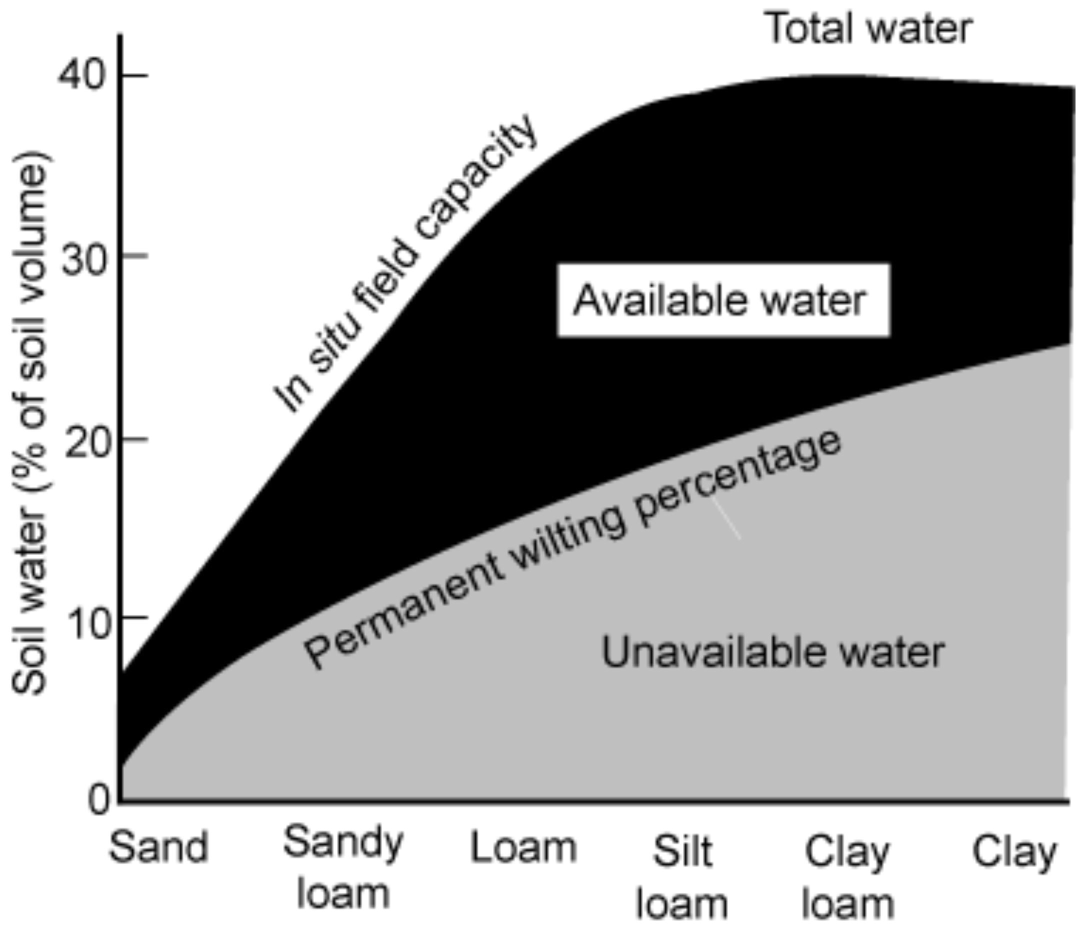
Infiltration of:

- Rainwater
- Snowmelt

into **macropores**

Field capacity

Permanent wilting point



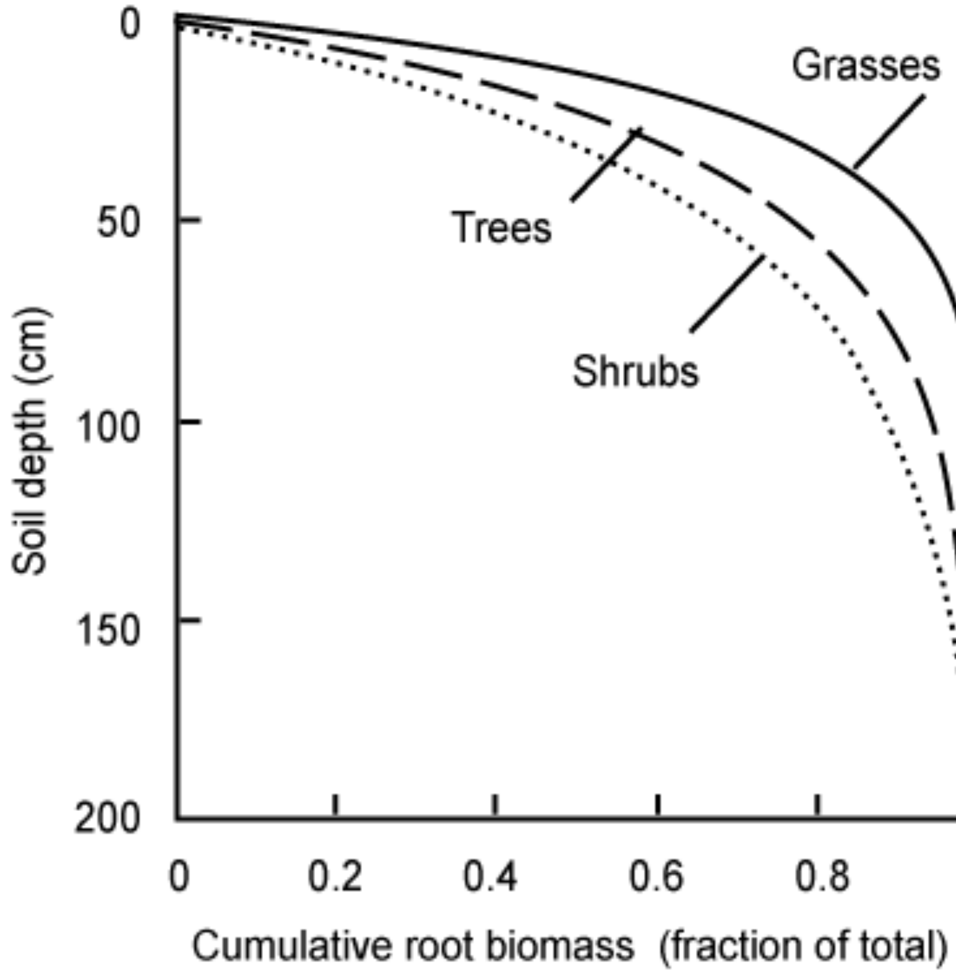
Water movements within soils

Water movement from soil to roots

"Water moves from soil to the roots of transpiring plants by flowing from high to low water potential"

Root hairs and mycorrhizal hypae

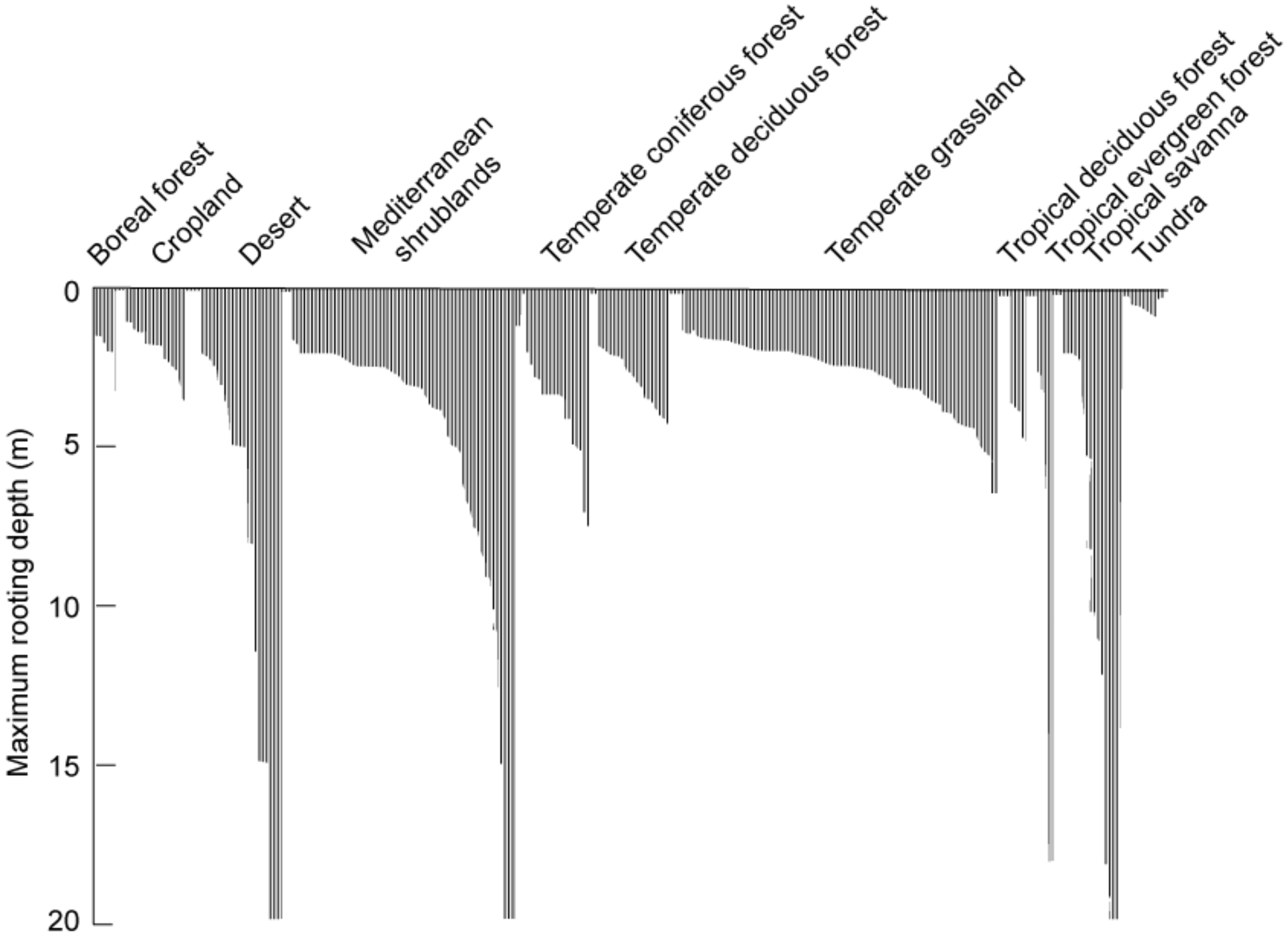
Rooting depth of plants



Water movements within soils

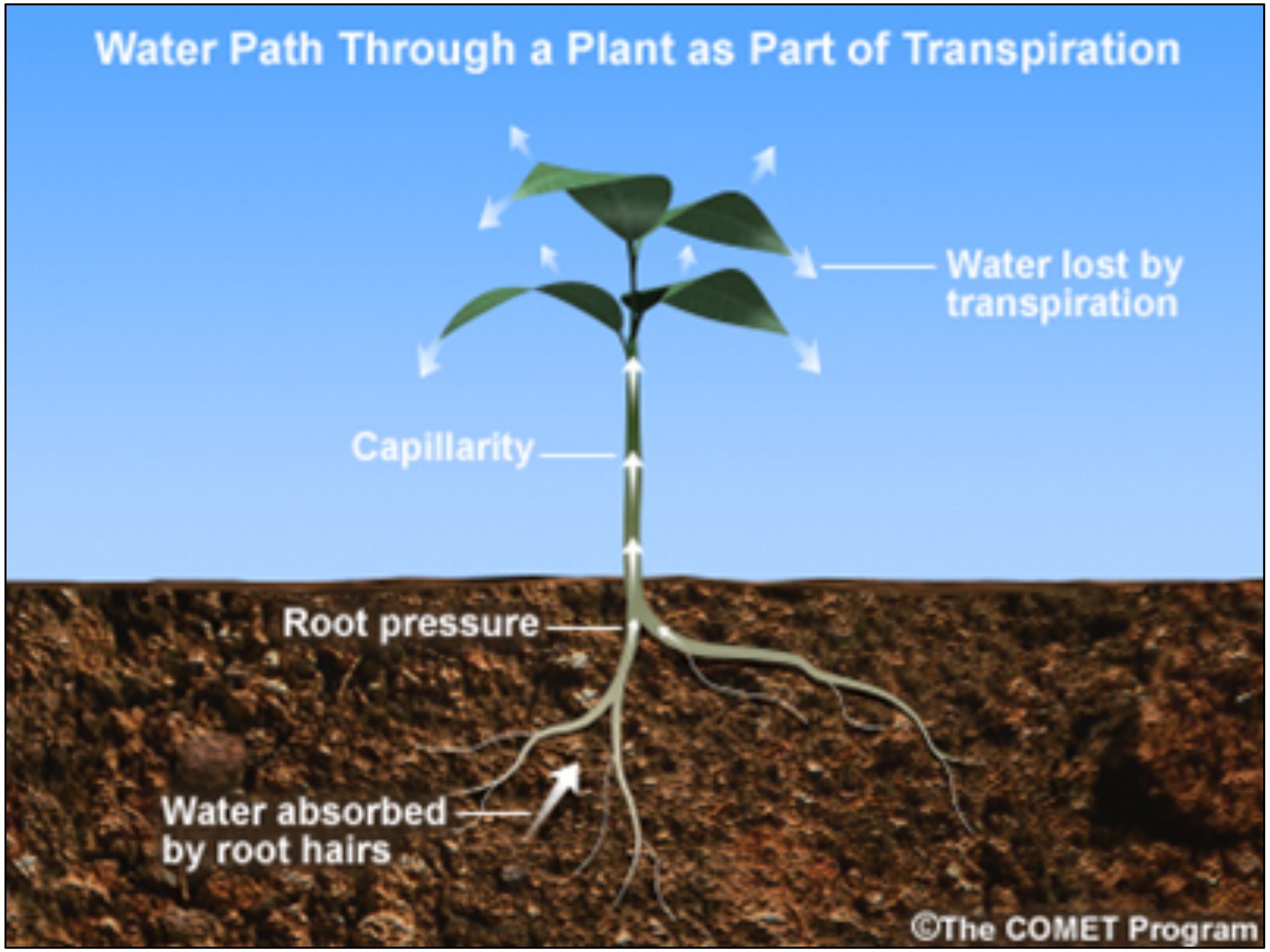
Water movement from soil to roots

Rooting depths



Water movements within Ecosystems

Water movement from soil to roots

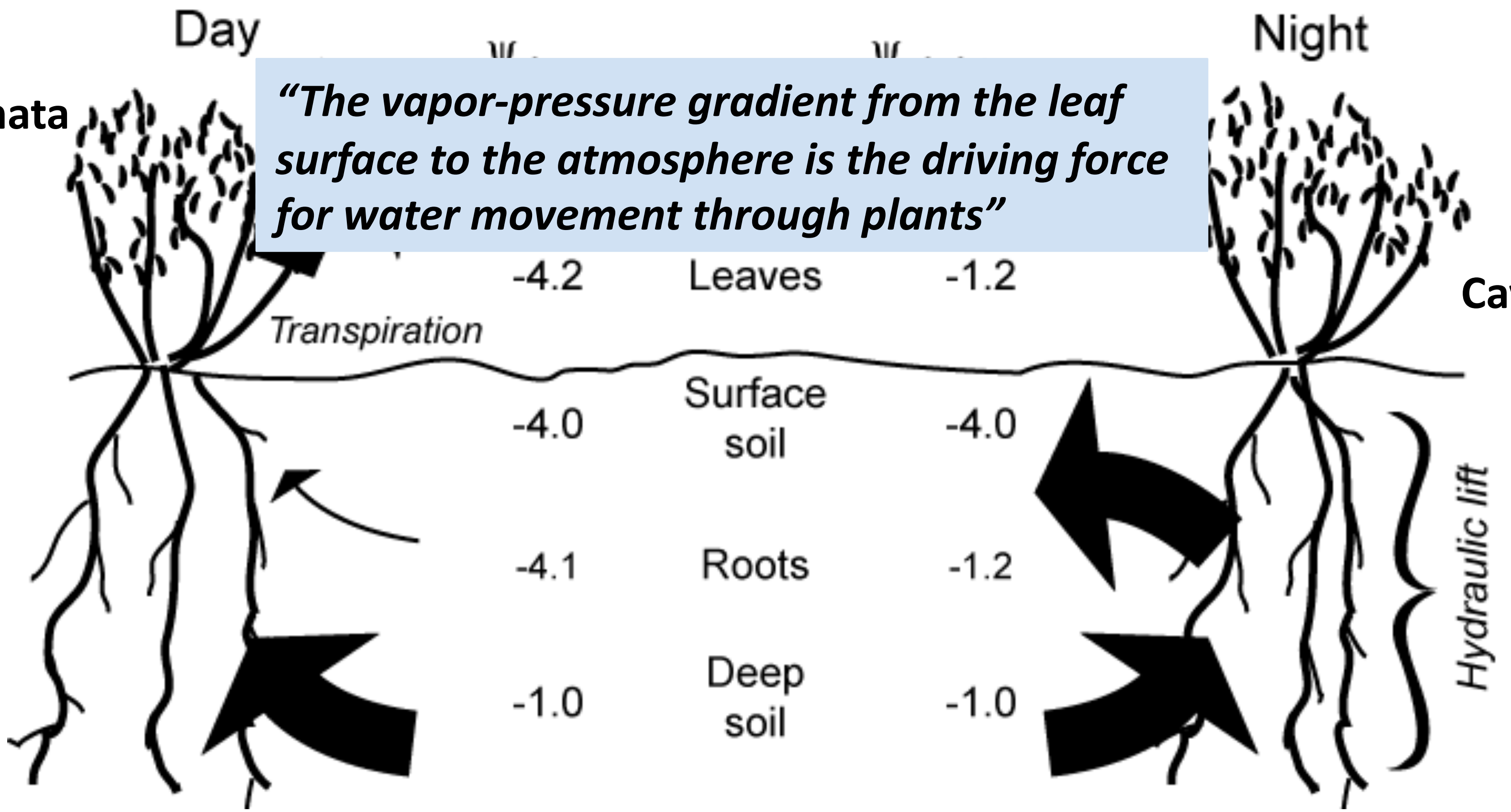


Water movements within Ecosystems

Water movement through plants

Soil ←→ Roots → Stems → Leaves

Stomata

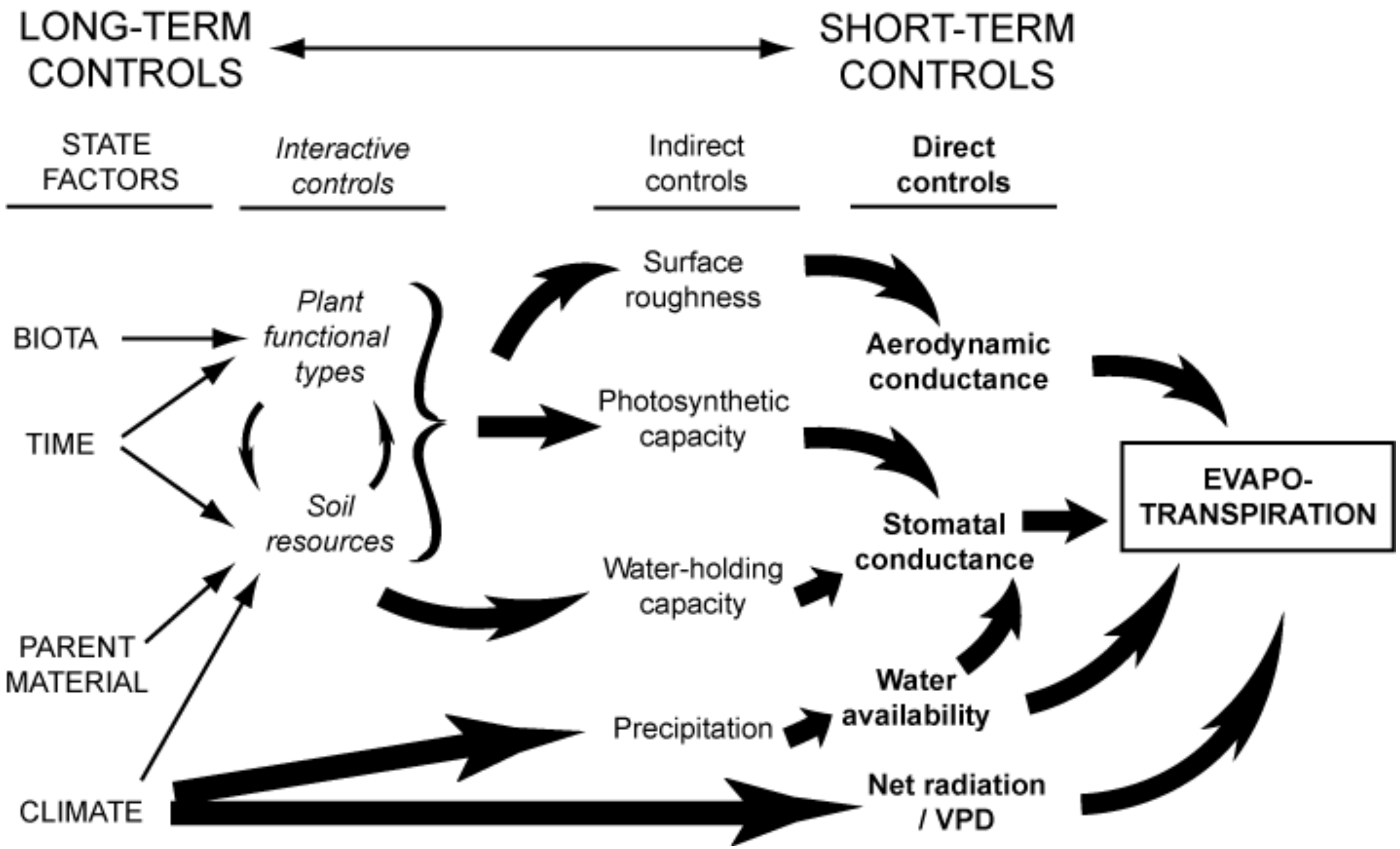


"The vapor-pressure gradient from the leaf surface to the atmosphere is the driving force for water movement through plants"

Cavitation

Water movements within Ecosystems

Water movement through plants



Water losses

$$P \underline{+} \Delta S = E + R$$

P Precipitation
ΔS Changes in water storage
E Evapotranspiration
R Runoff

Evaporation
from **wet canopies**

Surface roughness
Climate (prec./vpd)
LAI

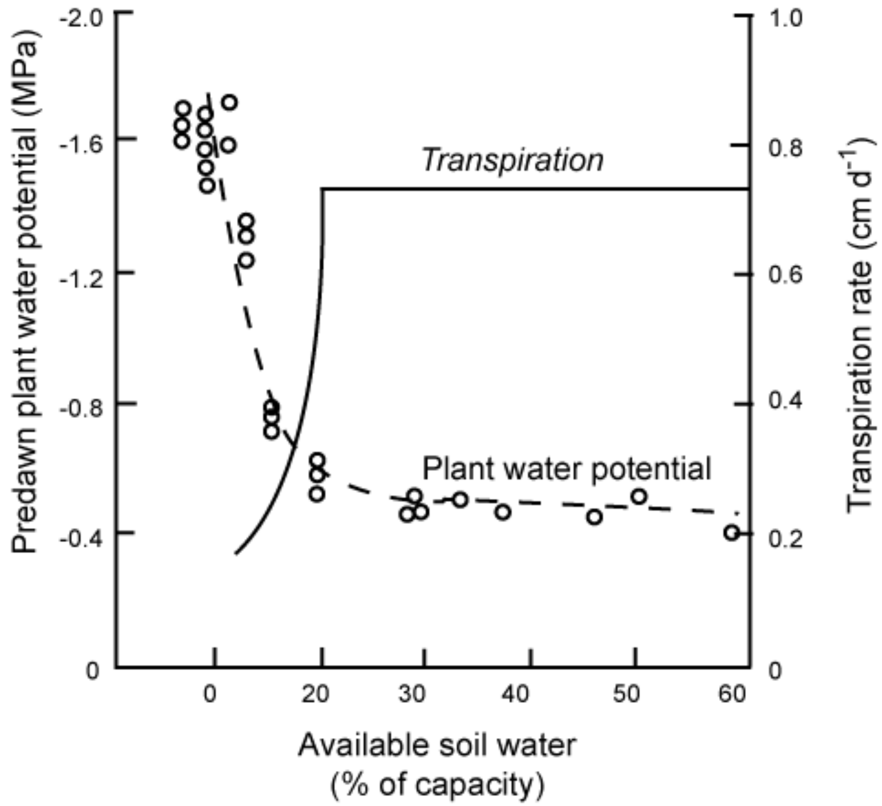
Evapotranspiration
from **dry canopies**

Diffusion
- surface conductance
  leaf stomata / soil surf. properties

Turbulent mixing
- boundary layer conductance
  ecosystem structure / soil moisture

Water losses

"As soil moisture declines, the control over evapotranspiration shifts from canopy structure to soil moisture"

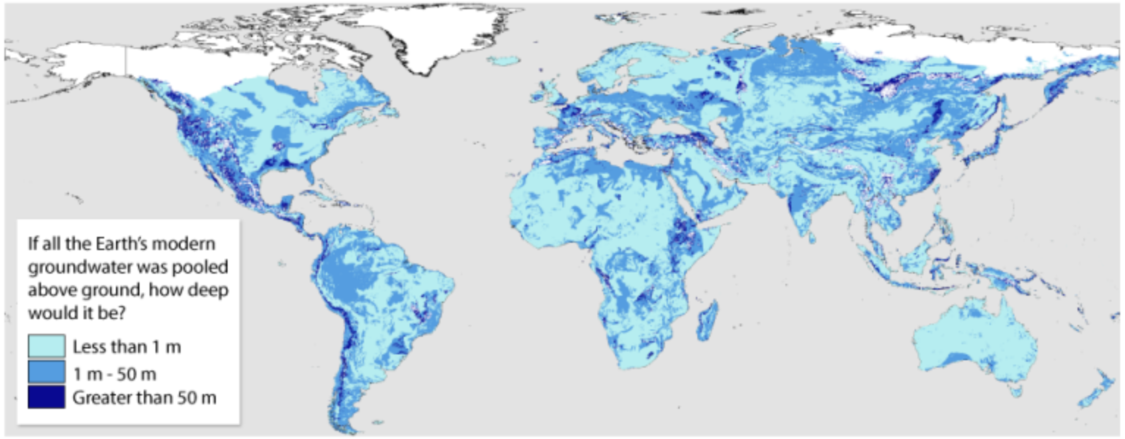


Water losses

Changes in storage

Snowpack
- sustains evaporation
- seasonal
- affected by climate / plants

Groundwater
- inaccessible water below certain depths
- influences salinity
- affected by climate / human activities
    - drying climate
    - wells
    - change in plant types



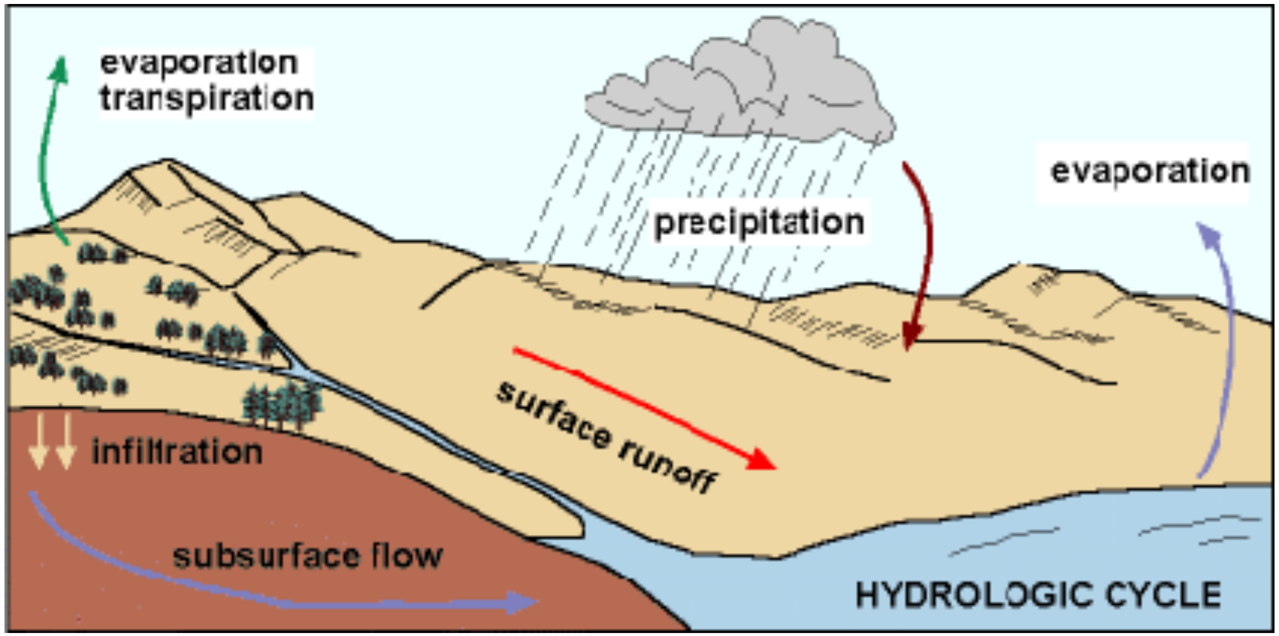
Tom Gleeson, Kevin M. Befus, Scott Jasechko, Elco Luijendijk and M. Bayani Cardenas (2015). *Nature Geoscience*, DOI: 10.1038/NGEO2590.

Water losses

Runoff

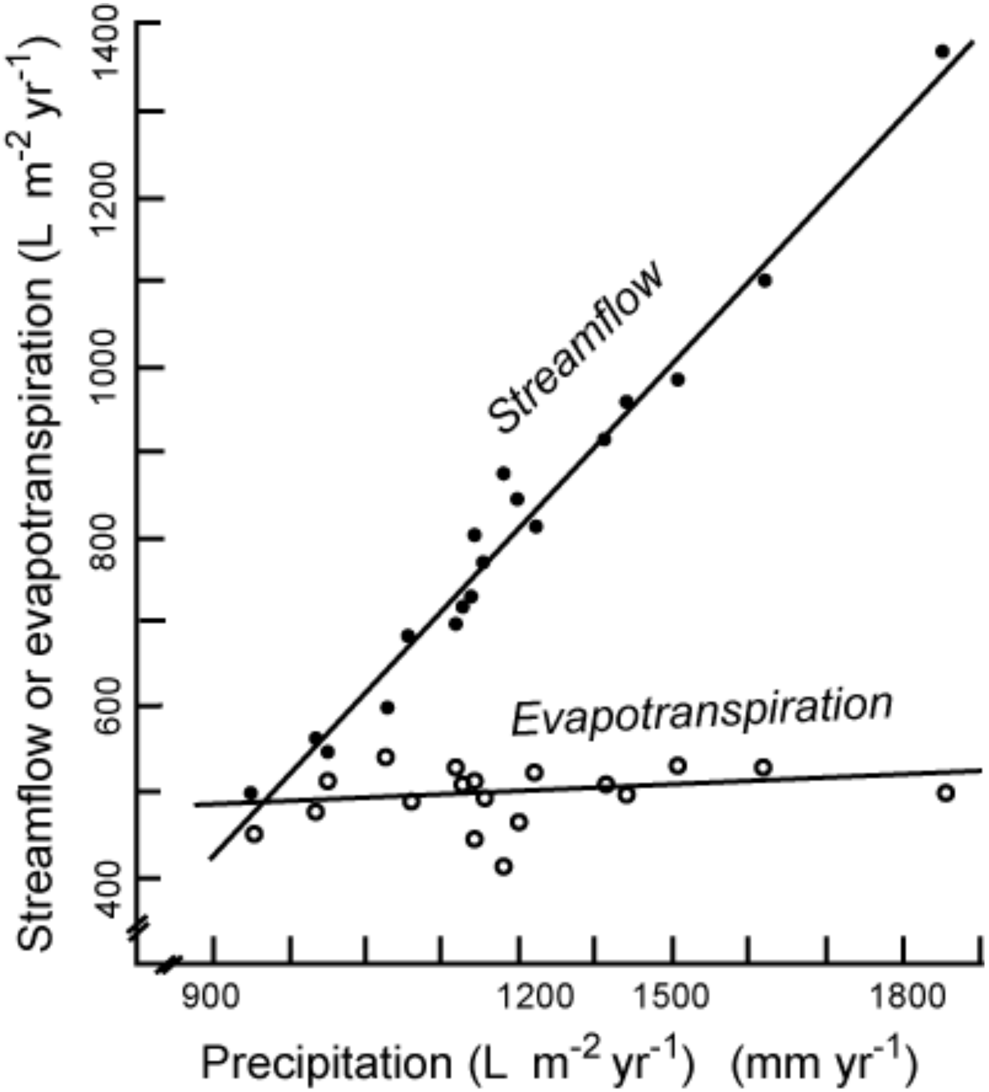
Leftover water from storage and evapotranspiration

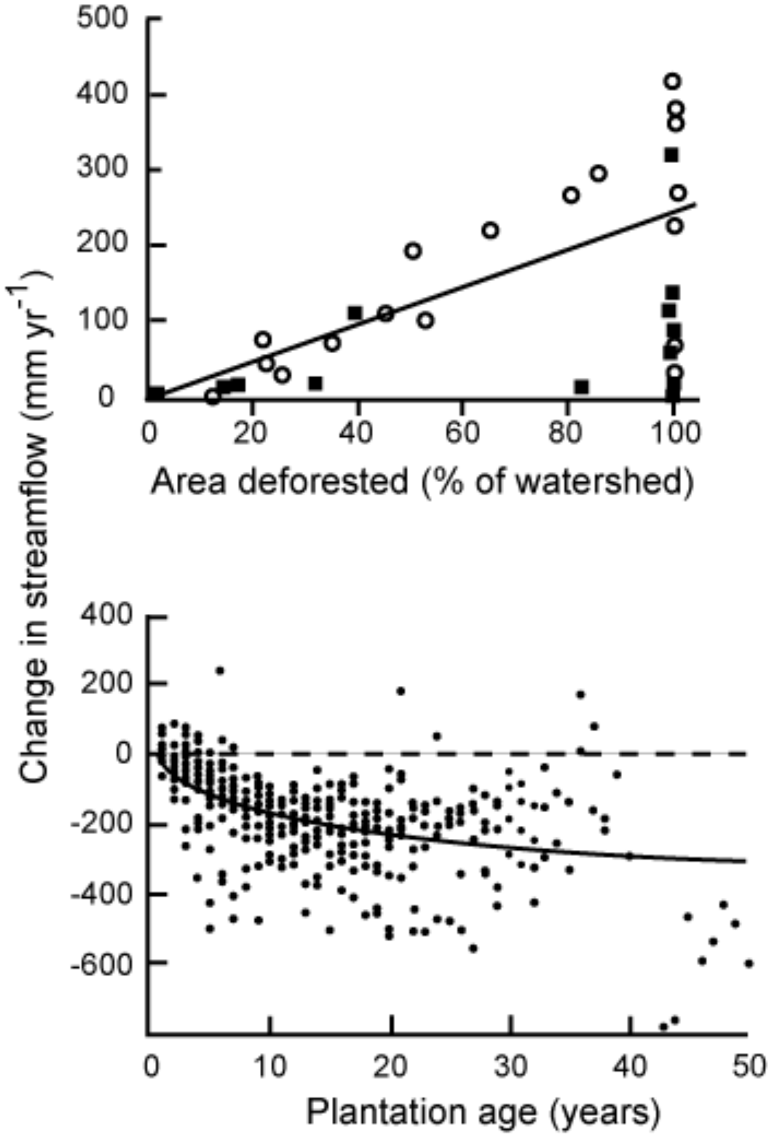
Depends on:
- precipitation
  - variation/frequency
- evapotranspiration
  - vegetation
- soil type
  - fine/coarse soil
  - frozen soil
- climate
  - snowpack
- topography



Water losses

Runoff

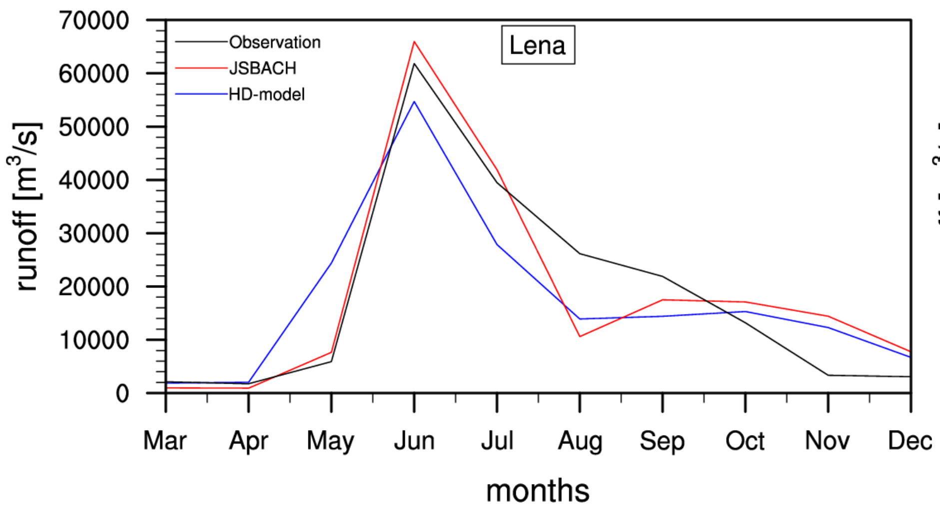


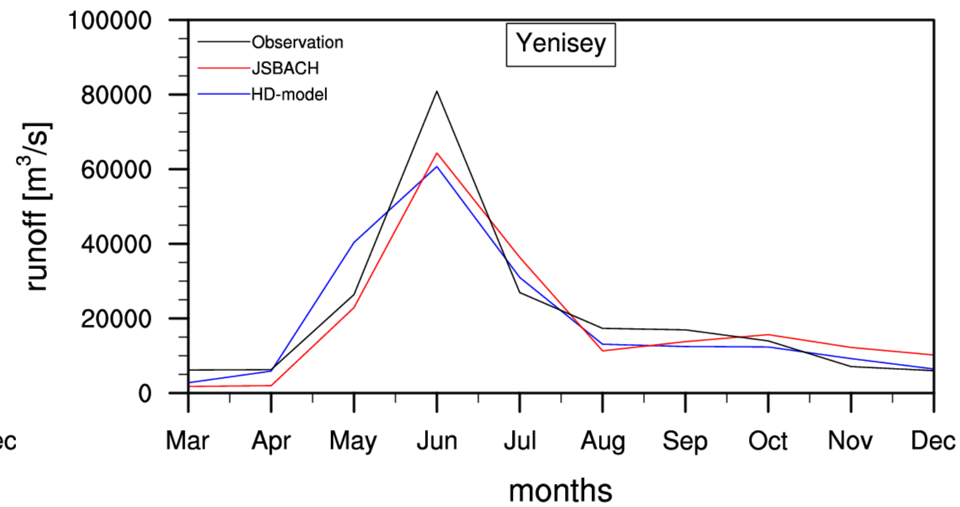


Water losses

Runoff

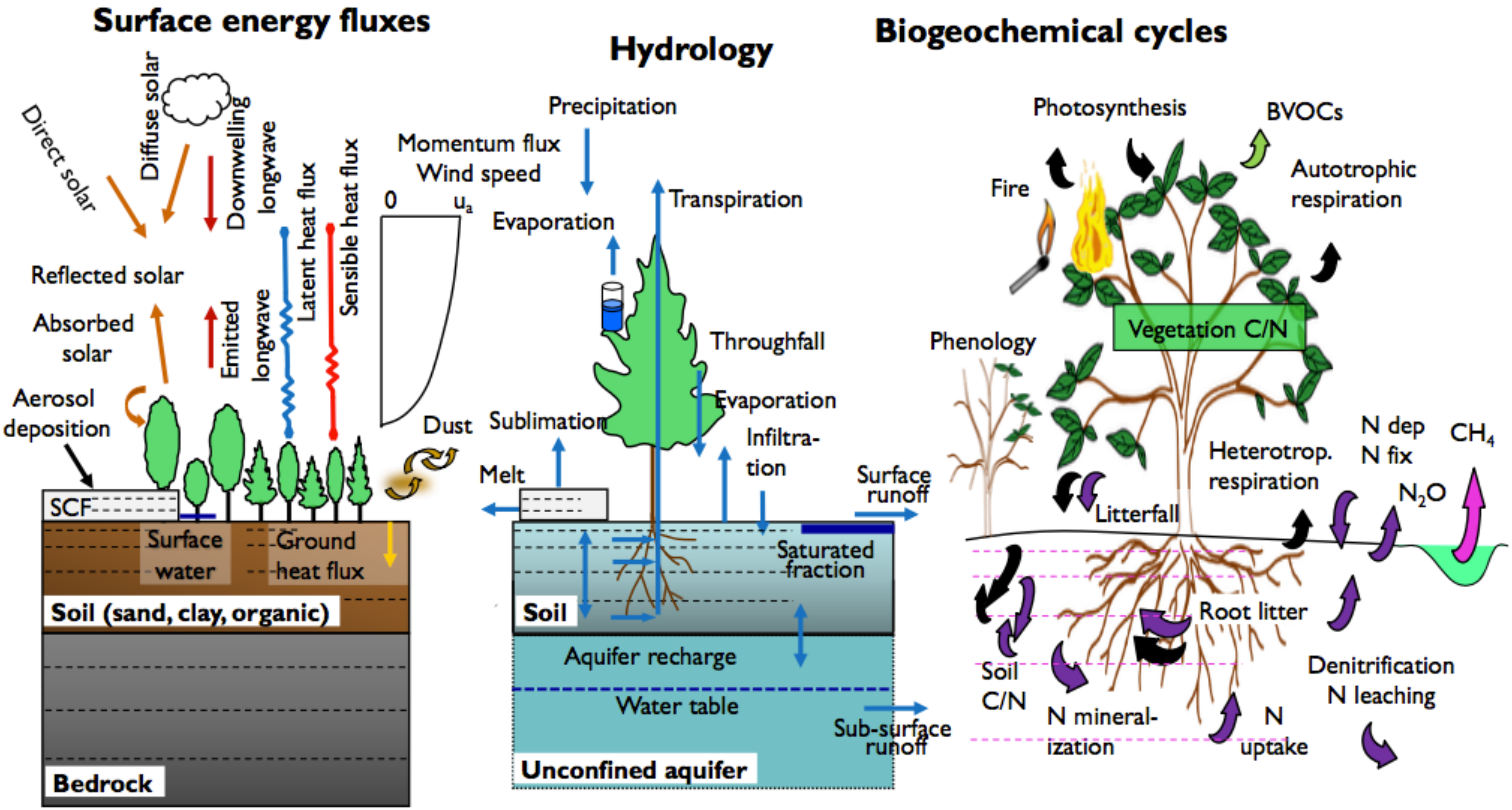
Effect of snow melt on runoff timing and intensity



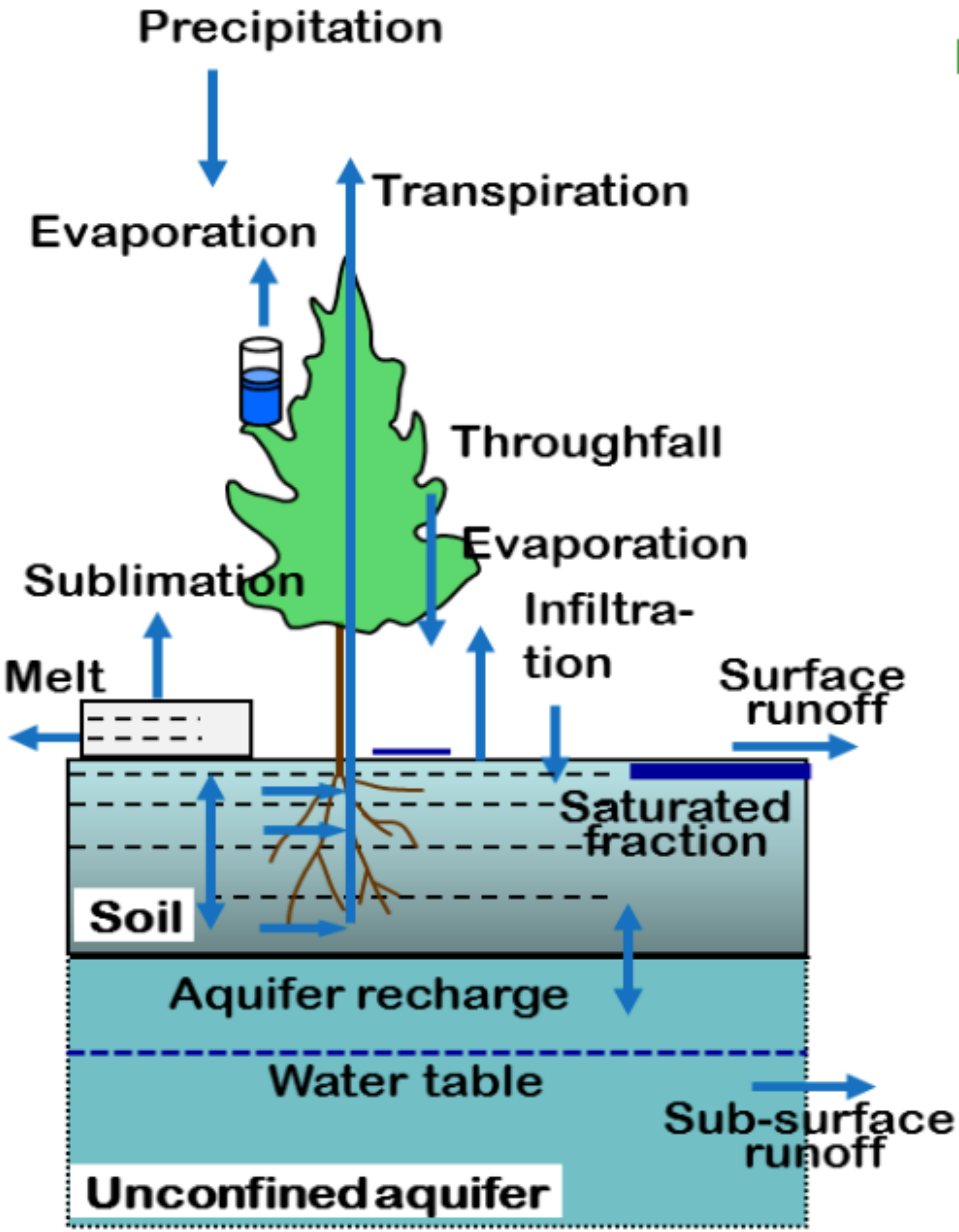


Ekici et al., 2014

Model representation (CLM)



… and the Surface Water Balance



$$P = E_S + E_T + E_C + R + (\Delta W_{soi} + \Delta W_{snw} + \Delta W_{sfcw} + \Delta W_{can}) / \Delta t$$

P is rainfall/snowfall,

E_S is soil evaporation,

E_T is transpiration,

E_C is canopy evaporation,

R is runoff (surf + sub-surface),

$\Delta W_{soi} / \Delta t$, $\Delta W_{snw} / \Delta t$, $\Delta W_{sfcw} / \Delta t$, $\Delta W_{can} / \Delta t$, are the changes in soil moisture, surface water, snow, and canopy water over a timestep

Change in water storage
(soil moisture, snow, surface
water, groundwater)

$$\frac{\partial S}{\partial t} = (P - E) - R_s - R_g$$

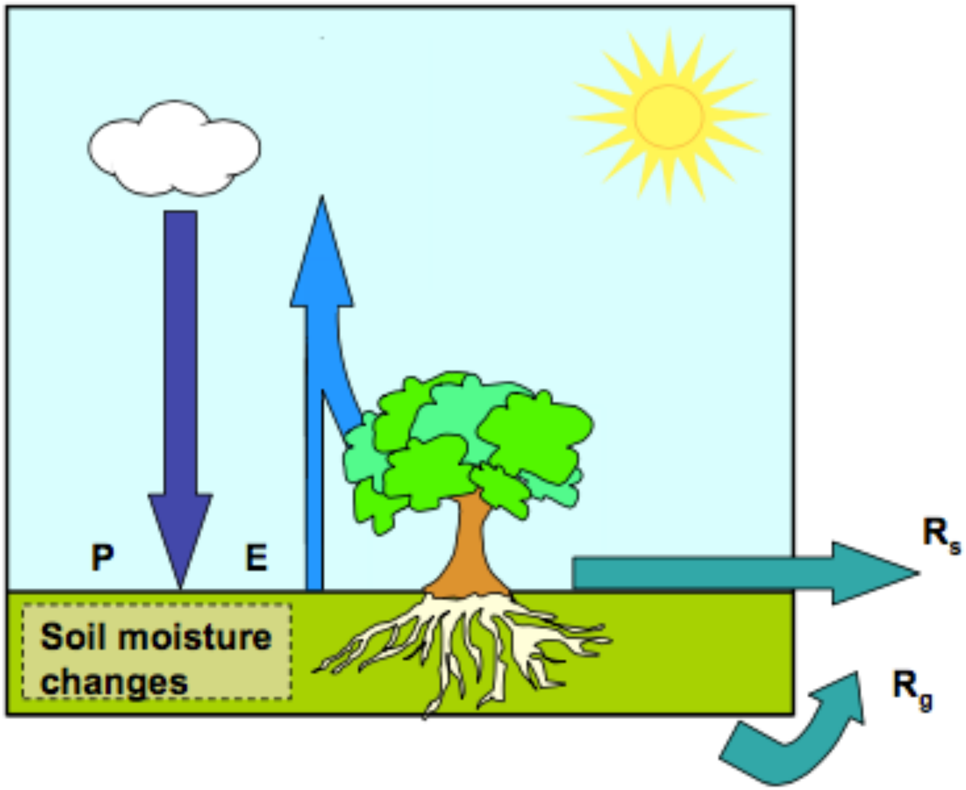
Precipitation

Evapo-
transpiration

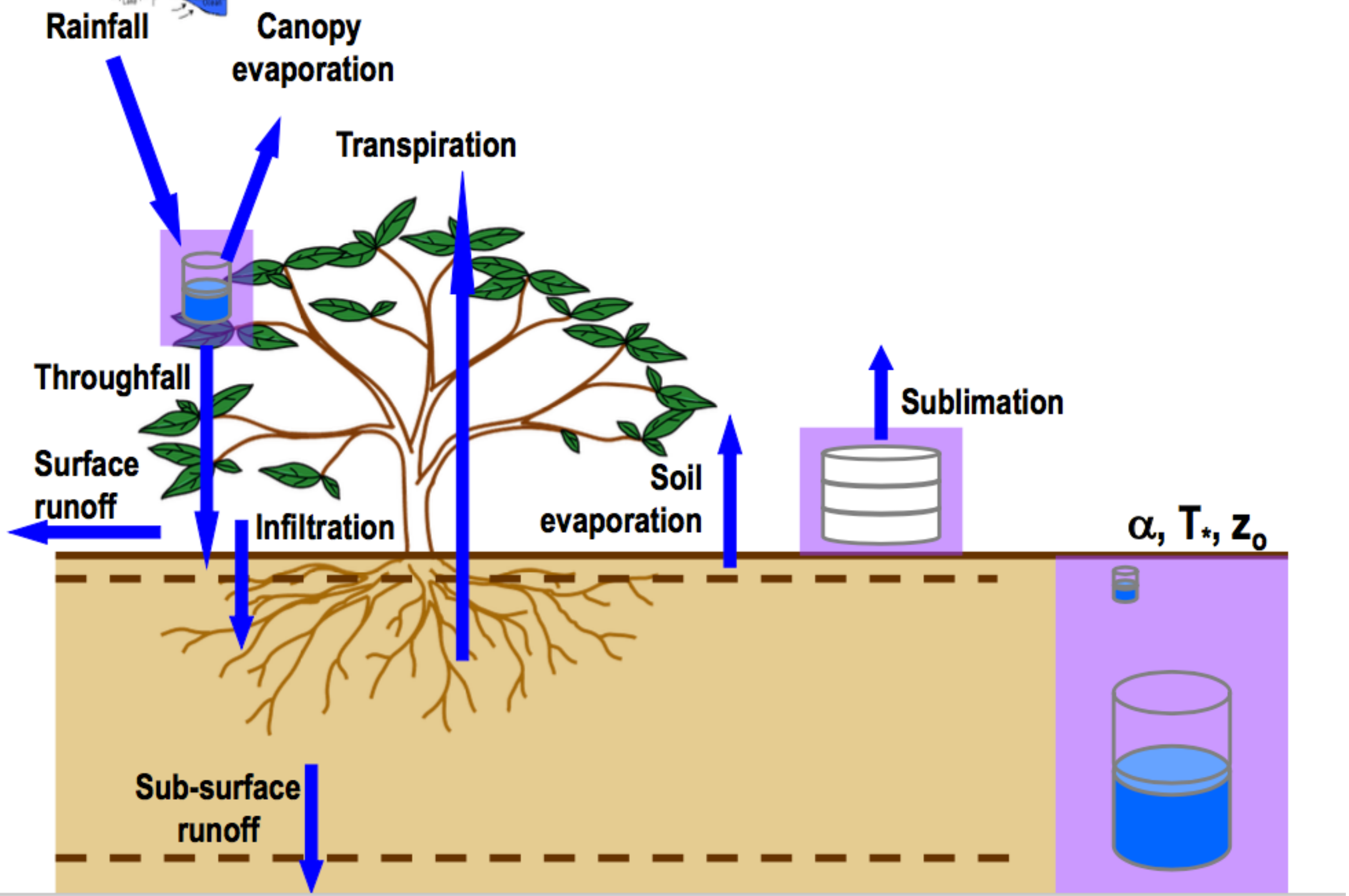
Surface
runoff

Ground-
water
runoff

Land water balance



Land model processes - Hydrology



At each timestep the CLM land scheme solves …

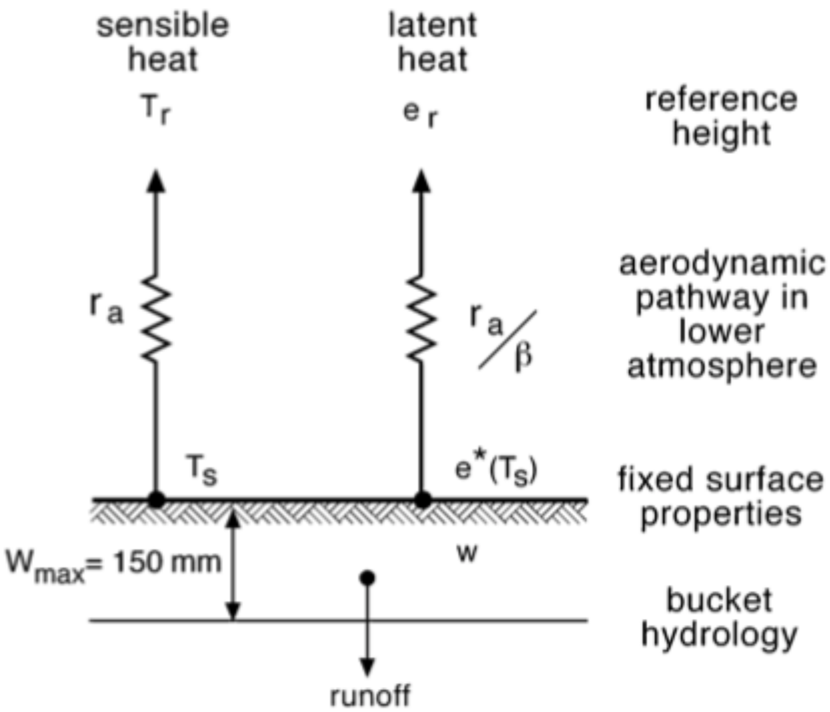
- **Surface energy balance**
  - $S^{\downarrow} - S^{\uparrow} + L^{\downarrow} - L^{\uparrow} = \lambda E + H + G$
    - $S^{\downarrow}$, $S^{\uparrow}$ are down(up)welling solar radiation,
    - $L^{\uparrow}$, $L^{\downarrow}$ are up(down)welling longwave radiation,
    - λ is latent heat of vaporization, E is evaporation,
    - H is sensible heat flux, and G is ground heat flux

- **Surface water balance**
  - $P = E_S + E_T + E_C + R_{surf} + R_{Sub\text{-}Surf} + (\Delta W_{soi} + \Delta W_{sno} + \Delta W_{can} + \Delta W_a) / \Delta t$
    - P is rainfall/snowfall,
    - E_S is soil evaporation, E_T is transpiration, E_C is canopy evaporation,
    - R_{Surf} is surface runoff, $R_{Sub\text{-}Surf}$ is sub-surface runoff, and
    - $\Delta W_{soi} / \Delta t$, $\Delta W_{sno} / \Delta t$, $\Delta W_{can} / \Delta t$, and $\Delta W_a / \Delta t$ are the changes in soil moisture, snow, canopy water, and aquifer water over a timestep

Final thoughts

Evolution of land models

Land Surface Models (LSMs) – 1st Generation

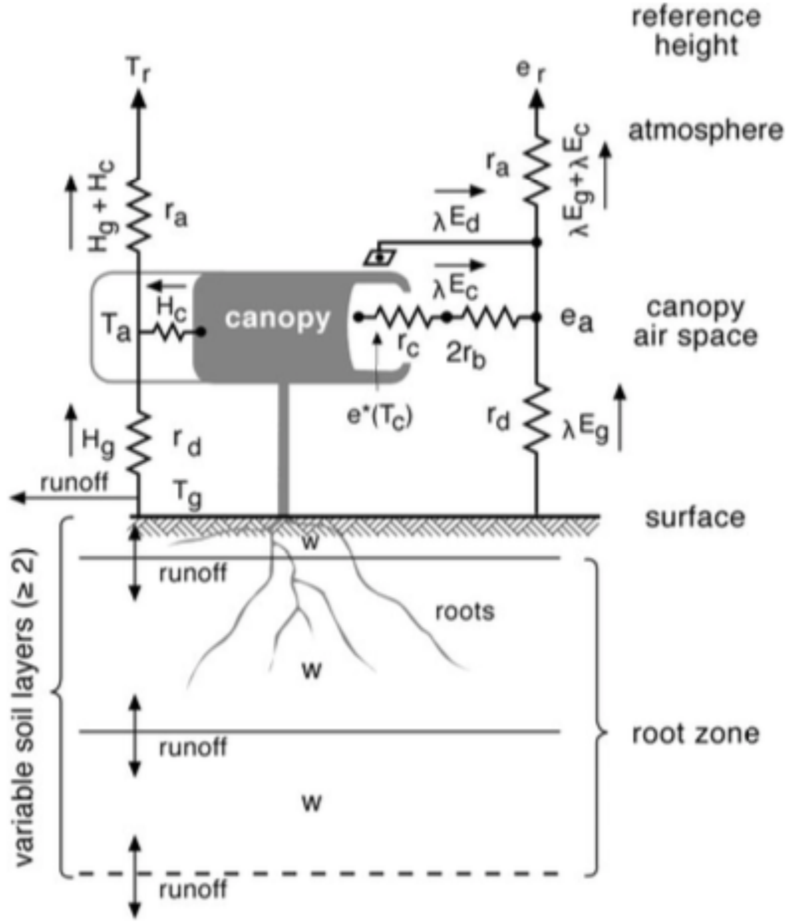


From Pitman (2003)

- "Manabe (1969)" bucket model
  - No explicit representation of vegetation
  - No heat conduction into soil
  - Globally constant soil depth and water holding capacity
  - Above some prescribed threshold, precipitation -> runoff
    - I.e., "bucket" hydrology

Evolution of land models

Land Surface Models (LSMs) – 2nd Generation

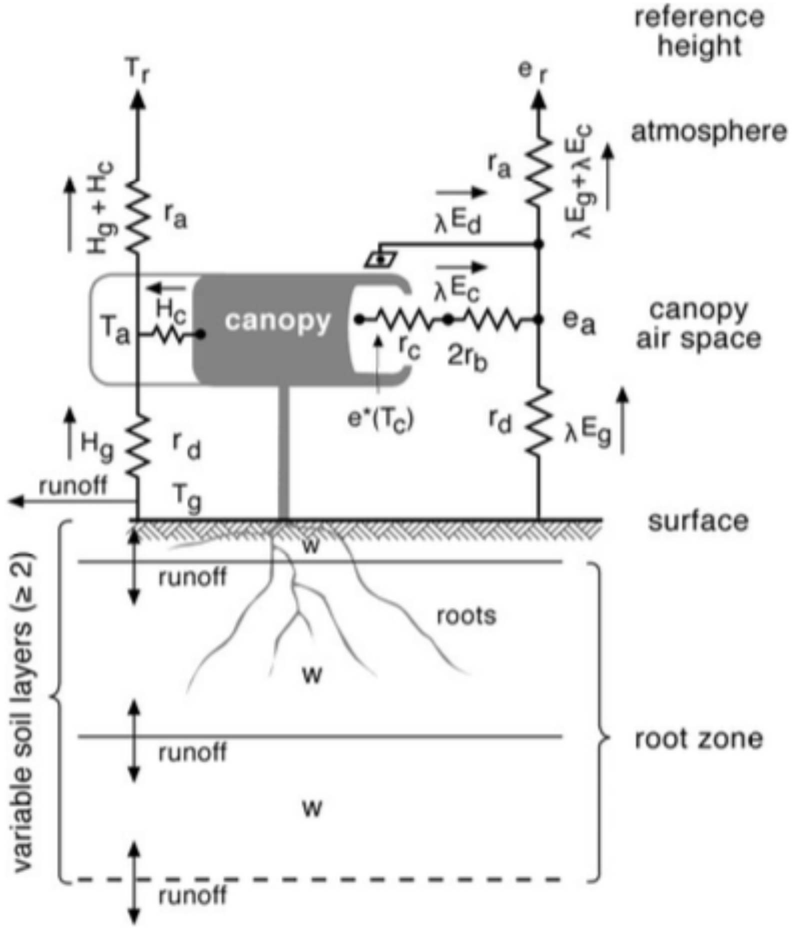


From Pitman (2003)

- Soil moisture and temperature in two layers (Deardorff 1978).
- Vegetation as a single-bulk layer
- Land surface interacts with atmosphere
- Vegetation and soil treated separately – Albedo varies across grid square
- Explicit representation of Visible (VIS) and Near Infra-red (NIR) wavebands
  - Plants absorb most energy in VIS but reflect more in NIR
- Integration of satellite data (e.g., albedo, into LSMs)
- Include impact of vegetation on H and LE
- Representation of evaporation from trees
  - Stomatal conductance (but empirical)

Evolution of land models

Land Surface Models (LSMs) – 2nd Generation

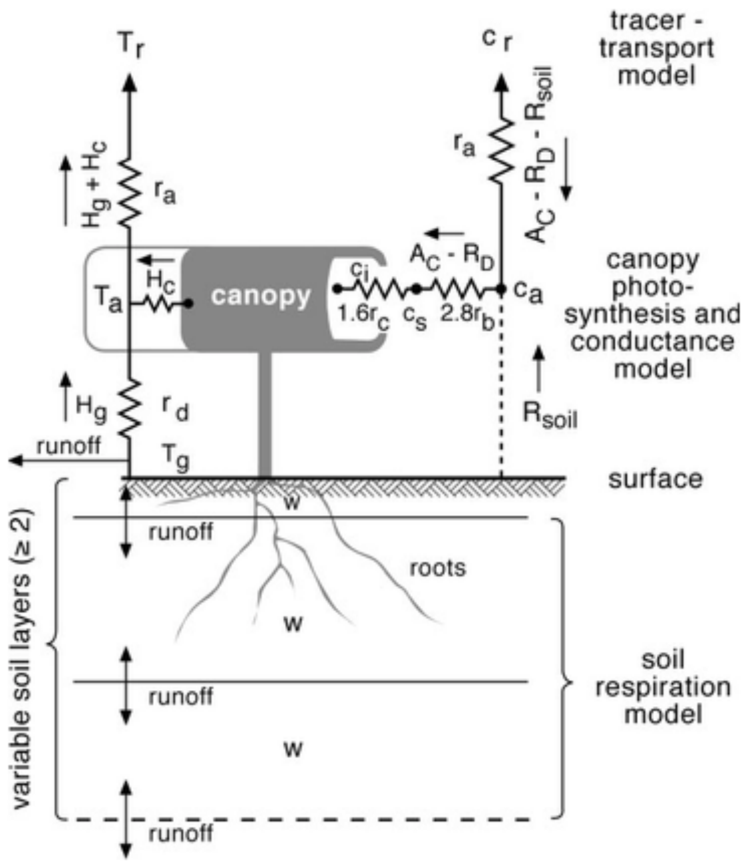


From Pitman (2003)

- Inclusion of canopy interception of precip
- Richards (1961) equations for soil moisture
  - Soil moisture potential (suction)
  - Soil hydraulic conductivity
- Runoff parameterization (varies widely across models)
- No river routing
  - Surface runoff is lost to the oceans immediately (still the case in many LSMs)
- Inclusion of multi-layer snow schemes
  - Snow evolution is very complex….
  - Evaluation is very hard….

Evolution of land models

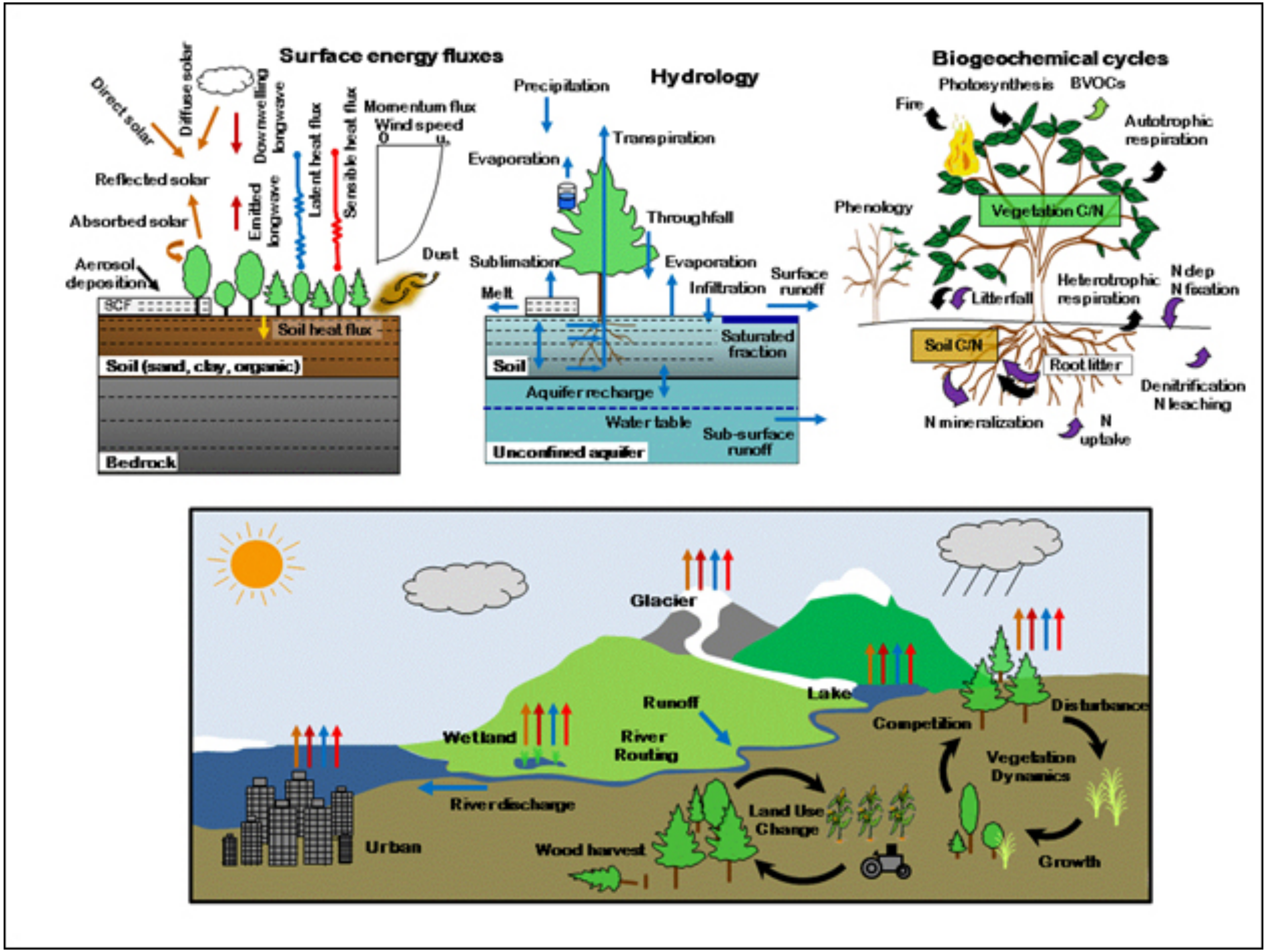
Land Surface Models (LSMs) – 3rd Generation



From Pitman (2003)

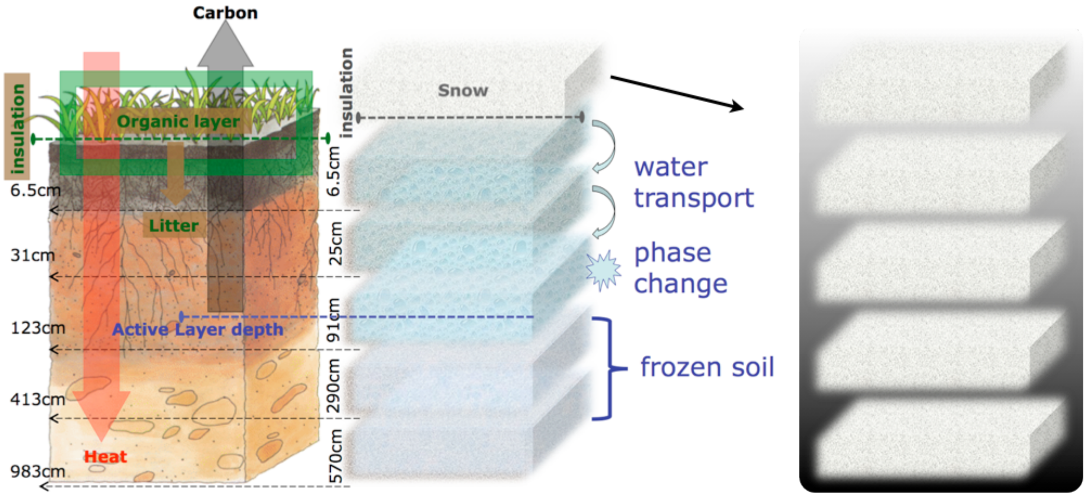
- ➢ Physically-based parameterization of stomatal conductance
  - ➢ Stomatal response to maximize efficiency of water use
- ➢ Inclusion of leaf photosynthesis:
  - ➢ Photosynthetic enzyme activity
  - ➢ Amount of VIS light captured by plant
- ➢ Allocate Carbon to simulate plant grow leaves, branches and roots
  - ➢ Start of "Dynamic vegetation"
- ➢ Inclusion of soil Carbon (and N and P models)
- ➢ Allow for simulation of role of land surface in Carbon cycle

CLM



Surface energy fluxes
Direct solar
Diffuse solar
Downwelling longwave
Reflected solar
Absorbed solar
Emitted longwave
Latent heat flux
Sensible heat flux
Momentum flux
Wind speed
Dust
Aerosol deposition
SCF
Soil heat flux
Soil (sand, clay, organic)
Bedrock
Hydrology
Precipitation
Transpiration
Evaporation
Throughfall
Sublimation
Evaporation
Infiltration
Surface runoff
Melt
Saturated fraction
Soil
Aquifer recharge
Water table
Sub-surface runoff
Unconfined aquifer
Biogeochemical cycles
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Phenology
Vegetation C/N
Heterotrophic respiration
N dep
N fixation
Litterfall
Soil C/N
Root litter
Denitrification
N leaching
N mineralization
N uptake
Glacier
Lake
Runoff
Wetland
River Routing
Competition
Disturbance
Vegetation Dynamics
River discharge
Land Use Change
Urban
Wood harvest
Growth

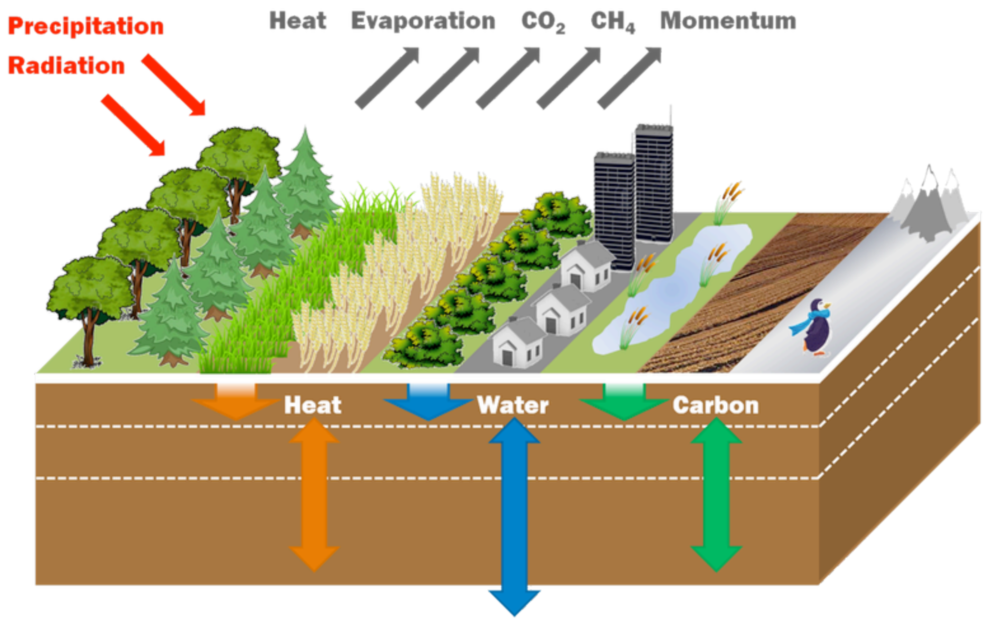
JSBACH model (MPI-ESM, Germany)



Ekici et al., Geoscientific Model Development, 2014

Ekici et al., 2014

JULES model (UK-ESM, UK)



Chadburn et al., 2015

Acknowledgements

The contents in this lecture are from a combination of different sources:

- Chapin, Principles of Terrestrial Ecosystem Ecology
- Dave Lawrence, NCAR
- IPCC
- ETHZ

and published work cited in the slides