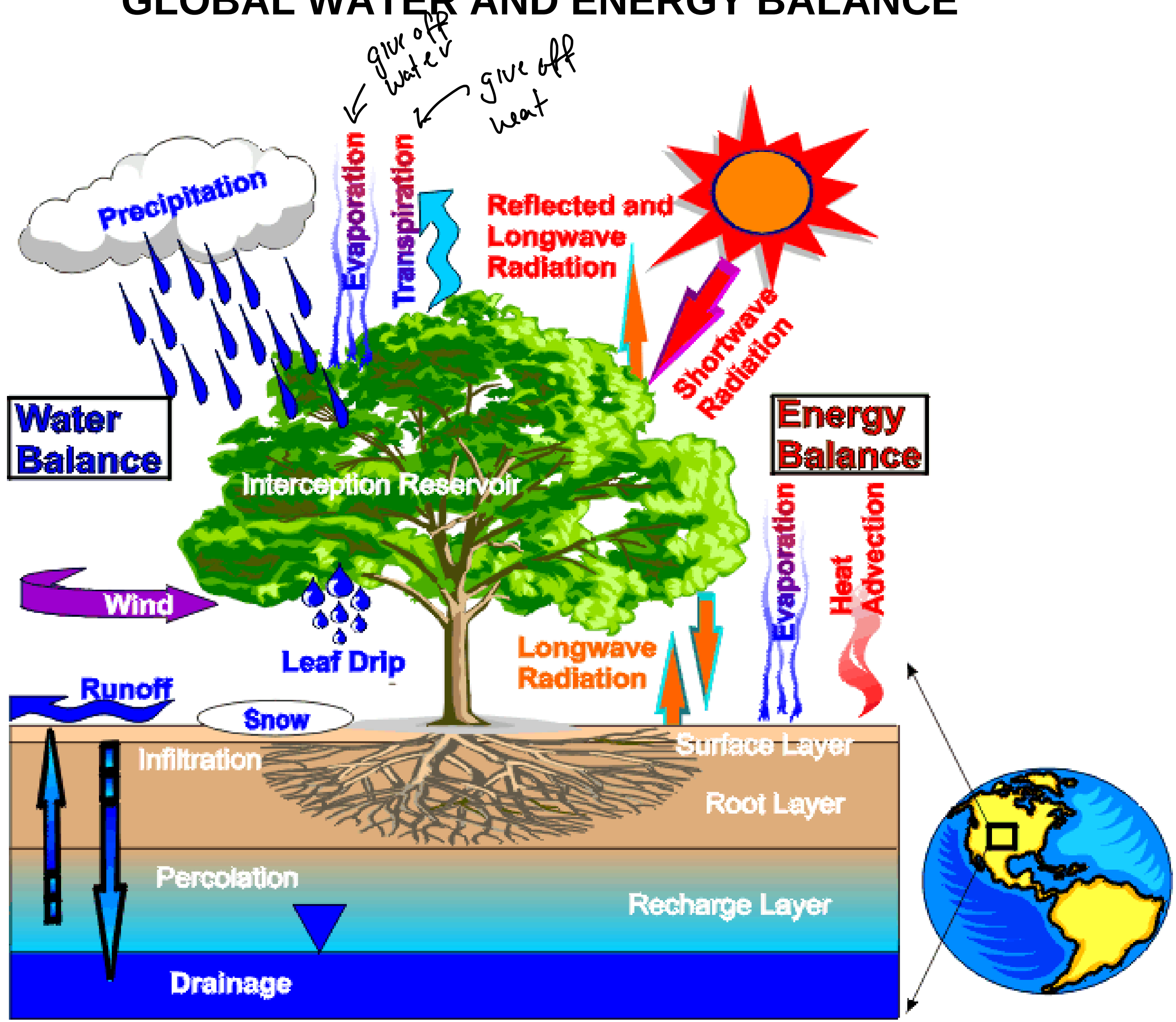
Module II

GLOBAL WATER AND ENERGY BALANCE

GLOBAL WATER AND ENERGY BALANCE



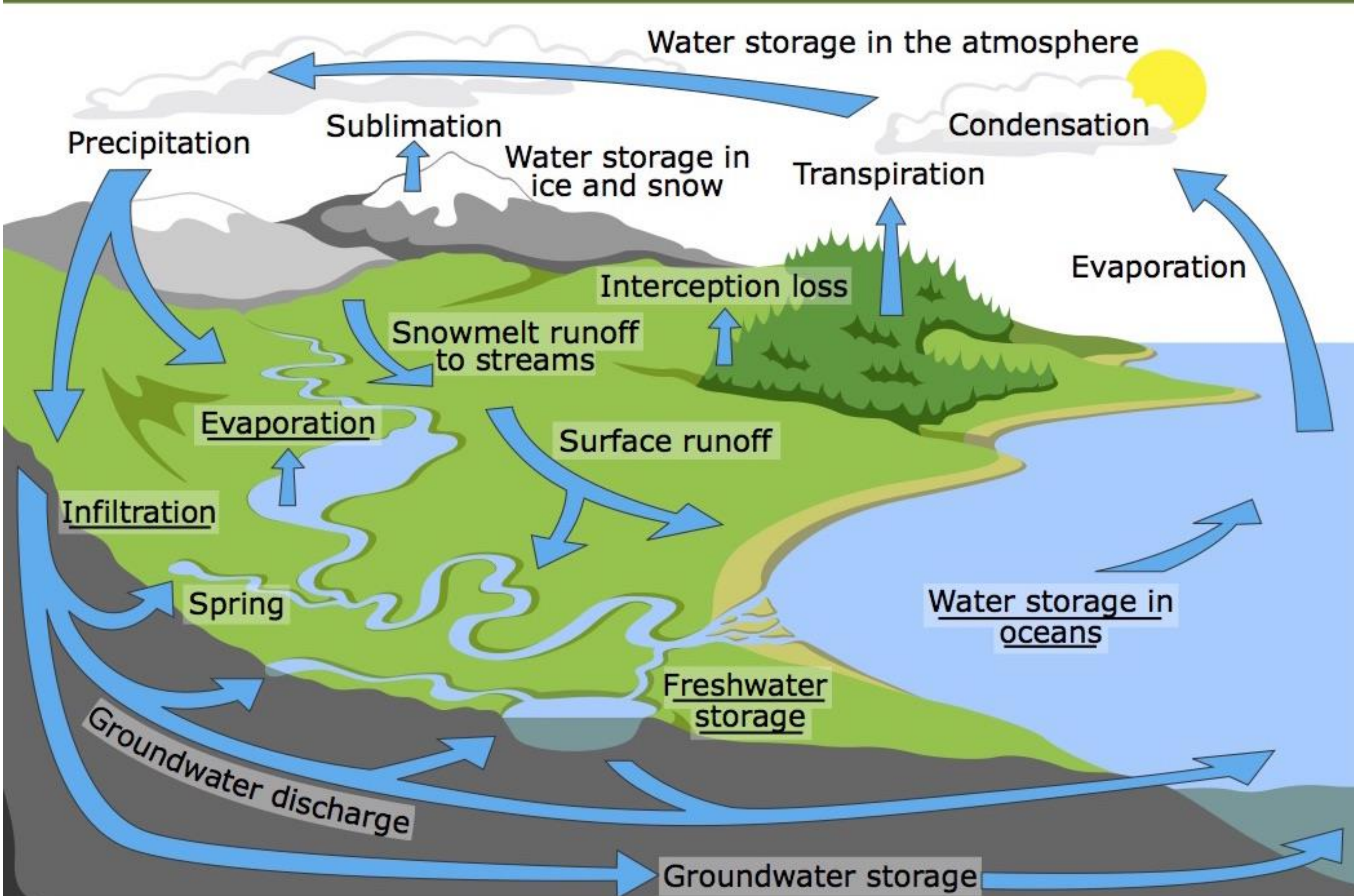
Introduction

The hydrologic (water) cycle:

- **Driven by solar energy**

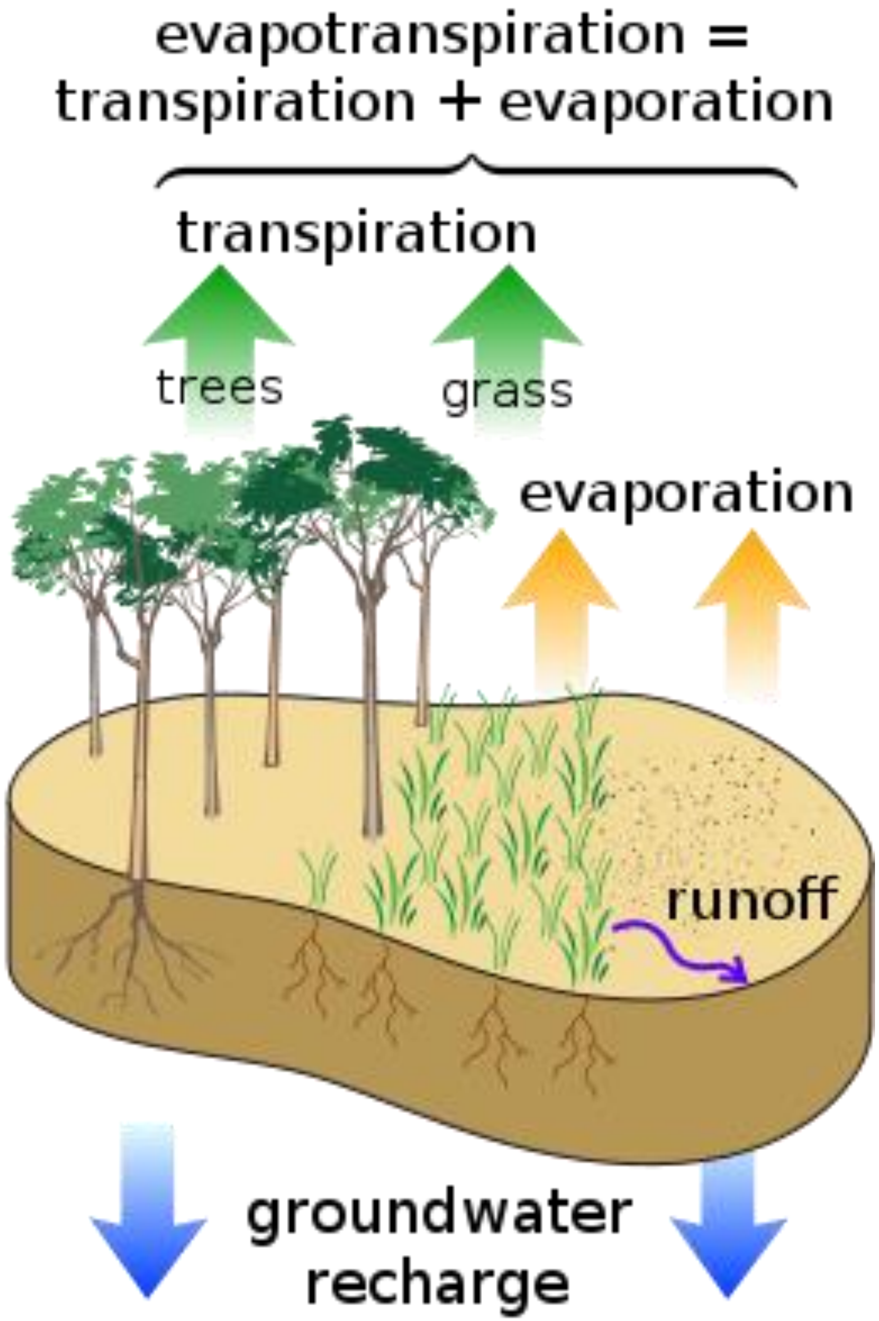
- **The "master cycle" that drives all other biogeochemical cycles**

DYNAMIC AND COMPLEX: THE GLOBAL WATER CYCLE



Water and **energy** cycles are so tightly **<u>intertwined</u>** that they cannot be treated separately

Solar energy drives the hydrologic cycle through evapotranspiration



The hydrologic cycle controls Earth's biogeochemical cycles by **dissolving nutrients and transferring them** within and among ecosystems

Earth's Energy Budget

The sun is the source of the energy available to <u>drive Earth's climate system</u> → primarily short-wave radiation (UV, visible, and near-infrared)

30% reflected back by clouds, air, dust, haze, etc. (backscatter)

23% absorbed by the atmosphere (ozone in upper atmosphere and clouds / water vapor in lower atmosphere)

47% reaches Earths surface

Earth <u>emits</u> most energy as low energy **longwave radiation**

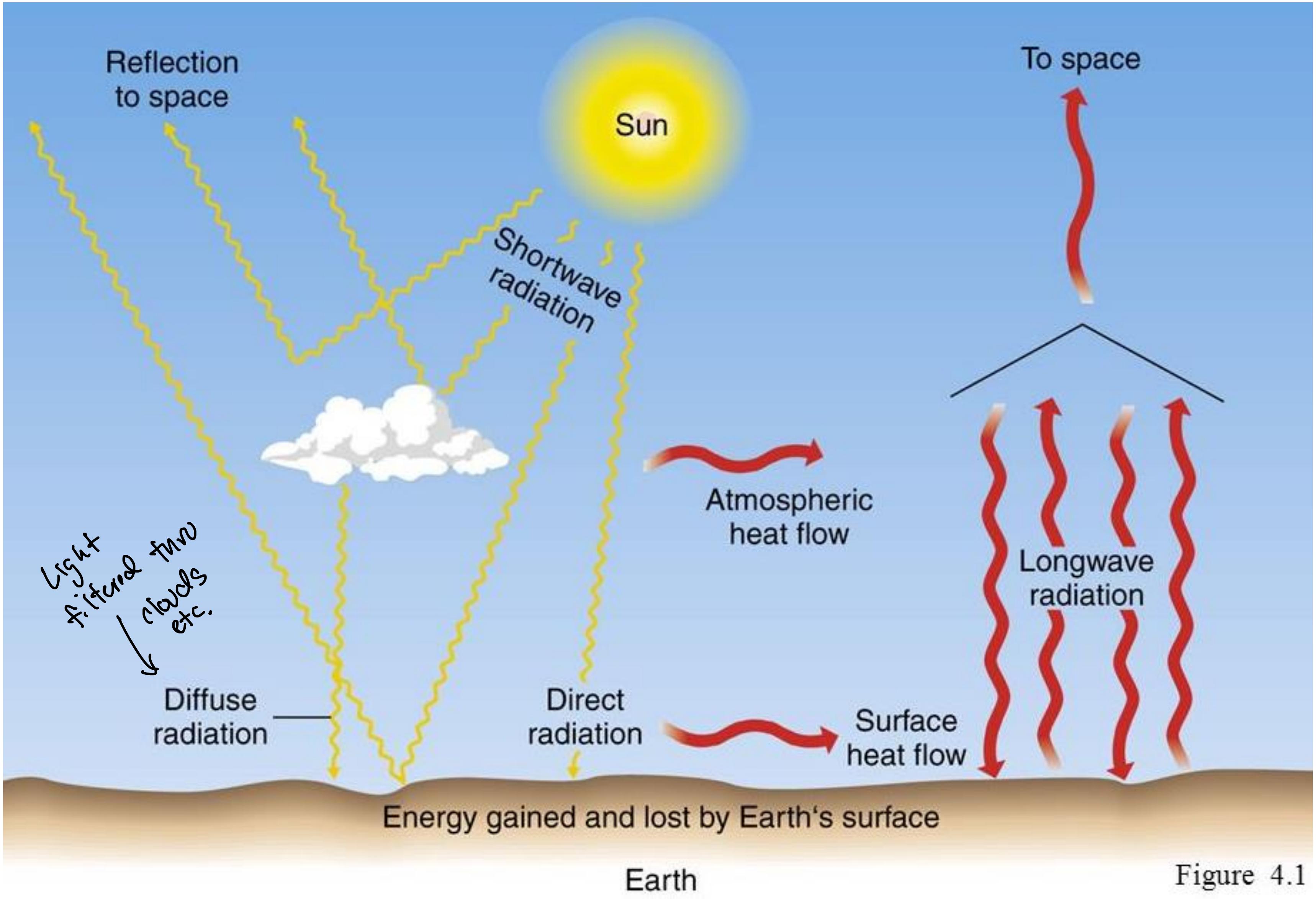
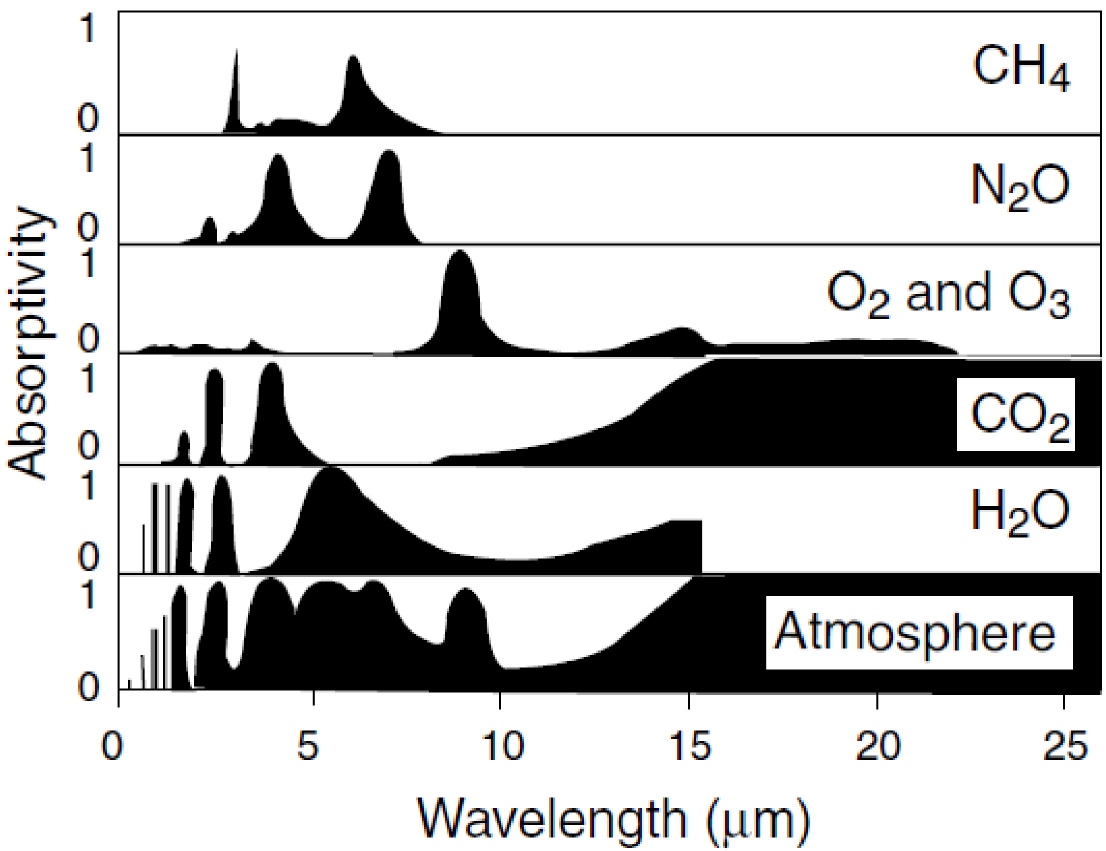


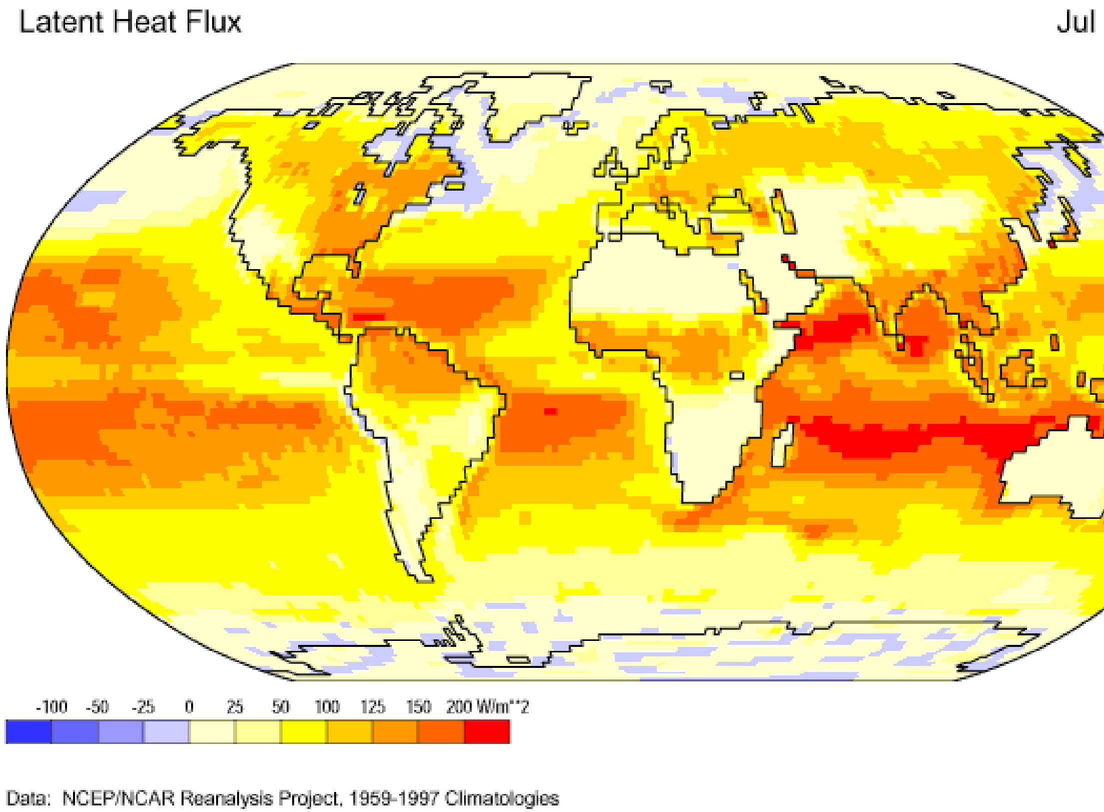
Figure 4.1

Radiatively active gases (water vapor, CO_2, CH_4, N_2O and industrial products like chlorofluorocarbons [CFCs]) **absorb 90% of the outgoing longwave radiation**

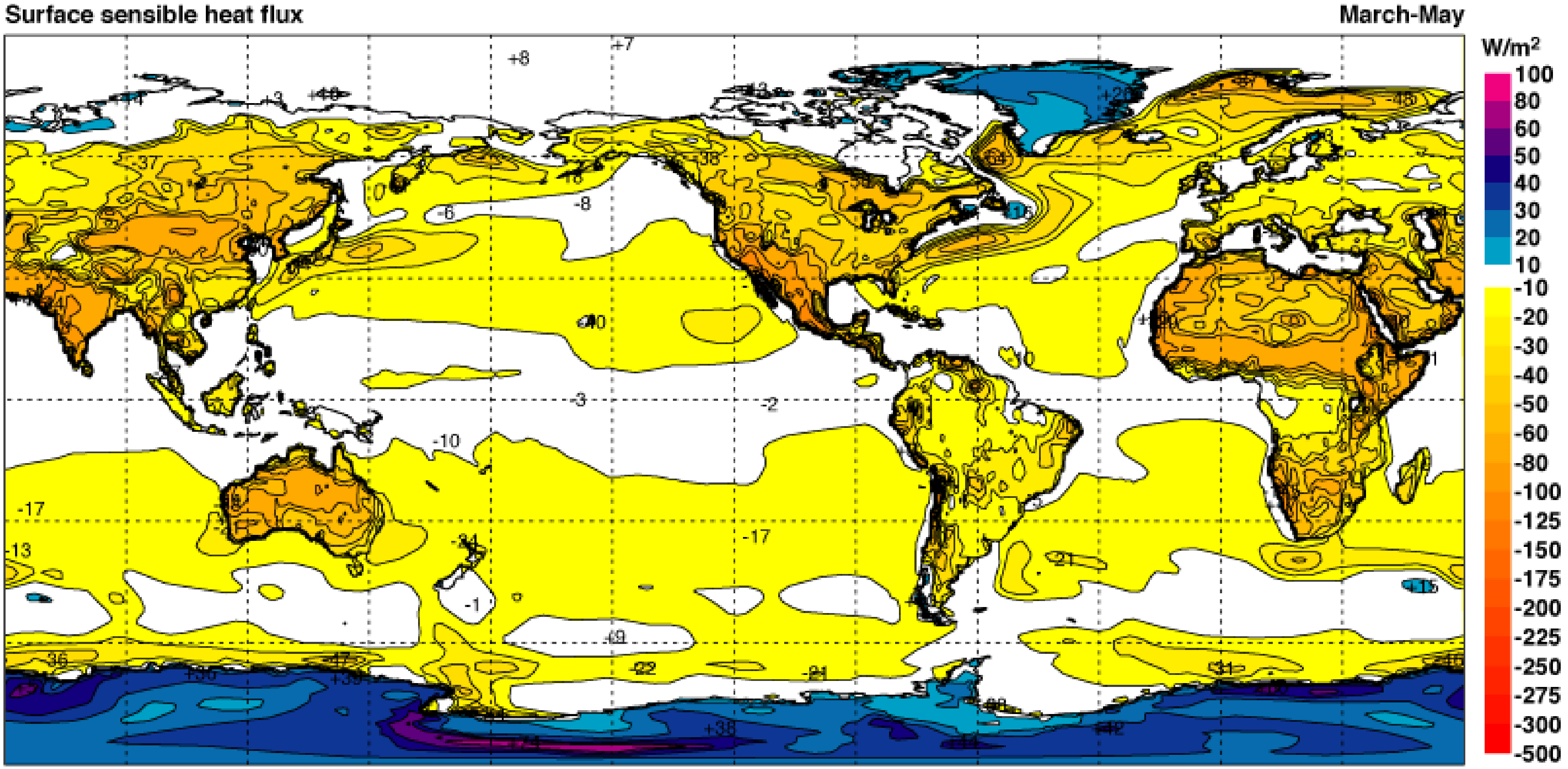


Non-radiative fluxes of heat are carried upward by <u>atmospheric turbulence</u>:

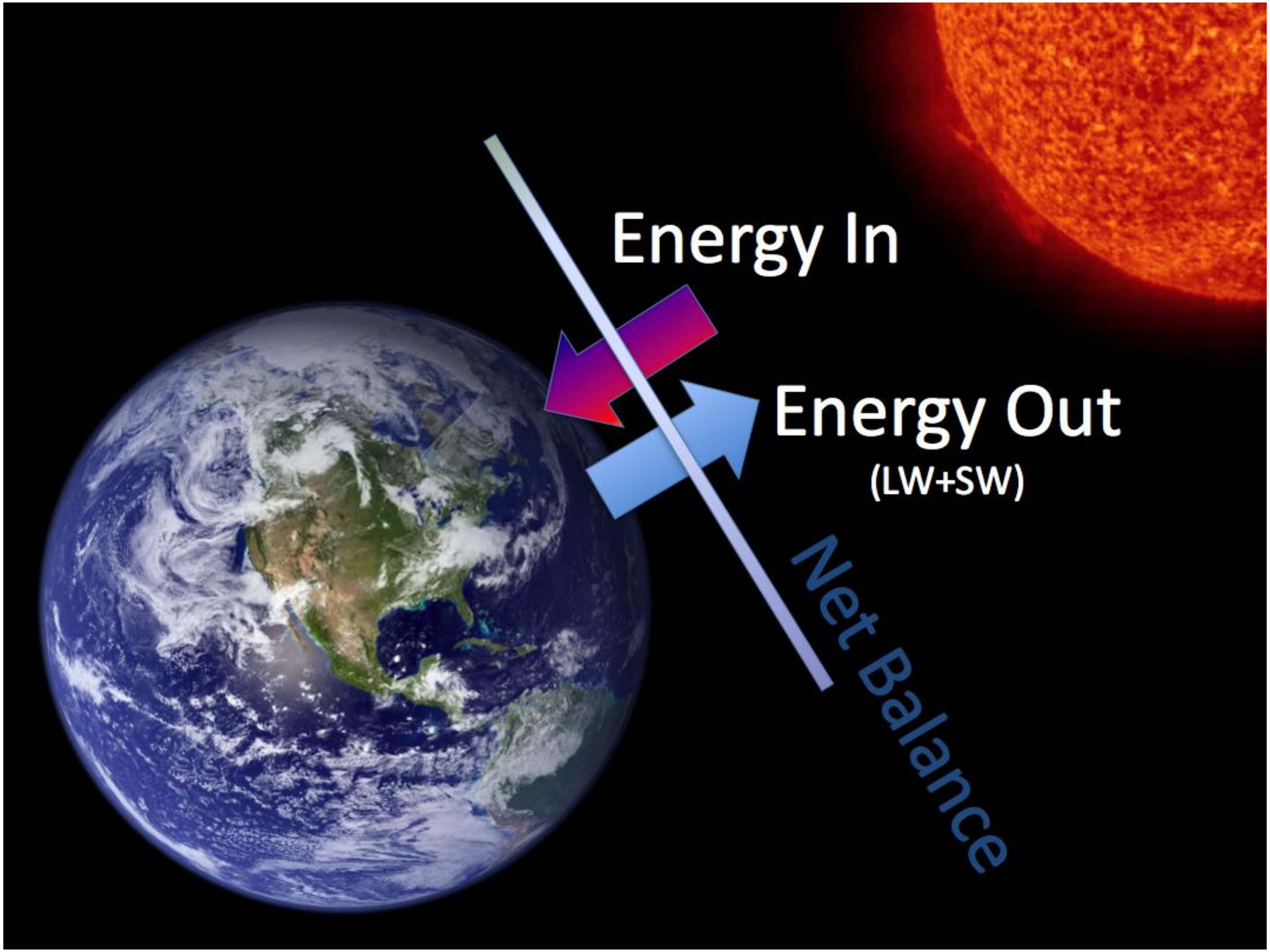
Latent heat flux – heat that evaporates surface water → water vapor → clouds → precipitation

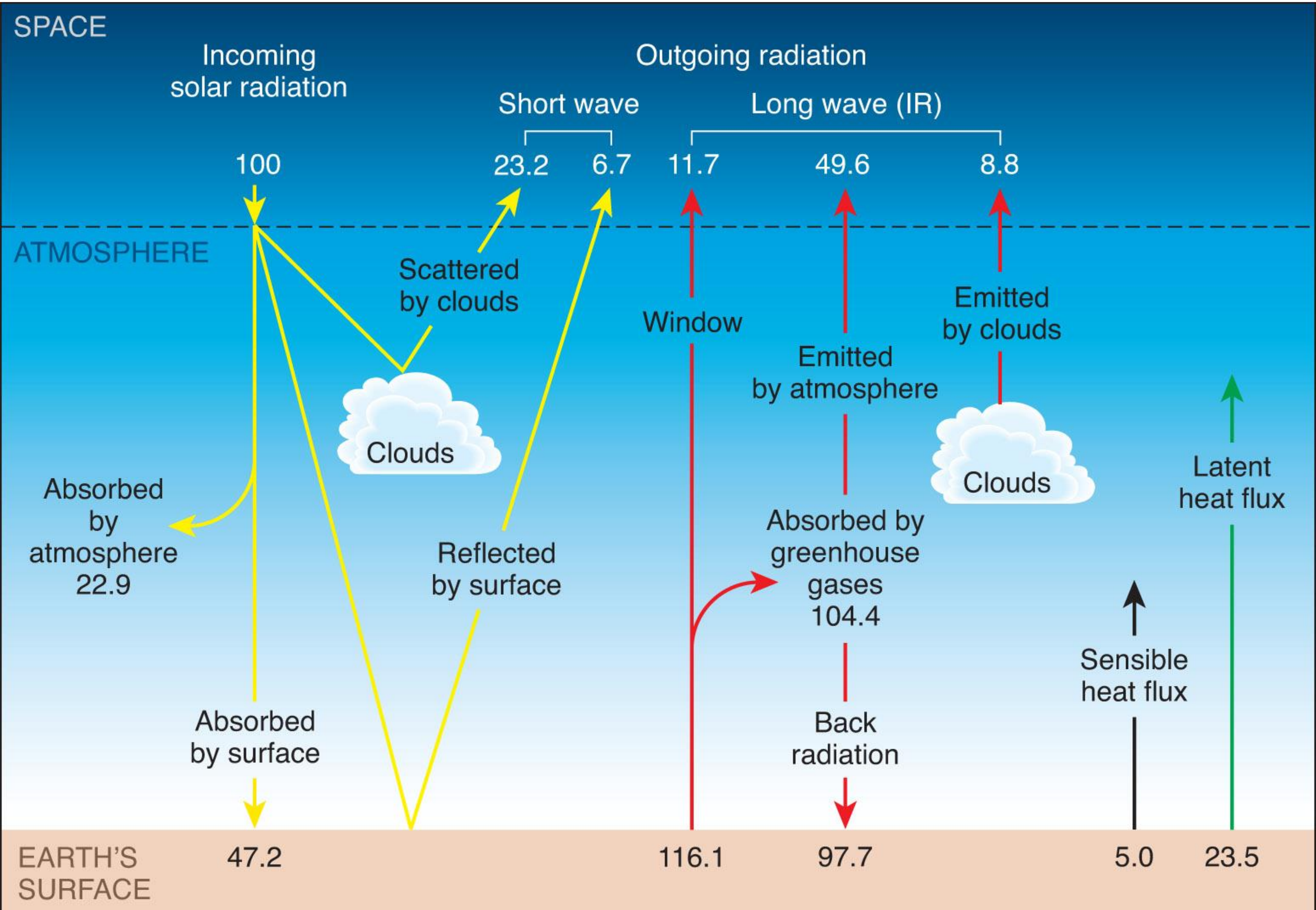


Sensible Heat flux –heat conducted from warm surfaces is carried upward by convection



Globally, long-term average is for earth to be in a state of radiative balance

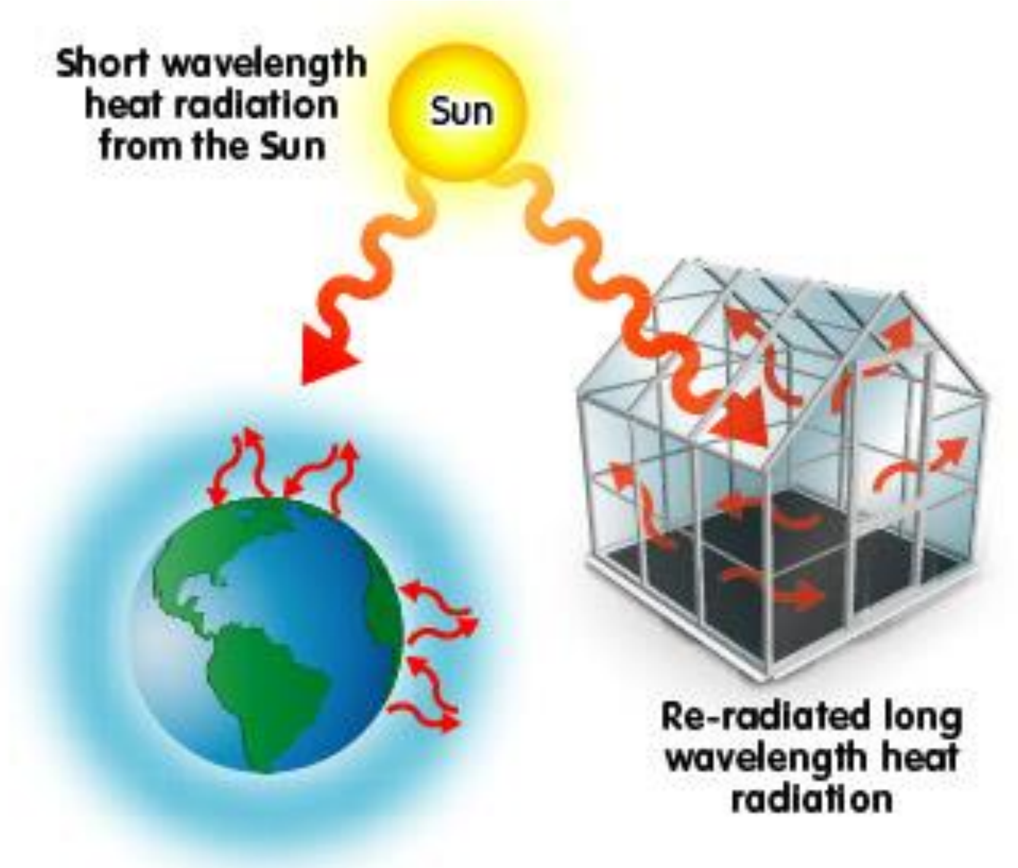



SPACE
Incoming solar radiation
100
Outgoing radiation
Short wave
23.2
6.7
Long wave (IR)
11.7
49.6
8.8
ATMOSPHERE
Scattered by clouds
Clouds
Window
Emitted by atmosphere
Emitted by clouds
Clouds
Latent heat flux
Absorbed by atmosphere 22.9
Reflected by surface
Absorbed by greenhouse gases 104.4
Sensible heat flux
Absorbed by surface
Back radiation
EARTH'S SURFACE
47.2
116.1
97.7
5.0
23.5

Some outgoing heat gets to the upper atmosphere / space

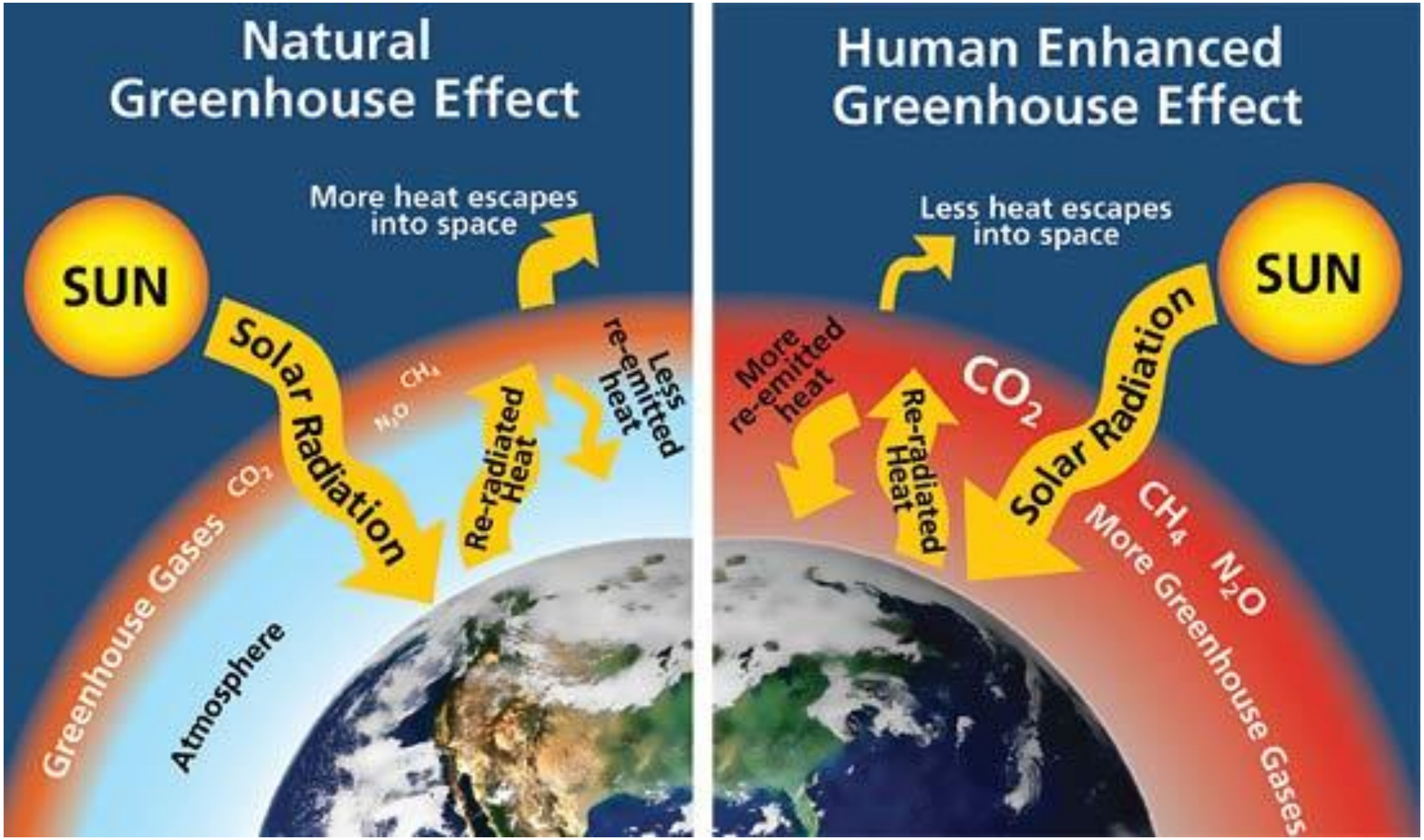
Some is intercepted and re-radiated back to the Earth's surface

(Natural Greenhouse Effect)

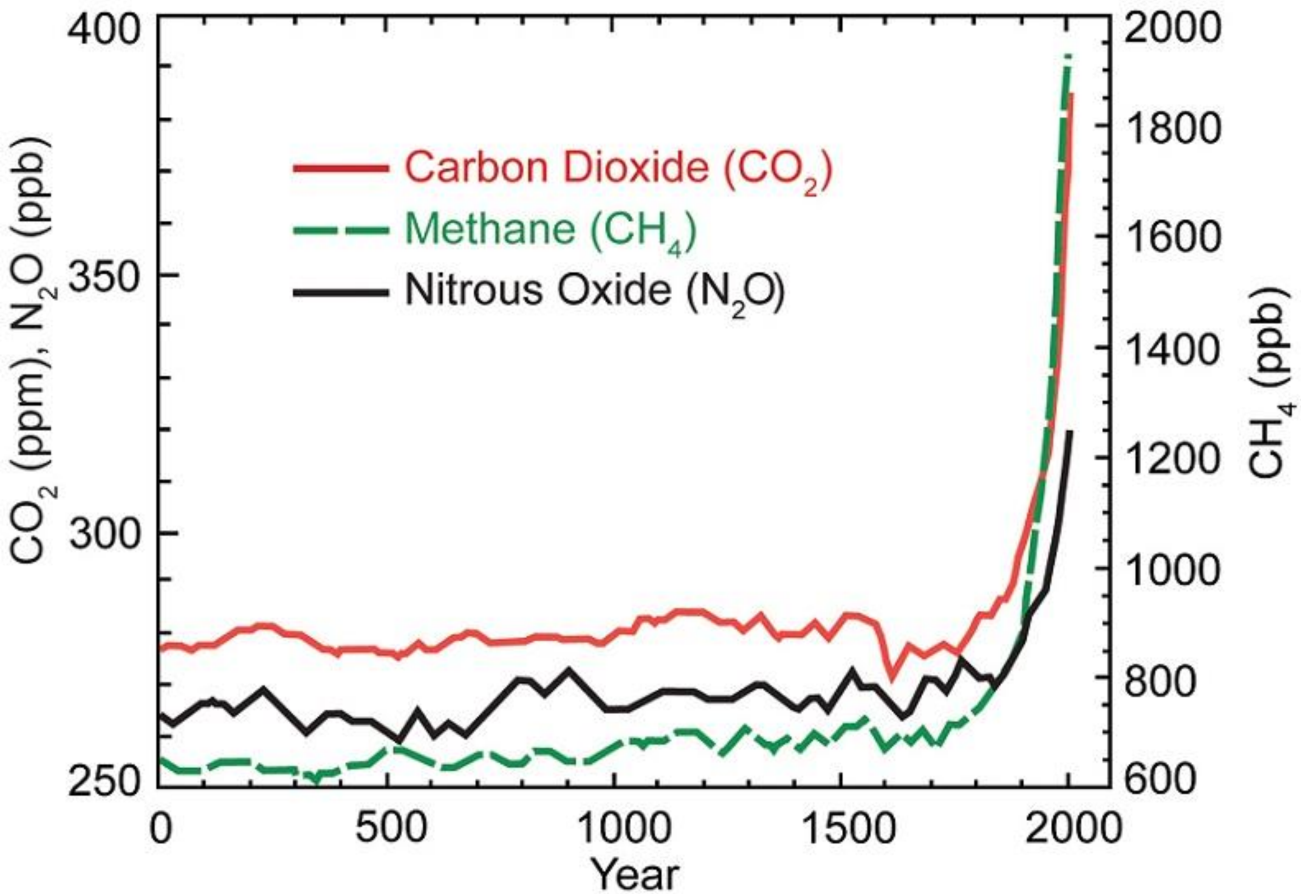


Human activities are changing the composition of the atmosphere resulting in an increase in the heat retained close to Earth's surface

Main takeaway: Human climate change = less heat escape to space

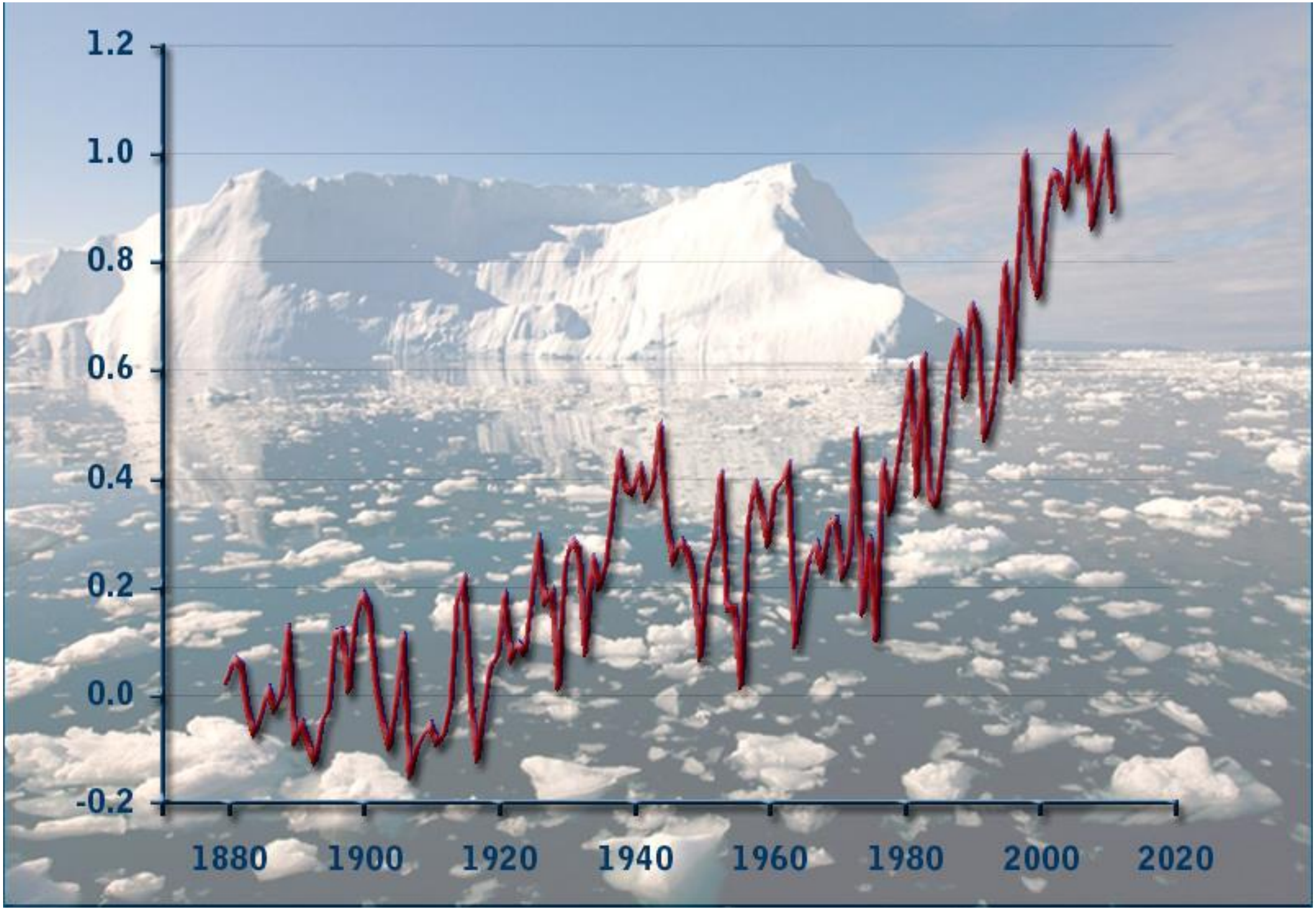


Long-term records (from direct atmospheric measurements and from air bubbles in ice cores) show large increases in the major radiatively active gases (CO_2, CH_4, N_2O, and CFCs) since the beginning of the industrial revolution (approx. 250 years ago)



Why?

Result? Upset energy balance → enhance GH effect → increase Earth's surface temp.



Atmospheric Influence on the Global Energy Budget

Chemical composition of the atmosphere determines its role in the Earth's energy budget… thousands of chemical substances – gases and particulates

Compound	Formula	Concentration (%)
Nitrogen	N_2	78.082
Oxygen	O_2	20.945
Argon	Ar	0.934
Carbon dioxide	CO_2	0.039

99% = N_2, O_2, Ar, CO_2

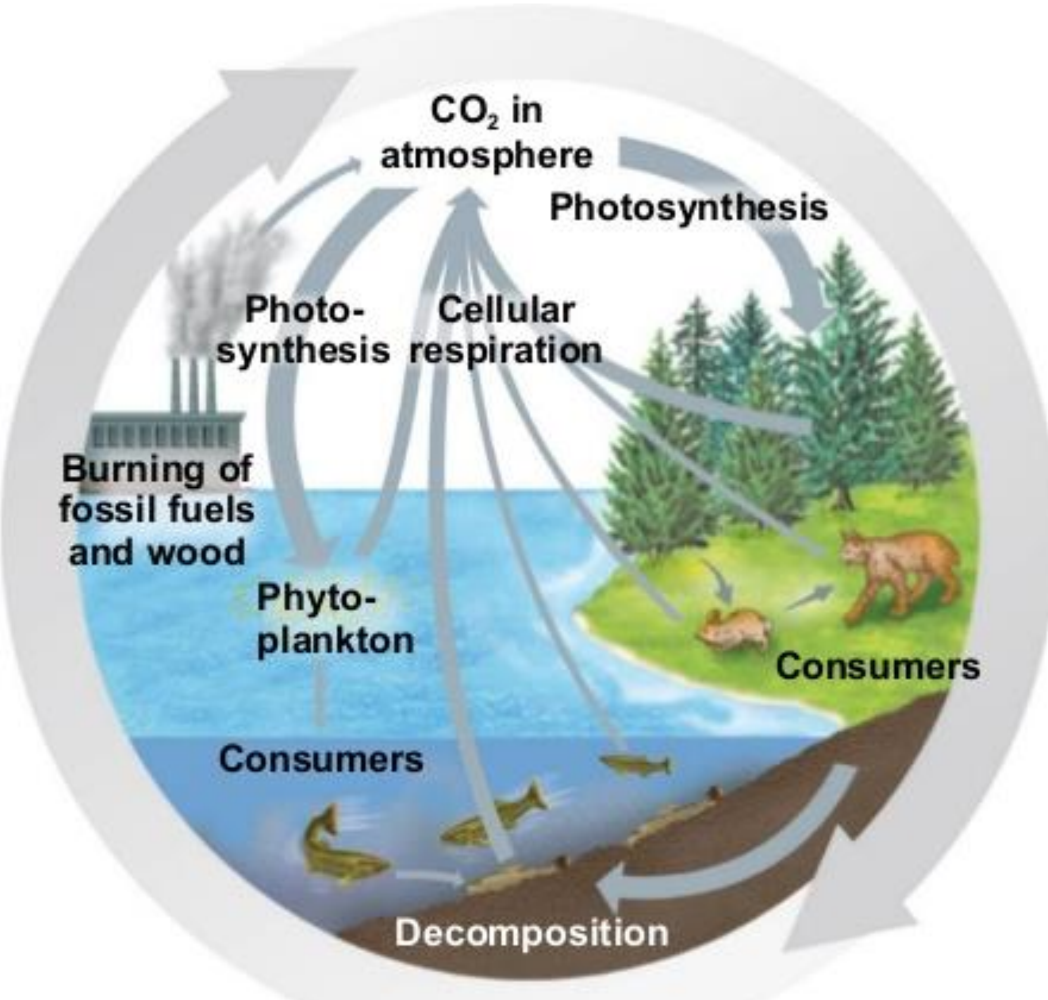
Atmospheric gases have different mean residence times (MRTs)

MRT = total mass of gas divided by flux into and out of the atmosphere over a given period of time

↳ OR: average amount of a given gas over time, given its influx & outflux

N_2 = 13 million years ← how long they reside in atmosphere
O_2 = 10,000 years
CO_2 = 5 years***
CH_4 = 8 - 20 years

***CO_2 is not broken down when absorbed by the ocean or atmosphere…. recycled through the Carbon Cycle



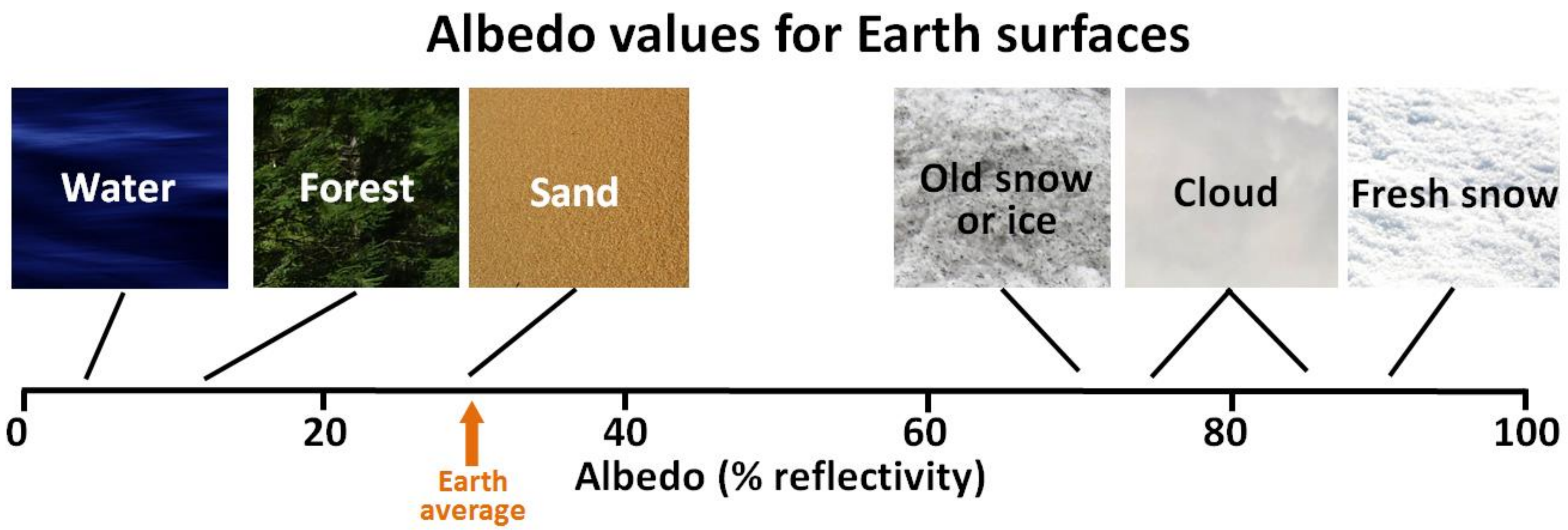
If all fossil fuel emissions ceased today, the excess CO_2 in the atmosphere (approx. 35% higher than "natural background levels"), would take a long time to decline:

- **50% in 30 years**
- **Another 20% within several hundred years**
- **The remaining 30% remains for several thousand years**

Aerosols + gases + clouds + surface characteristics determine reflectivity (albedo) → exerts significant control over Earth's energy budget (<u>and climate</u>)

Global surface albedo – NASA image

The albedo of a surface determines the quantity of solar energy absorbed by the surface (and is subsequently available for transfer to the atmosphere as longwave radiation)

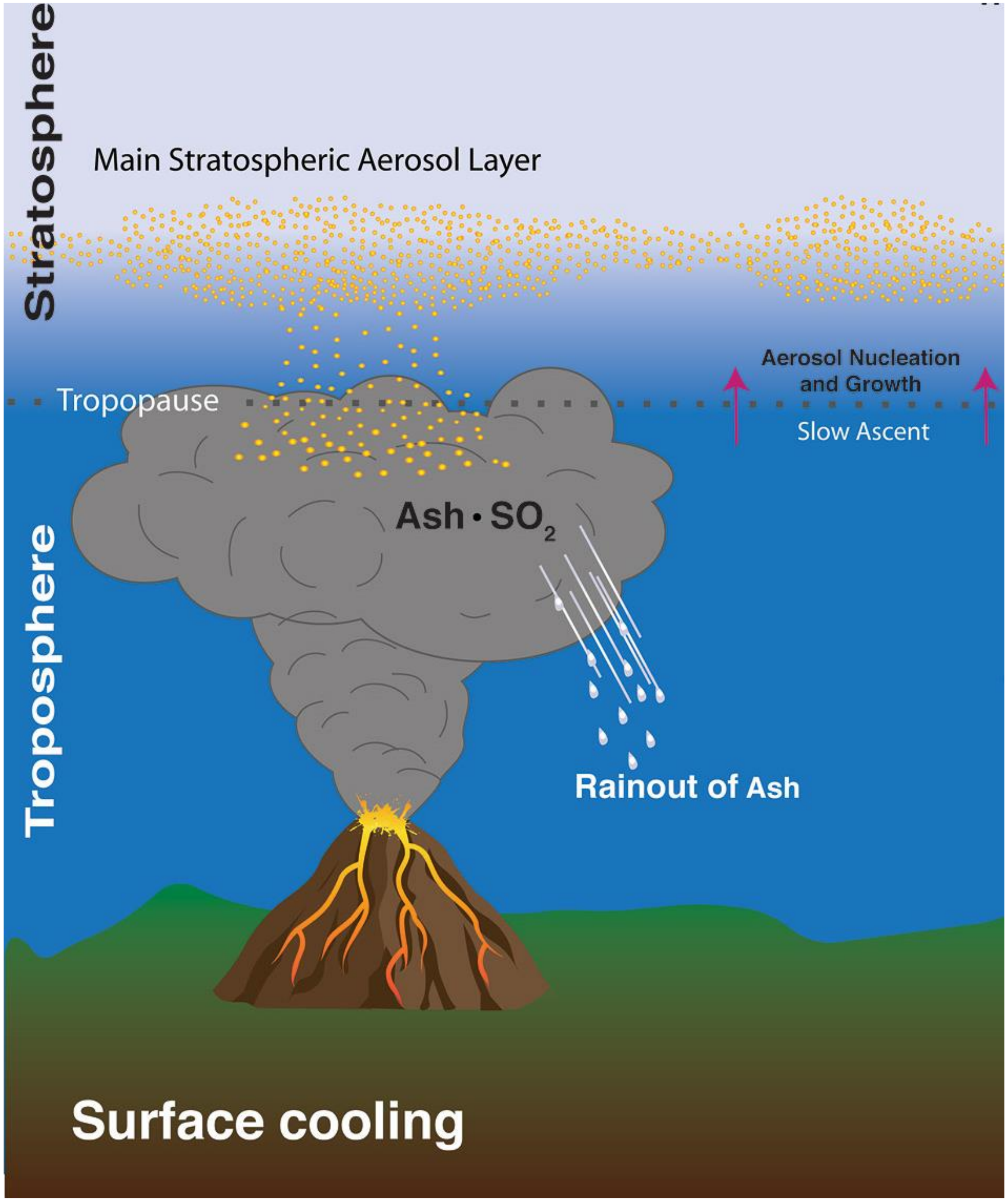


Aerosols scatter (reflect) some incoming shortwave radiation (cools climate)

aerosols <u>COOL</u>

climate

↳ reflect incoming shortwave



<u>Ex</u>: In 1991 Mt. Pinatubo in the Philippines produced sulfate aerosols that cooled the global climate for a year!!!

Clouds…..

Have a high albedo and reflect short wave radiation (cooling effect)

AND

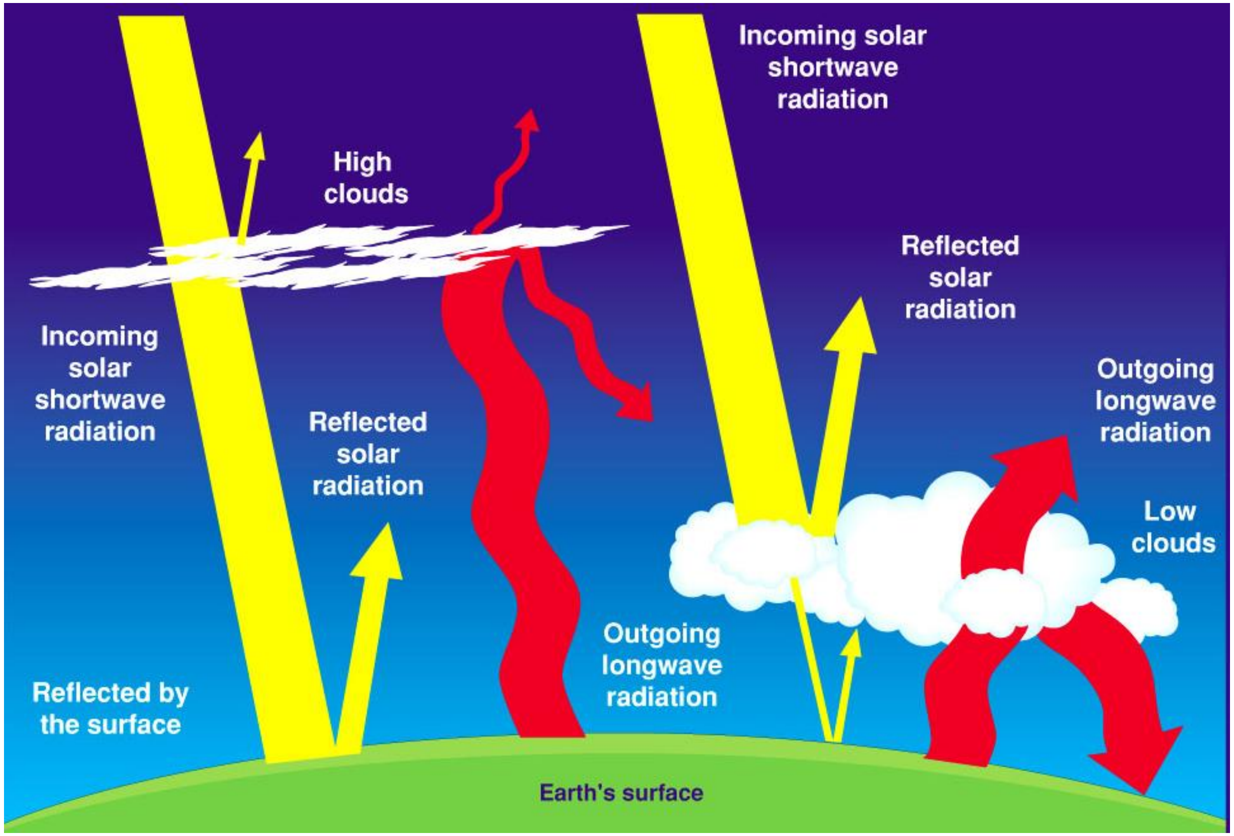
Absorb re-radiated longwave radiation from earth (warming effect)

High clouds = cooling

↳ reflect

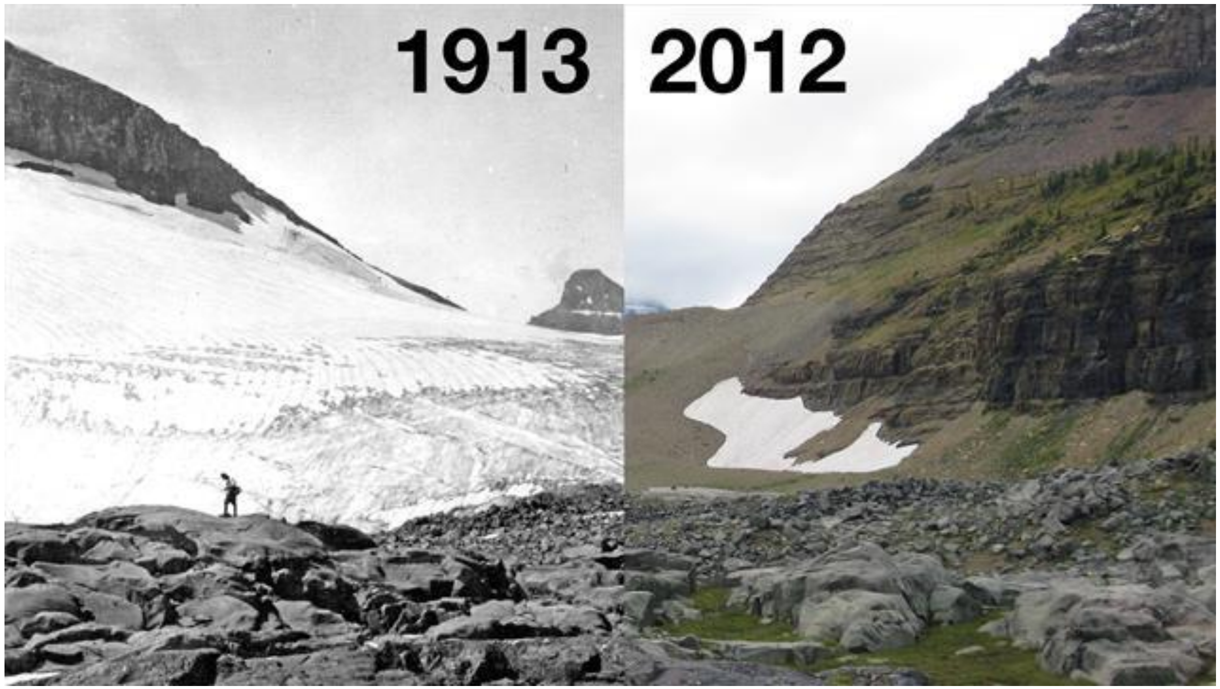
Low clouds = warming

↳ trap



The change from snow covered (little energy absorbed) to snow-free (more energy absorbed) occurs at a threshold (31^{o}F → 33^{o}F):

Glacier National Park



So, in ecosystems where snow plays a part, a small change in temperature can produce a <u>major shift</u> in energy absorbance!!!

Land use change can also have large effects on albedo:

Ex: Conversion of **grassland** (20% reflectance) to **dark fallow field** (5% reflectance)

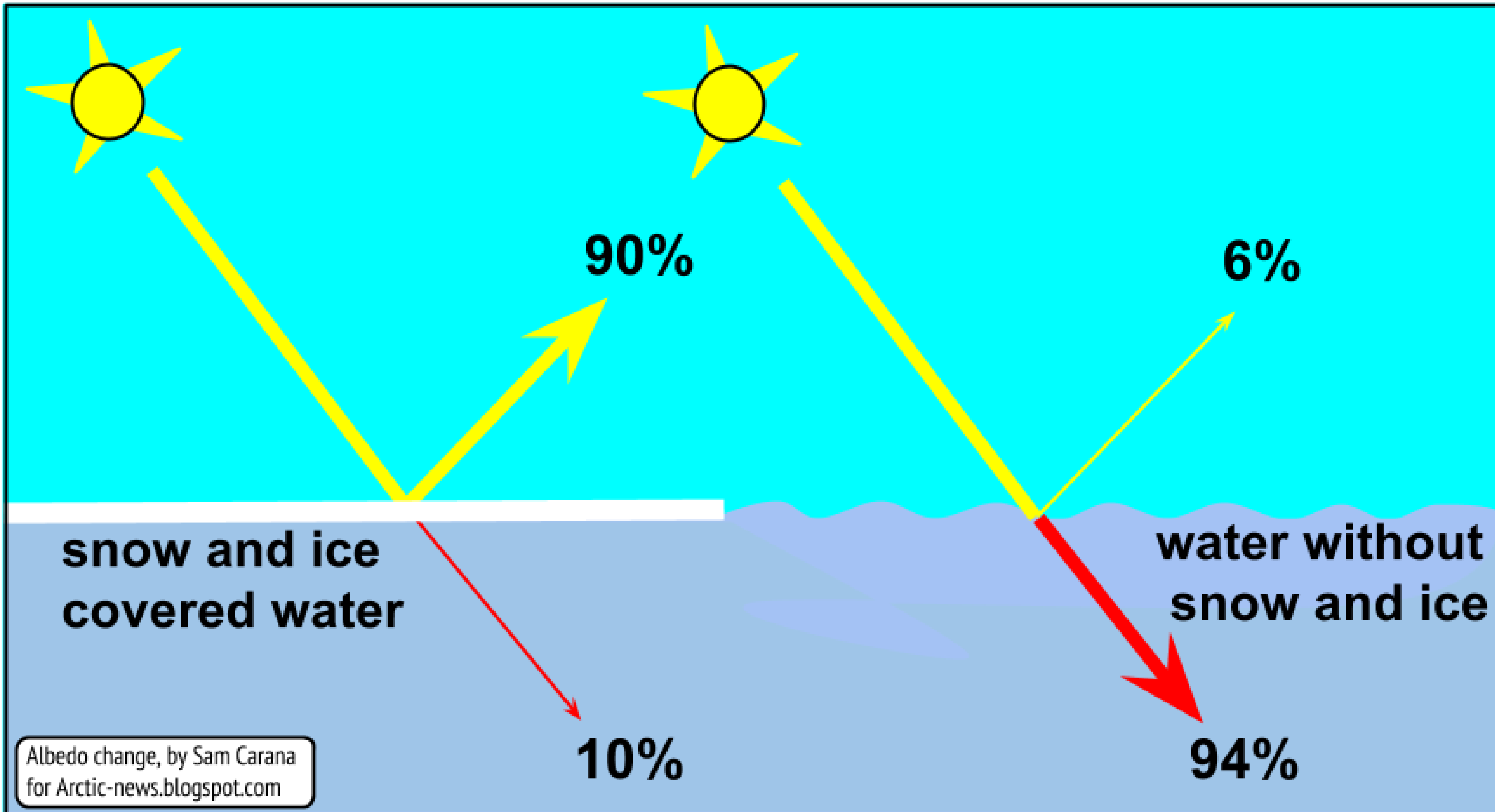
How does this affect temperature?

↳ makes thing warmer
↳ more absorption potential

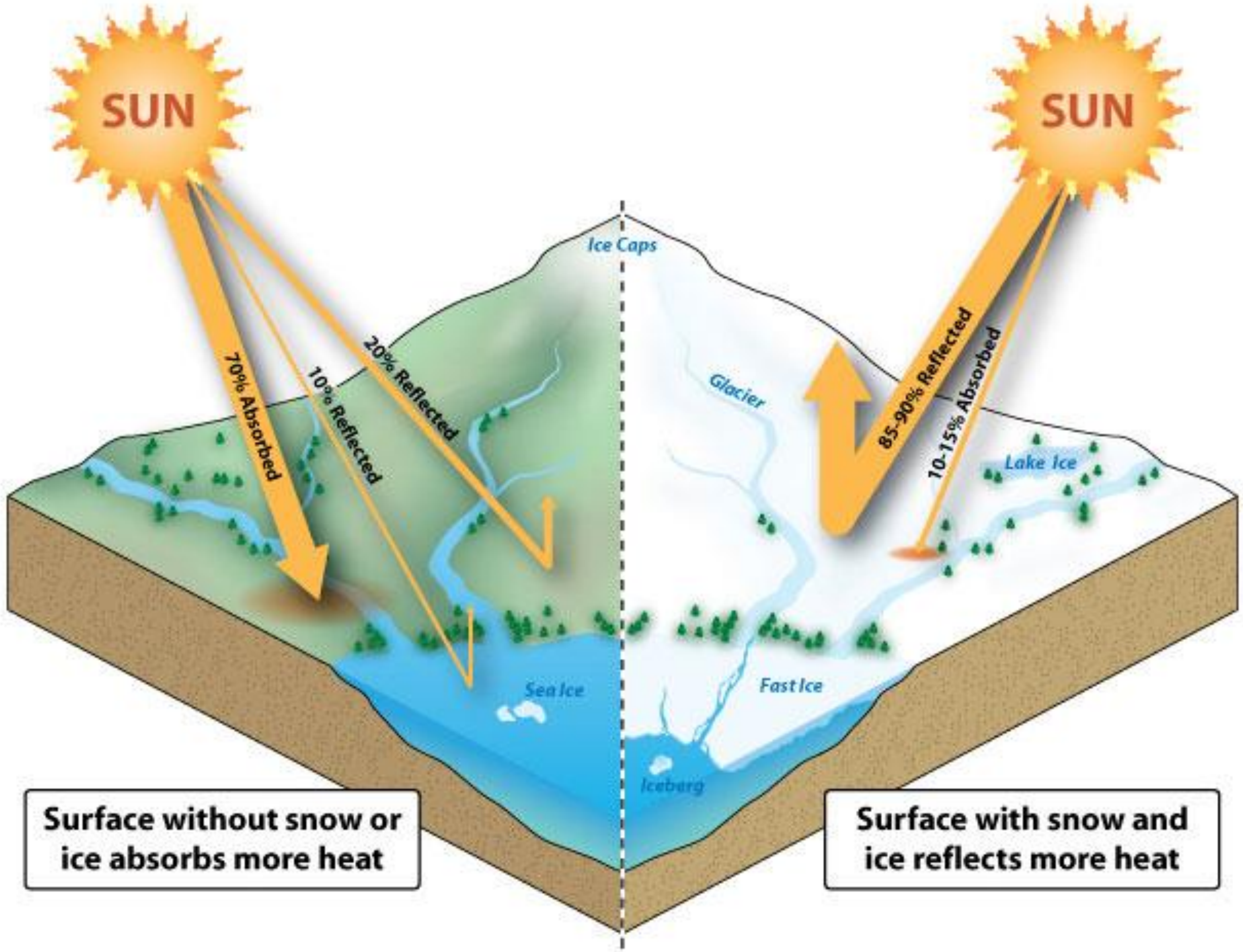
Conversion of grassland (20% reflectance) to light sandy soils via desertification (40% reflectance)

What effect does this have on temperature?

Water generally has a low albedo, so lakes and oceans absorb considerable solar energy

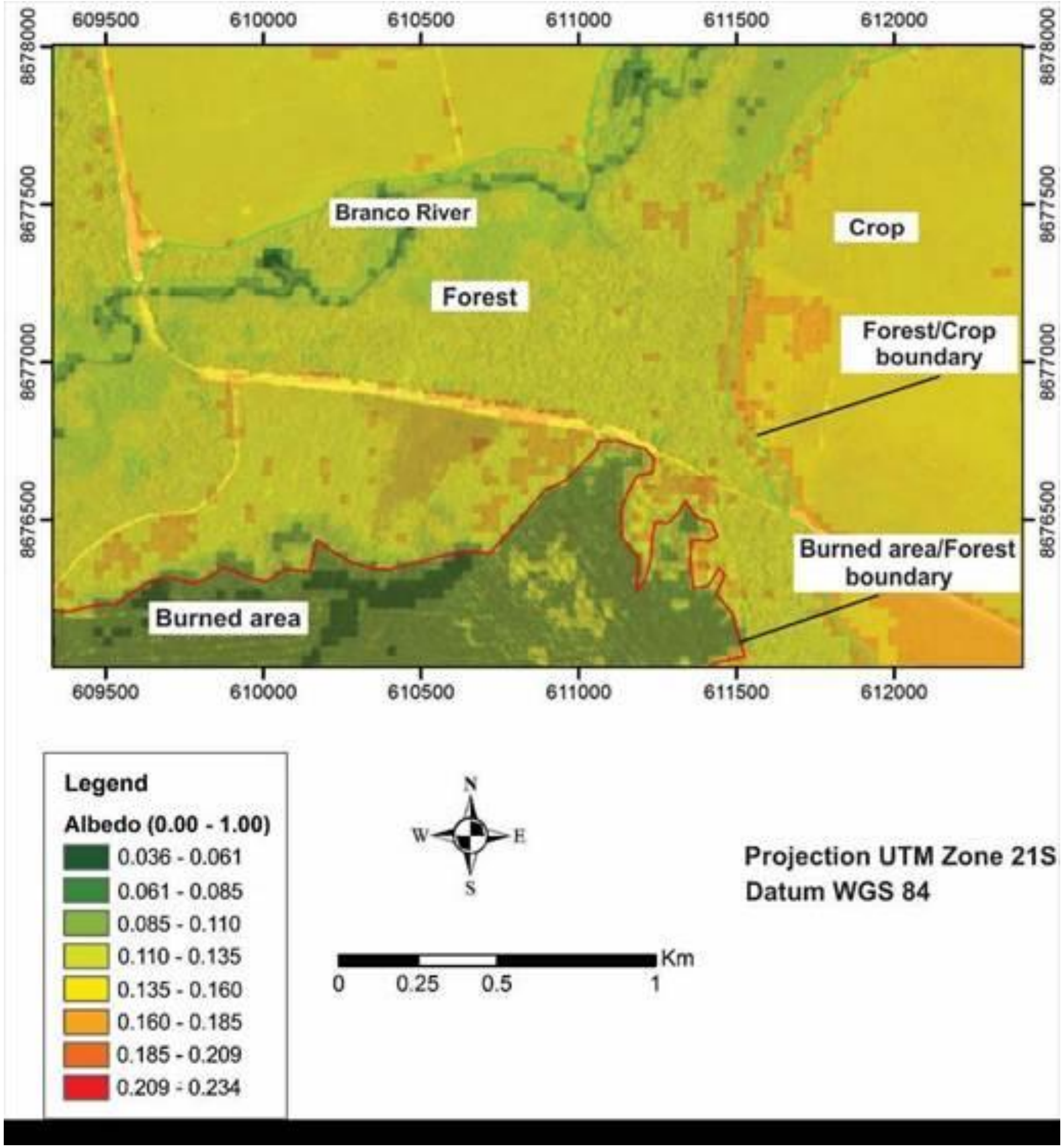


Snow and ice have a <u>high</u> albedo and hence absorb little solar radiation, contributing to the cold conditions required for their persistence



Vegetation is intermediate in albedo…

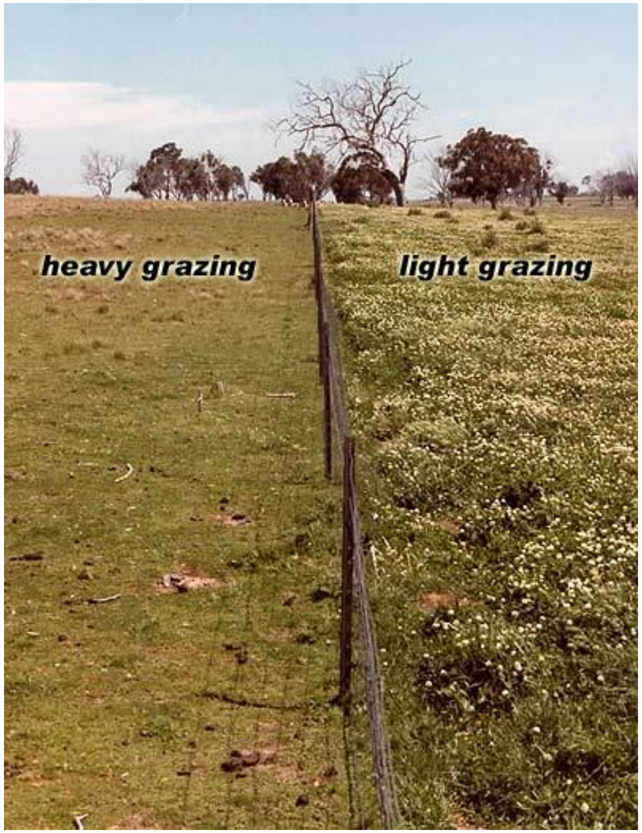
Grasslands (with highly reflective standing dead leaves) > **deciduous forests** > **coniferous forests**



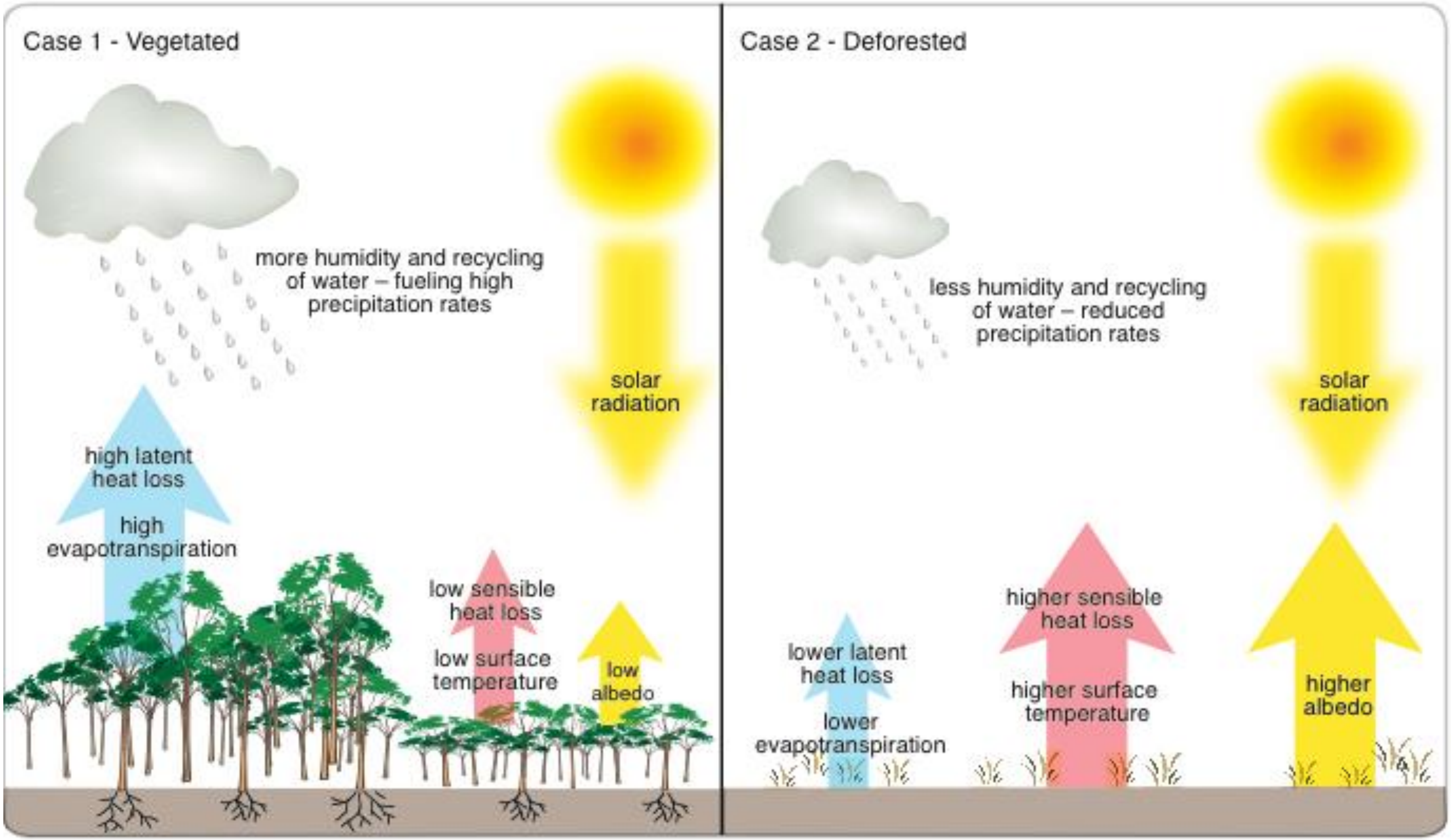
The **albedo of soil** depends on soil type and wetness but is often higher than that of vegetation in dry climates

Many land-use changes substantially alter regional albedo by increasing the area of exposed bare soil….

Overgrazing <u>increases</u> albedo → reduces energy absorption and the transfer of energy to the atmosphere → → reduces precipitation and the capacity of vegetation to recover from overgrazing … (vicious cycle)



Consequences of tropical deforestation and conversion to pasture



In forested conditions, the low albedo provides ample energy absorption to drive high transpiration rates that cool the surface and supply abundant moisture to the atmosphere to fuel high precipitation rates. In pasture conditions that develop after deforestation, low vegetation cover and shallow roots restrict transpiration and therefore the moisture available to support precipitation. This leads to a warmer, drier climate.

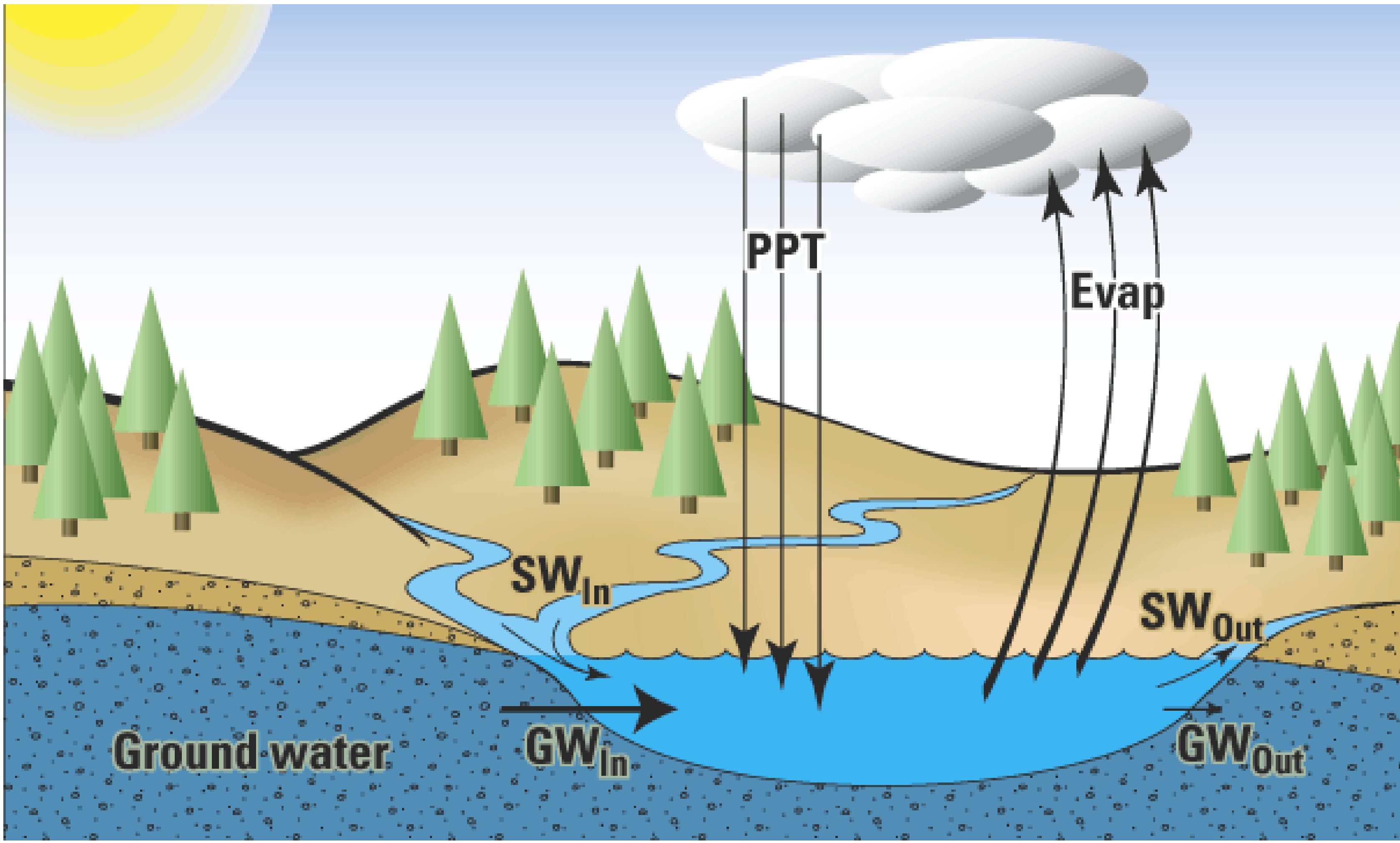
Ecosystem Water Budgets

Water is the resource that <u>most strongly constrains</u> the productivity of the biosphere

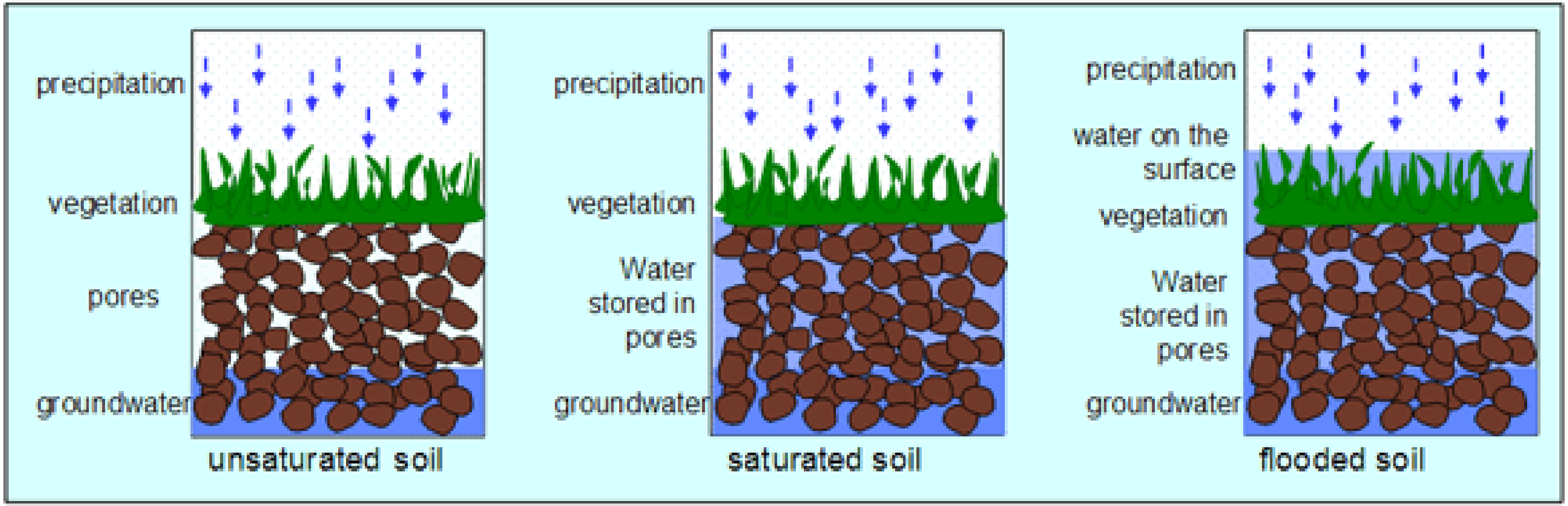
The water available to support the productivity of ecosystems depends on the balance between inputs and outputs

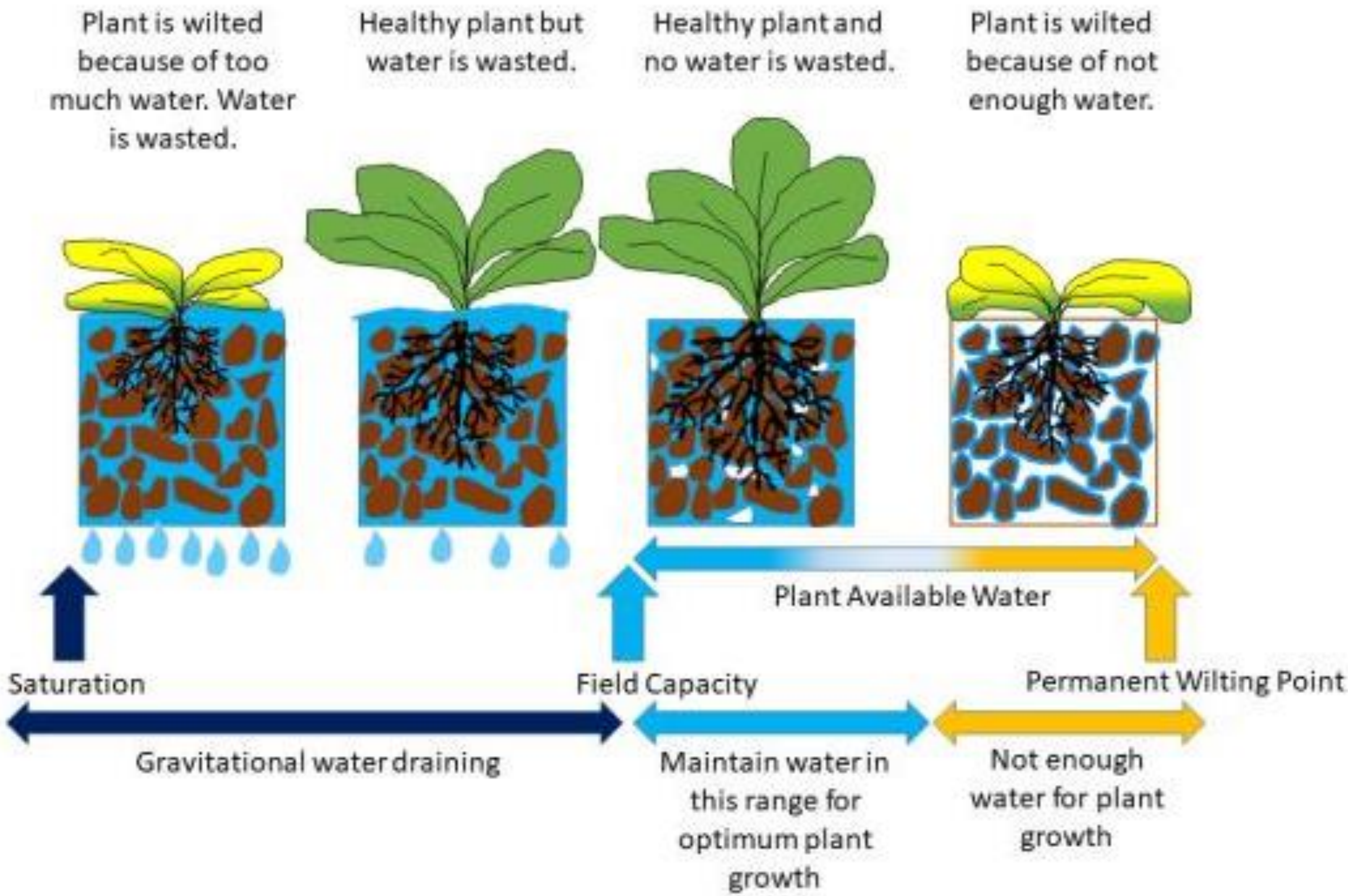
An ecosystem behaves like a bucket that is filled by precipitation and emptied by evapotranspiration and runoff

Lakes are filled by precipitation and inflow; water leaves by evaporation and outflow

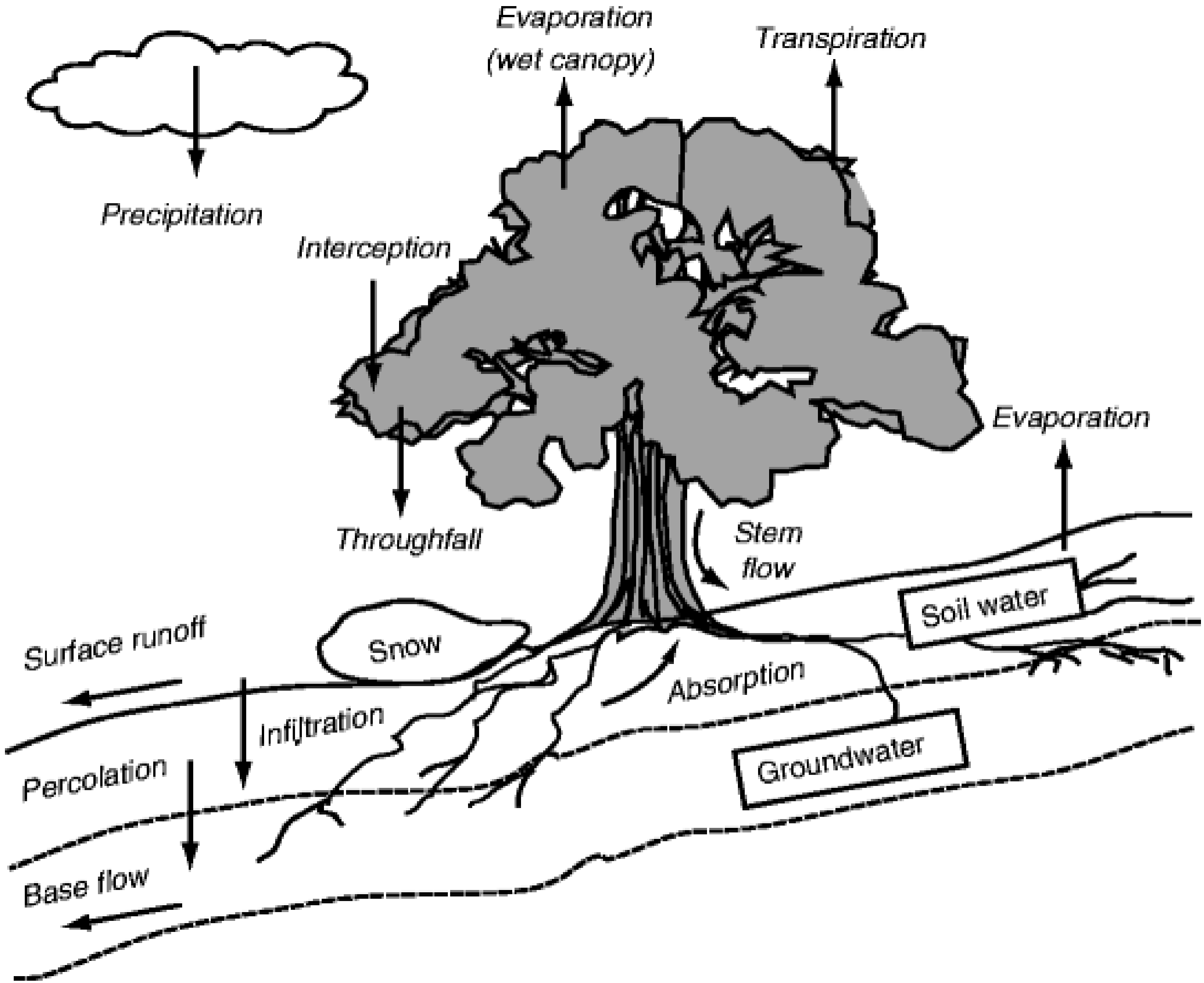


In terrestrial ecosystems, water accumulates in the ecosystem until the <u>water-holding capacity of soils</u> is exceeded…. excess water drains to groundwater <u>or</u> runs over the ground surface




Plant is wilted because of too much water. Water is wasted.
Healthy plant but water is wasted.
Healthy plant and no water is wasted.
Plant is wilted because of not enough water.
Plant Available Water
Saturation
Field Capacity
Permanent Wilting Point
Gravitational water draining
Maintain water in this range for optimum plant growth
Not enough water for plant growth

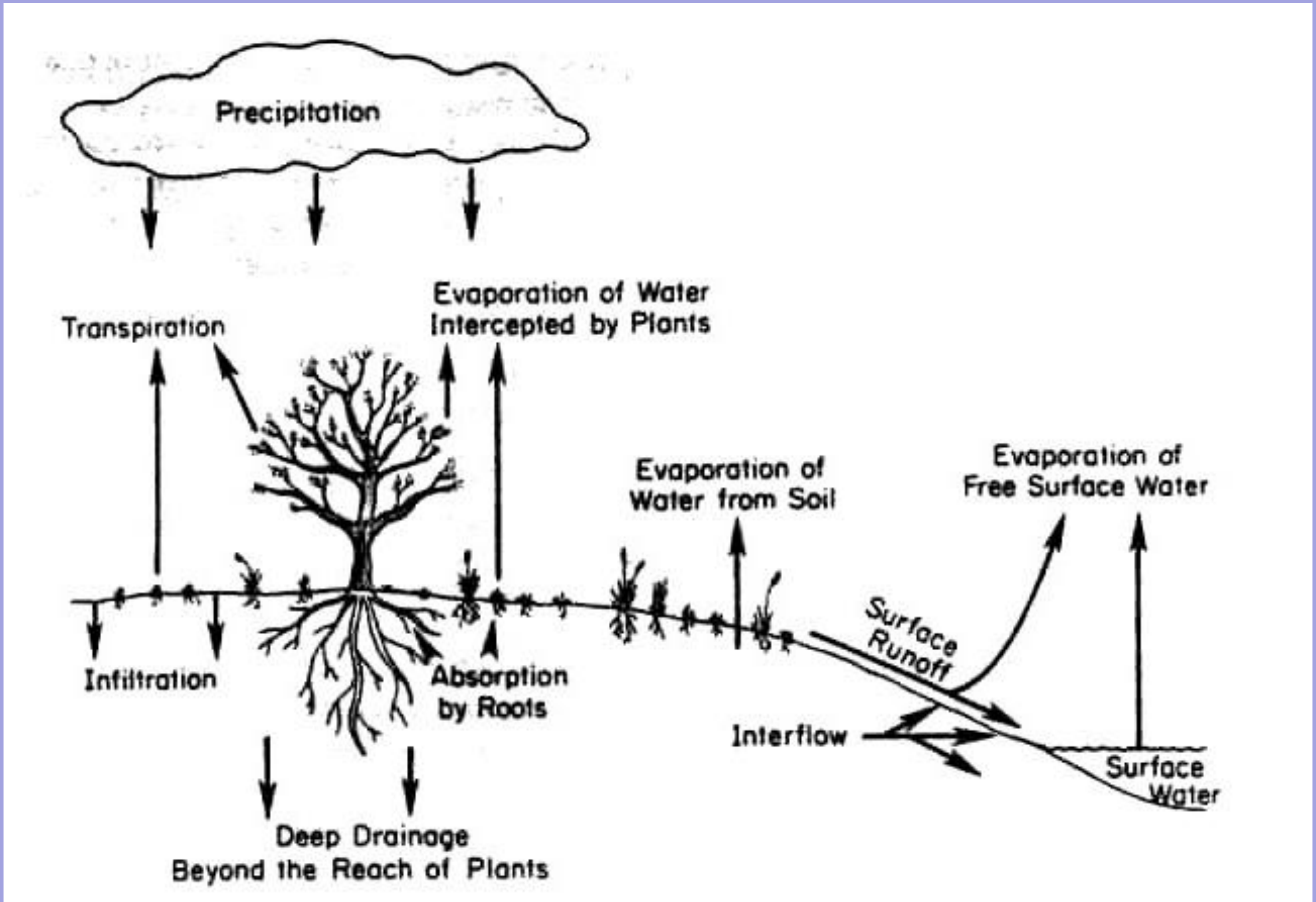
Water <u>losses from the ecosystem</u> can move <u>laterally</u> to other ecosystems



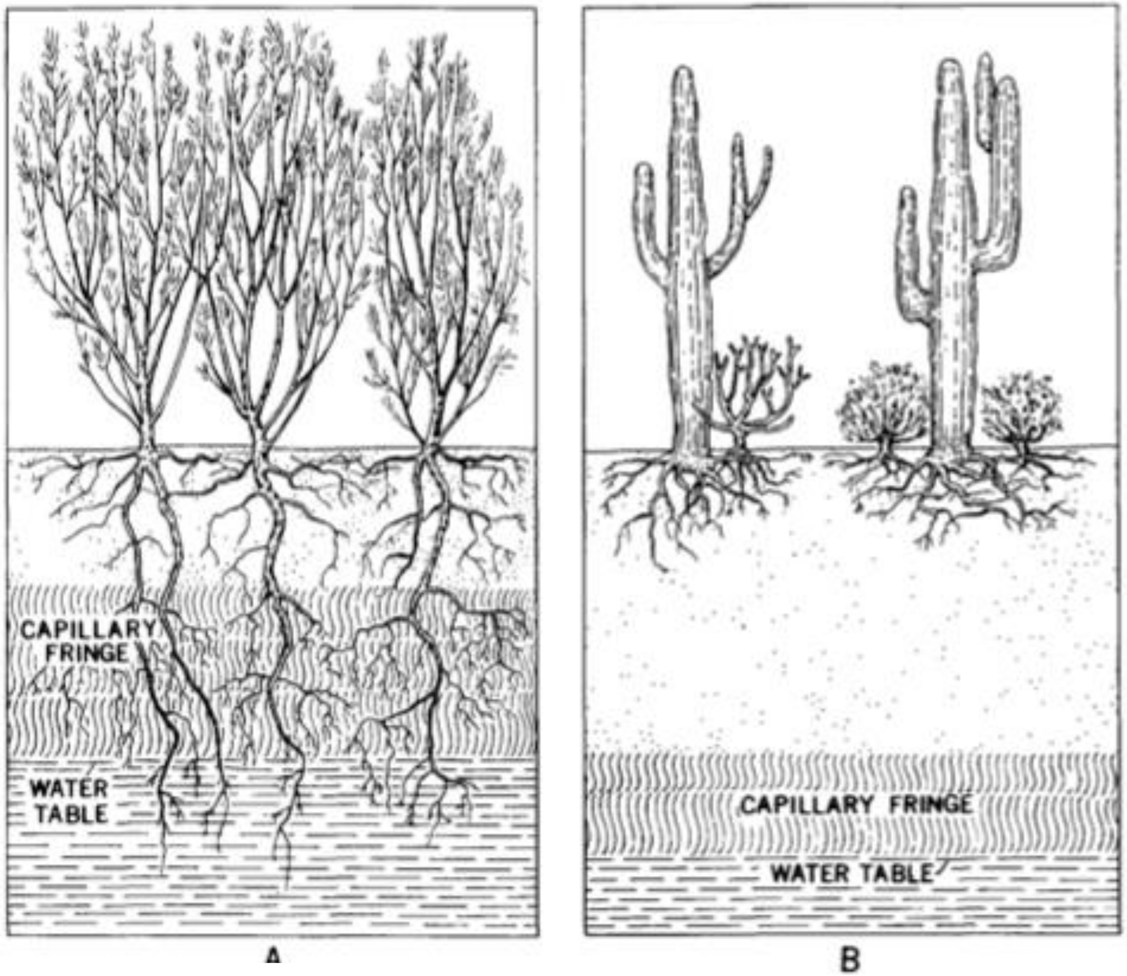
Major water fluxes in a terrestrial ecosystem

Water Inputs to Ecosystems

Precipitation is the major water input to terrestrial ecosystems



In desert communities of **phreatophytes** (deep-rooted plants that tap groundwater) **transpiration may exceed precipitation!!**



Phreatophytes

Xerophytes

EX: Creosote (*Larrea tridentata*)

In ecosystems with frequent fog, canopy interception of fog increases the water inputs

(cloud droplets that might not otherwise precipitate are deposited on leaf - surfaces and drip from the canopy to the soil)

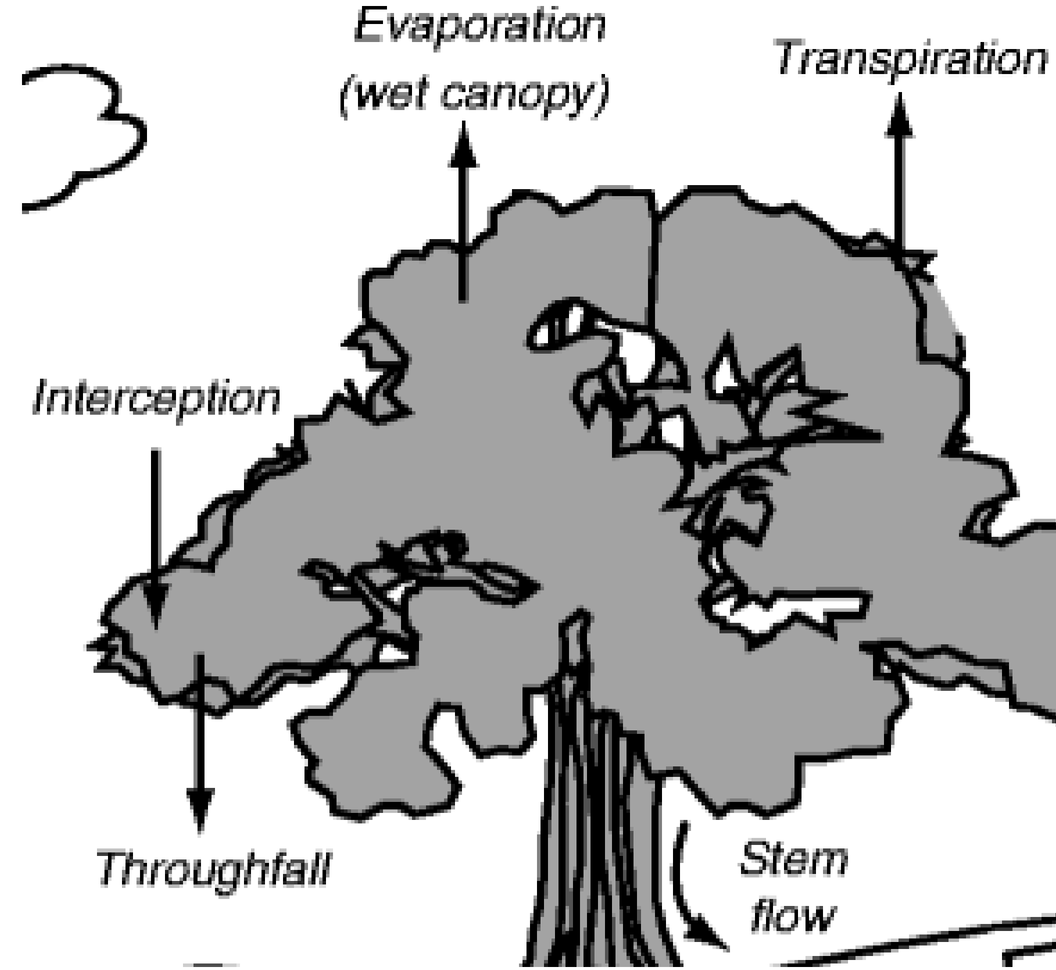
Coastal redwood trees of California depend on fog-derived water inputs during summer, when precipitation is low, but fog occurs frequently

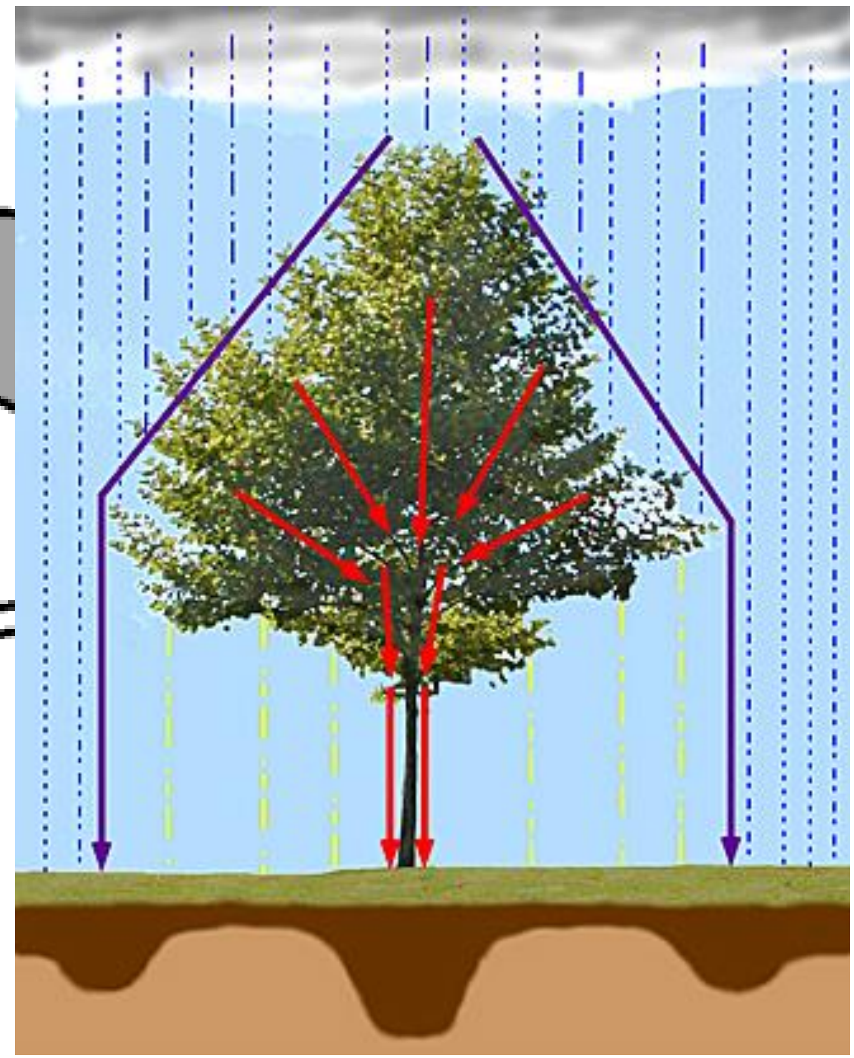
Water Movement Within Ecosystems

Water Movement from the Canopy to the Soil

In closed-canopy forests, a substantial proportion of incoming precipitation lands in the canopy:

- evaporated back to the atmosphere,
- absorbed by the leaves,
- drip to the ground (throughfall), or
- run down stems to the ground (stemflow)



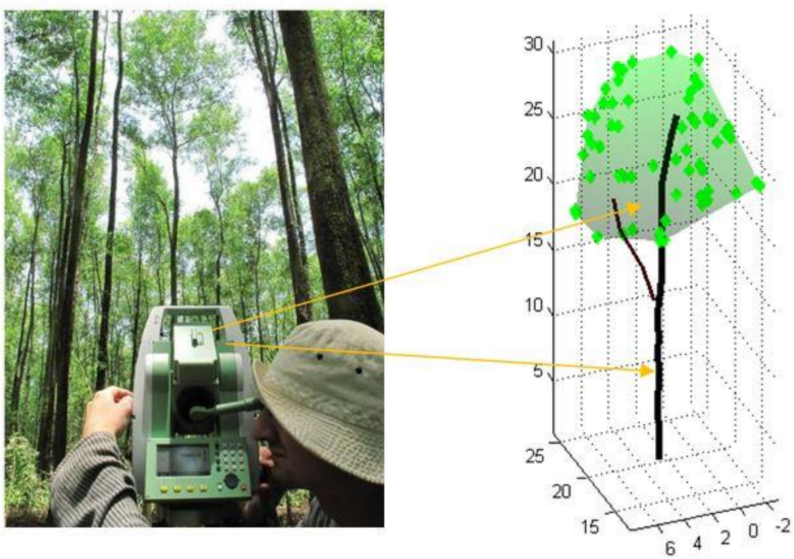


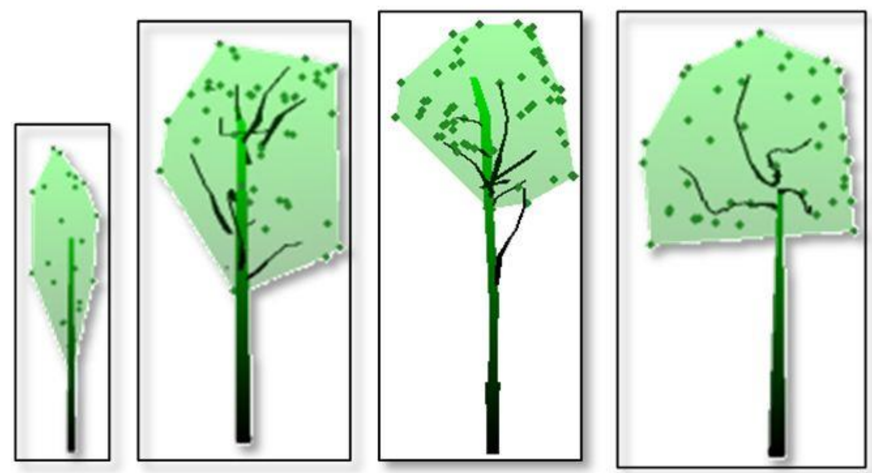
Throughfall delivers <u>most</u> of the water from the canopy to the soil

Canopy interception is the fraction of precipitation that does <u>not reach the ground</u> (approx. 10–20% for closed-canopy ecosystems) – **significant during light rain or snow**

Epiphytes **depend <u>entirely</u> on <u>canopy interception</u> for their water supply and <u>increase canopy interception</u>**

The capacity of the canopy to intercept and store water differs among ecosystems… depends on canopy surface area, particularly the surface area of leaves





The bark texture and architecture of stems and trunks influences the amount and direction of stemflow

smooth bark = greater stem flow (about 12% of precipitation)

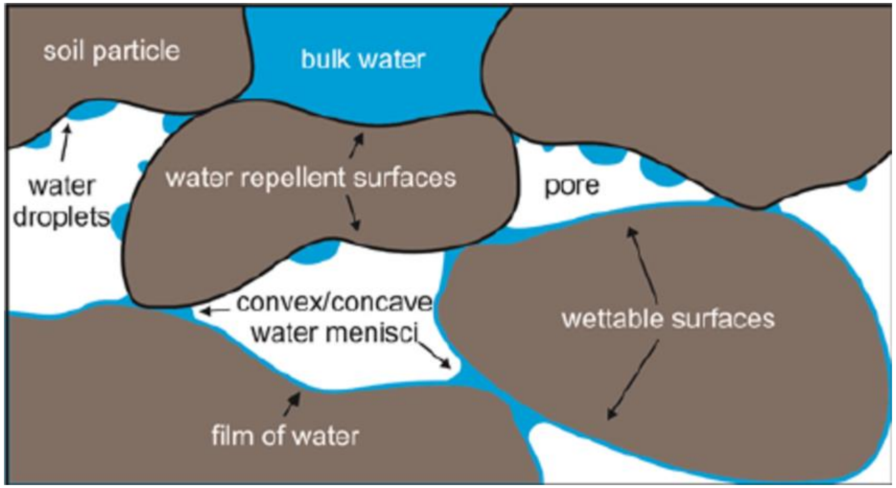
rough bark = lower stem flow (about 2% of precipitation)

In grasslands, interception is often 30–40% of precipitation

For small precipitation events, 70% of the precipitation can be intercepted by a dry grassland canopy

Water Storage and Movement in the Soil

Soil water is stored primarily in thin water films on the surfaces of soil particles



The water-holding capacity of a soil depends on its <u>total pore volume</u> and the <u>surface area of the surrounding particles</u>

Water enters the soil

⬇

Moves downward under the force of gravity

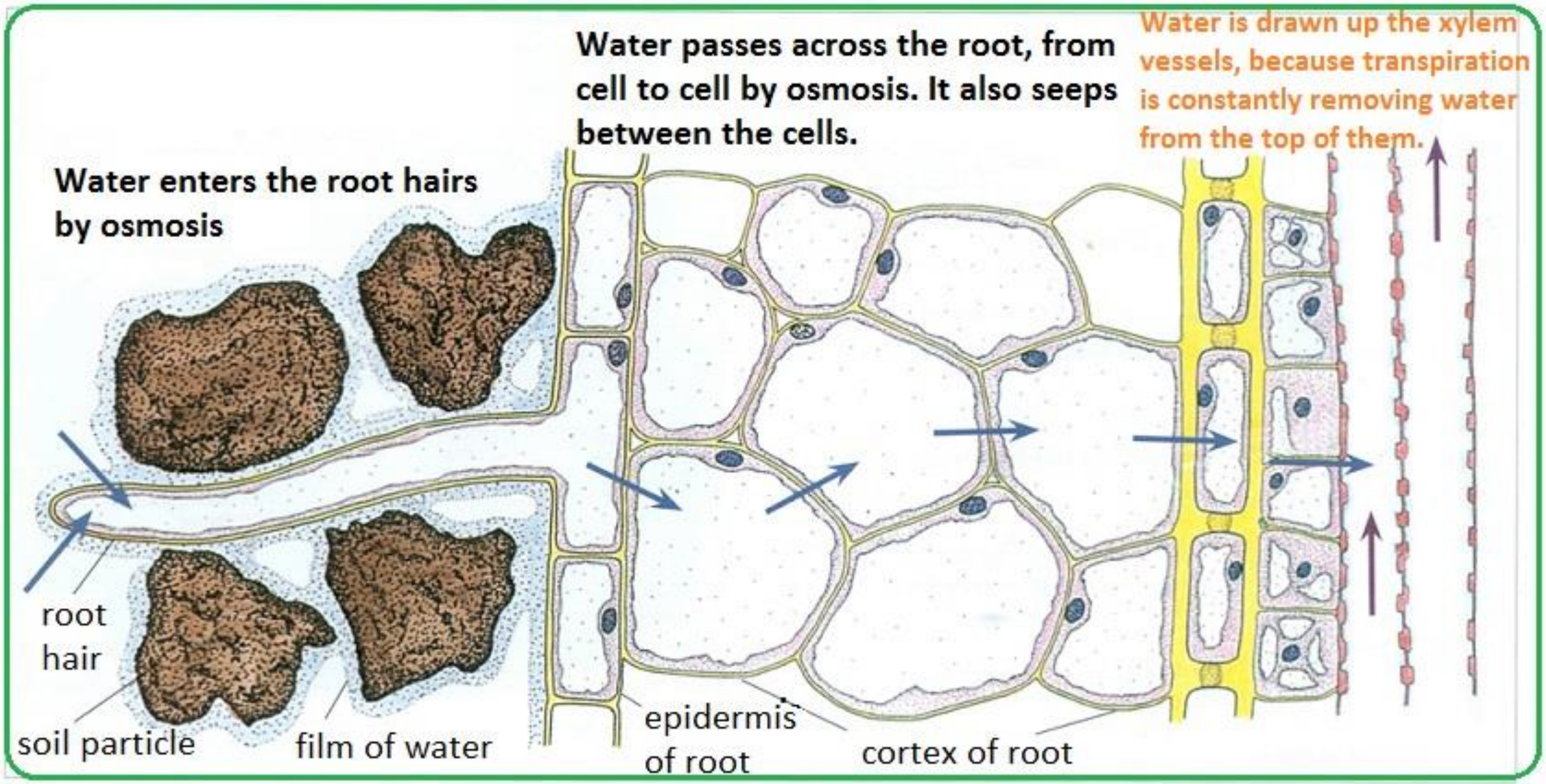
⬇

Stops when matric forces (water held by soil particles and spaces) exceed the gravitational potential

Water <u>not retained by matric forces</u> drains through the soil to groundwater → then to streams and lakes

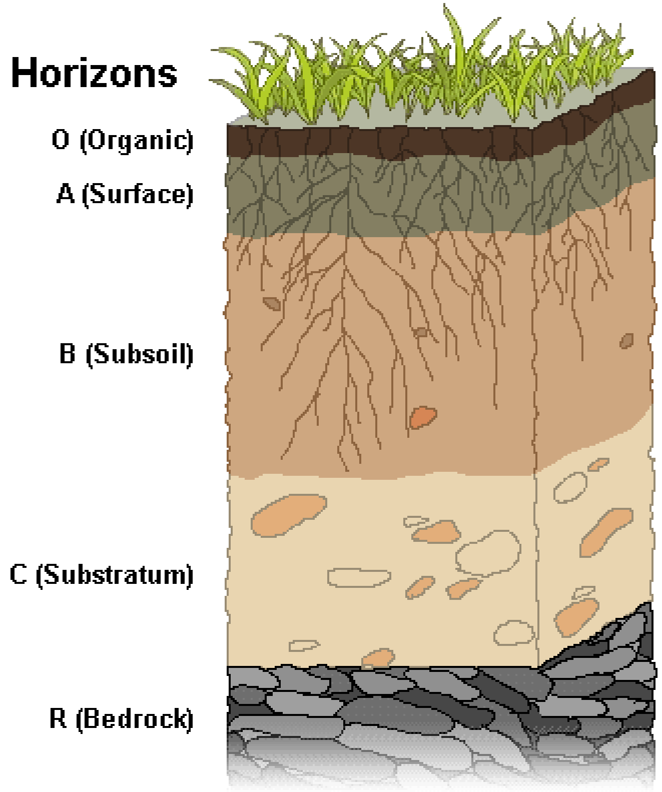
Movement of Water from Soil to Roots

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



Rooting depth reflects a compromise between water and nutrient availability

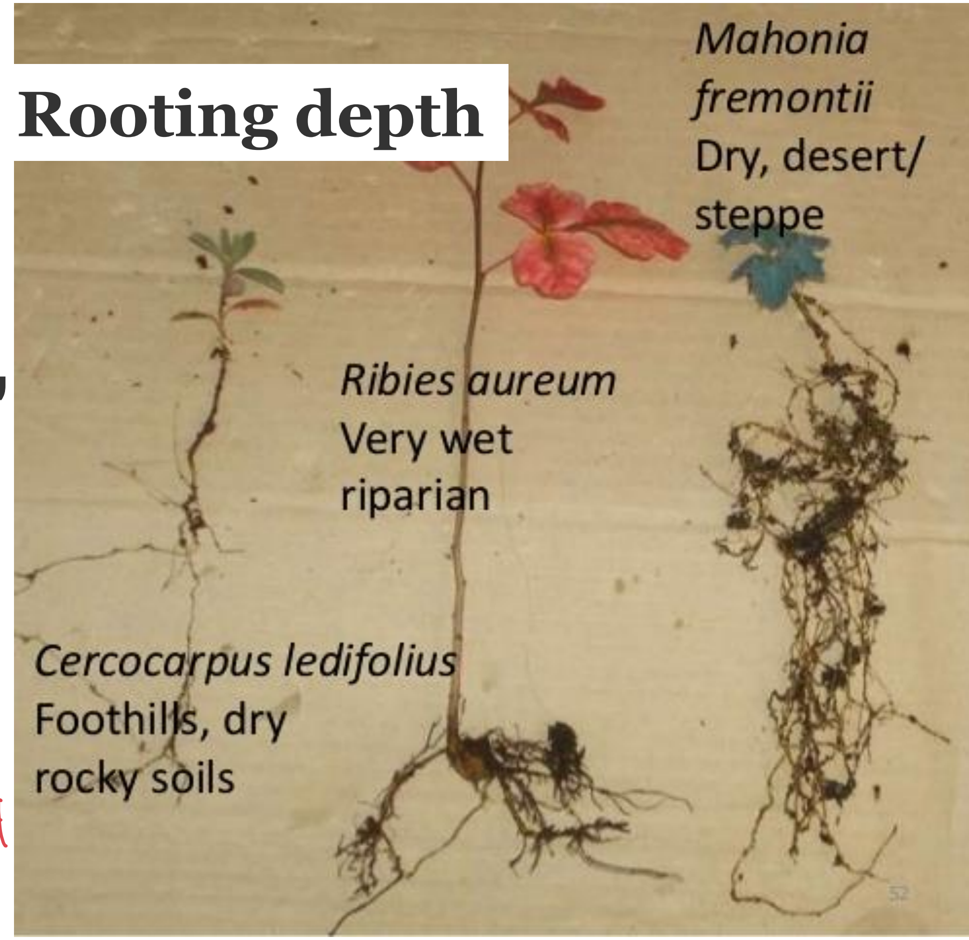
Most plant roots are in the upper soil horizons where nutrients are most abundant / available



Short-lived herbaceous plants are generally more shallow-rooted than long-lived shrubs and trees; thus, depend more on surface moisture

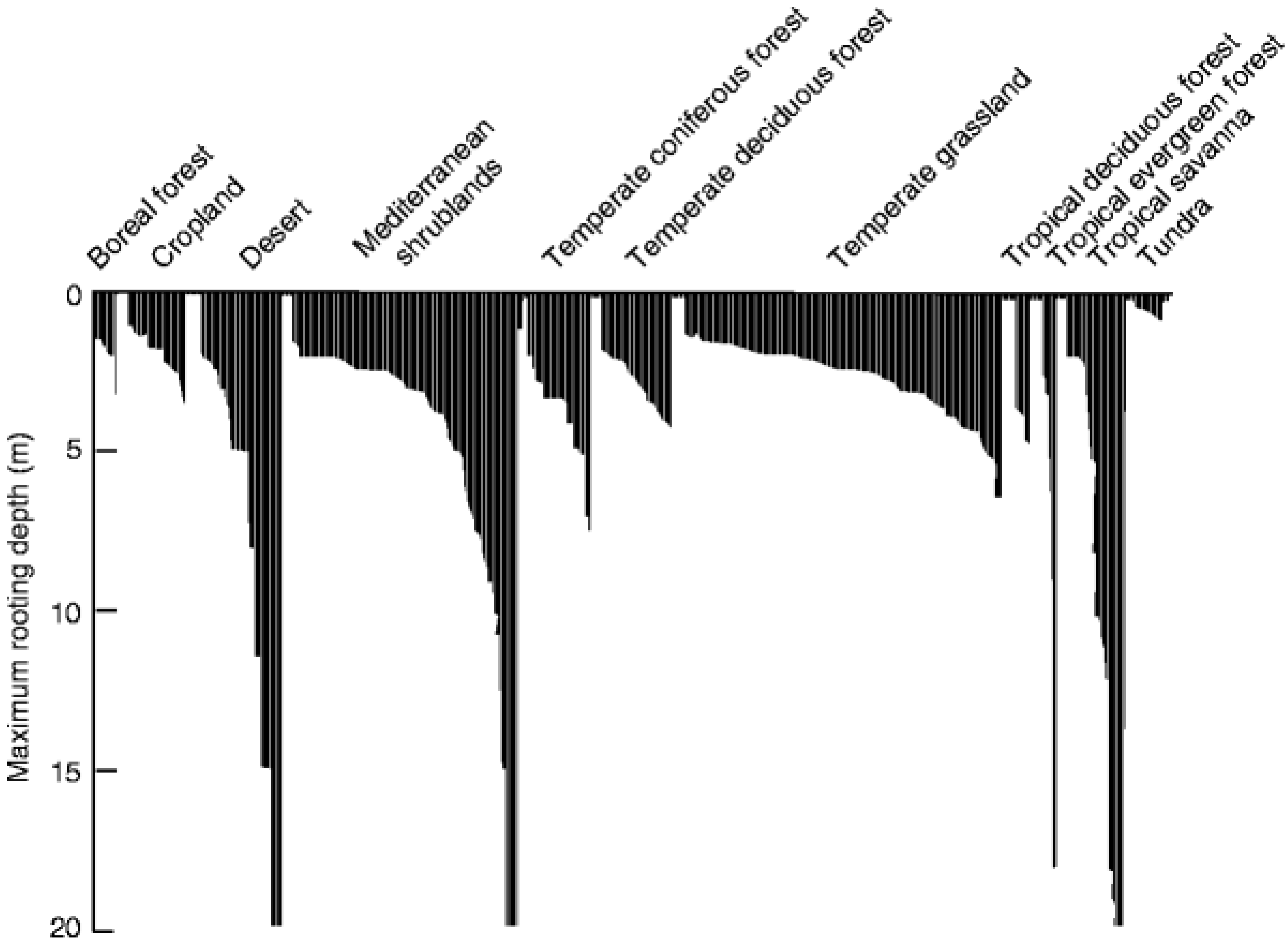
In arid ecosystems, surface evaporation and transpiration dry out the surface soils….. Thus, deserts, arid shrublands, and tropical savannas have many <u>deep-rooted species</u>

↳ ecosystems w/ high evaporative potential breed plants w/ low-reaching roots that take up more water from far below ground



Phreatophytes are an extreme example of deep-rooted plants… Roots extend to the water table, often a depth of tens of meters

Most wet ecosystems have dry seasons, with some deep-rooted tropical trees that tap water from depths of more than 8 m

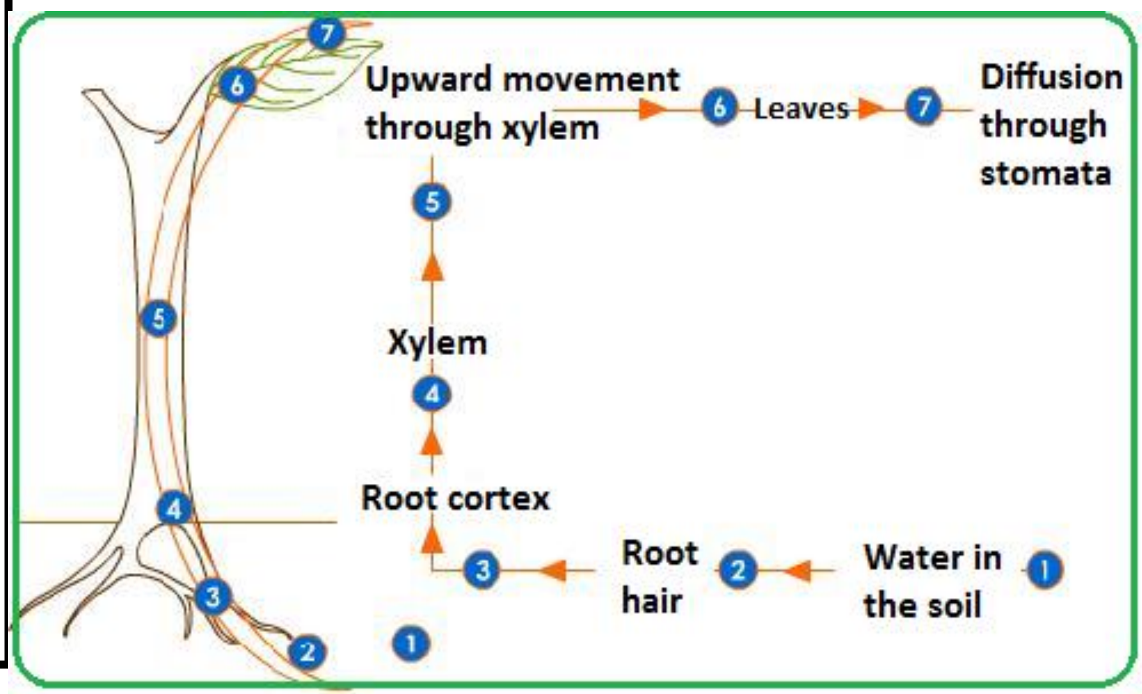


Maximum rooting depths of selected species in the major biome types of the world. Species in each biome differ widely in rooting depth.

Movement of Water Through Plants

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

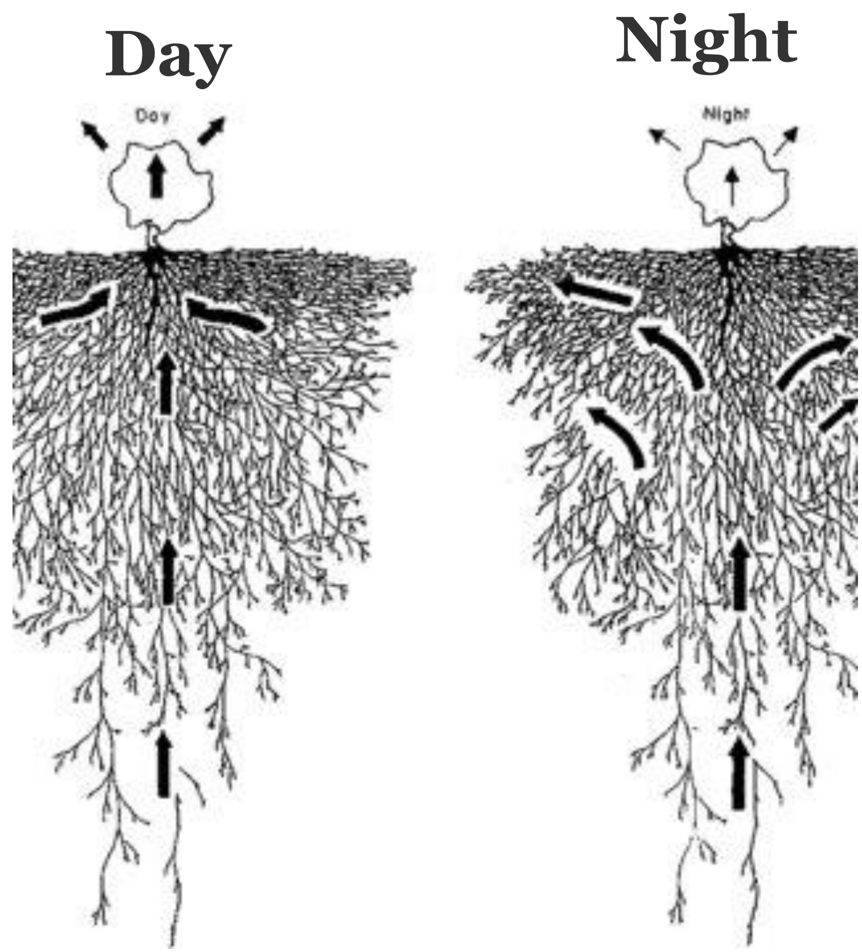
Water transport takes place in a **soil–plant–atmosphere continuum** that is interconnected by a continuous film of liquid water



→ water in soil → plant → leaf → atmosphere → soil

At **night**, when stomata close and transpiration ceases, **plant-water potential equilibrates** with the water potential of deep soils

The gradient in water potential drives **hydraulic lift**, the vertical movement of water from deep soils ***through roots*** to shallow soils along a water-potential gradient

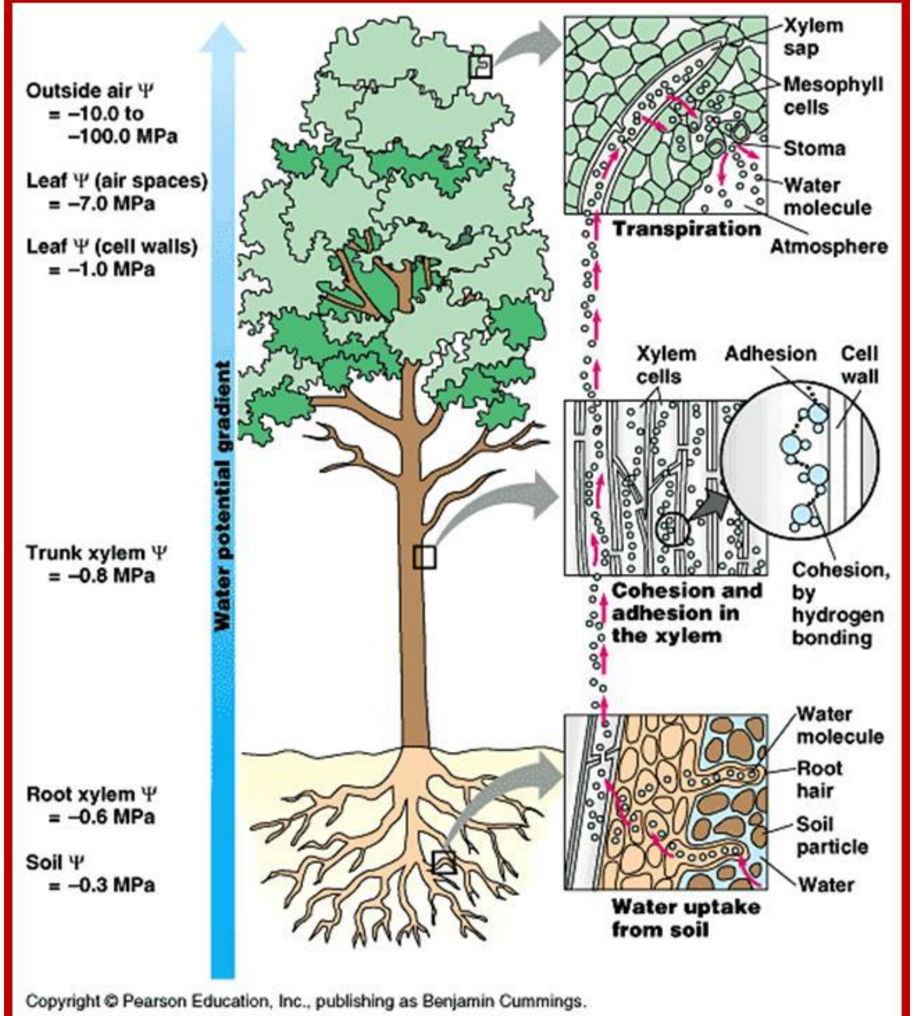


In the **Great Basin deserts** of western North America, **20–50% of the water used by shallow-rooted grasses** comes from water that is **hydraulically lifted** by deep-rooted sagebrush shrubs

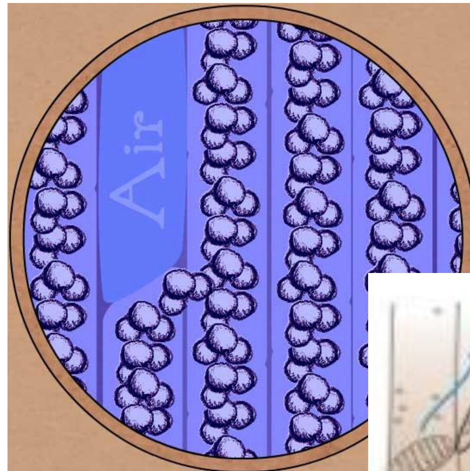
Stems

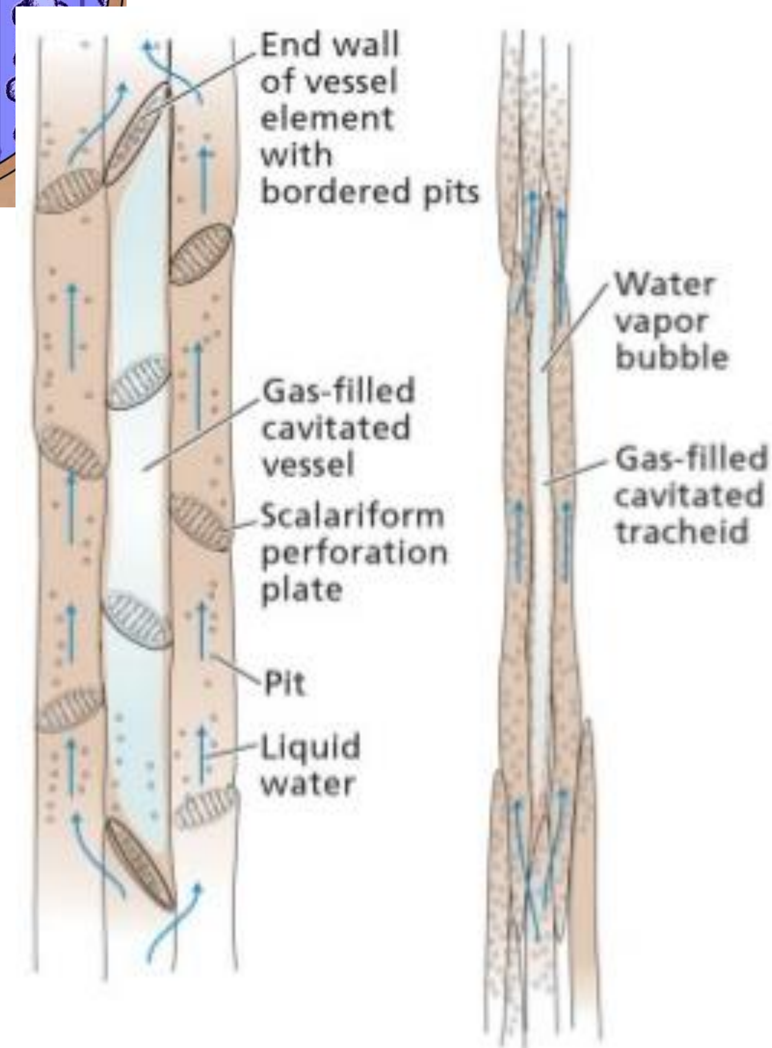
Water moves through stems to replace water lost by transpiring leaves

Water is "sucked up" by capillary action through **xylem cells** in response to the **water-potential gradient** created by **transpirational water loss**



There is a tradeoff between hydraulic conductivity of xylem vessels and their risk of cavitation, i.e., the breakage of water columns under tension (air bubbles = embolism)





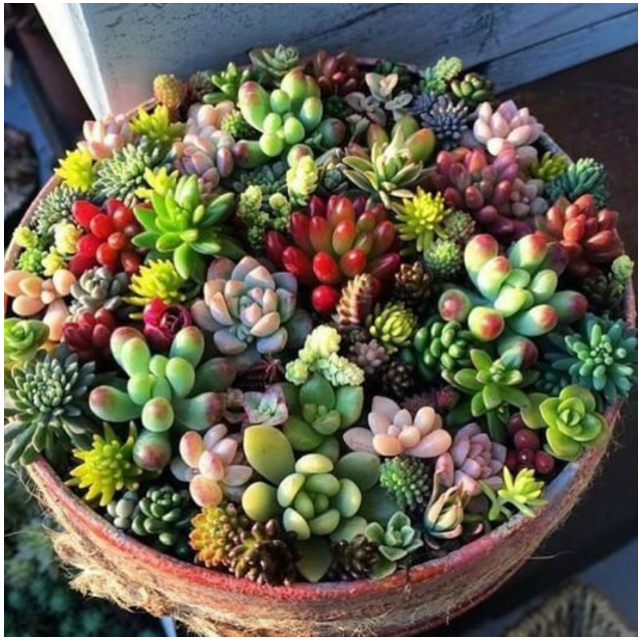
Herbaceous plants in moist environments function close to the water potential where cavitation occurs…. Energy-saving strategy

Plants from dry environments produce stems that resist cavitation at much lower water potentials than they commonly experience… Water-saving strategy

Water storage in stems buffers the plant from imbalances in water supply and demand

Water stored in **sapwood** is equivalent to as much as 5–10 days of transpiration

Water stored by **desert succulents** may allow transpiration to continue for several weeks after water absorption from the soil has ceased



Leaves

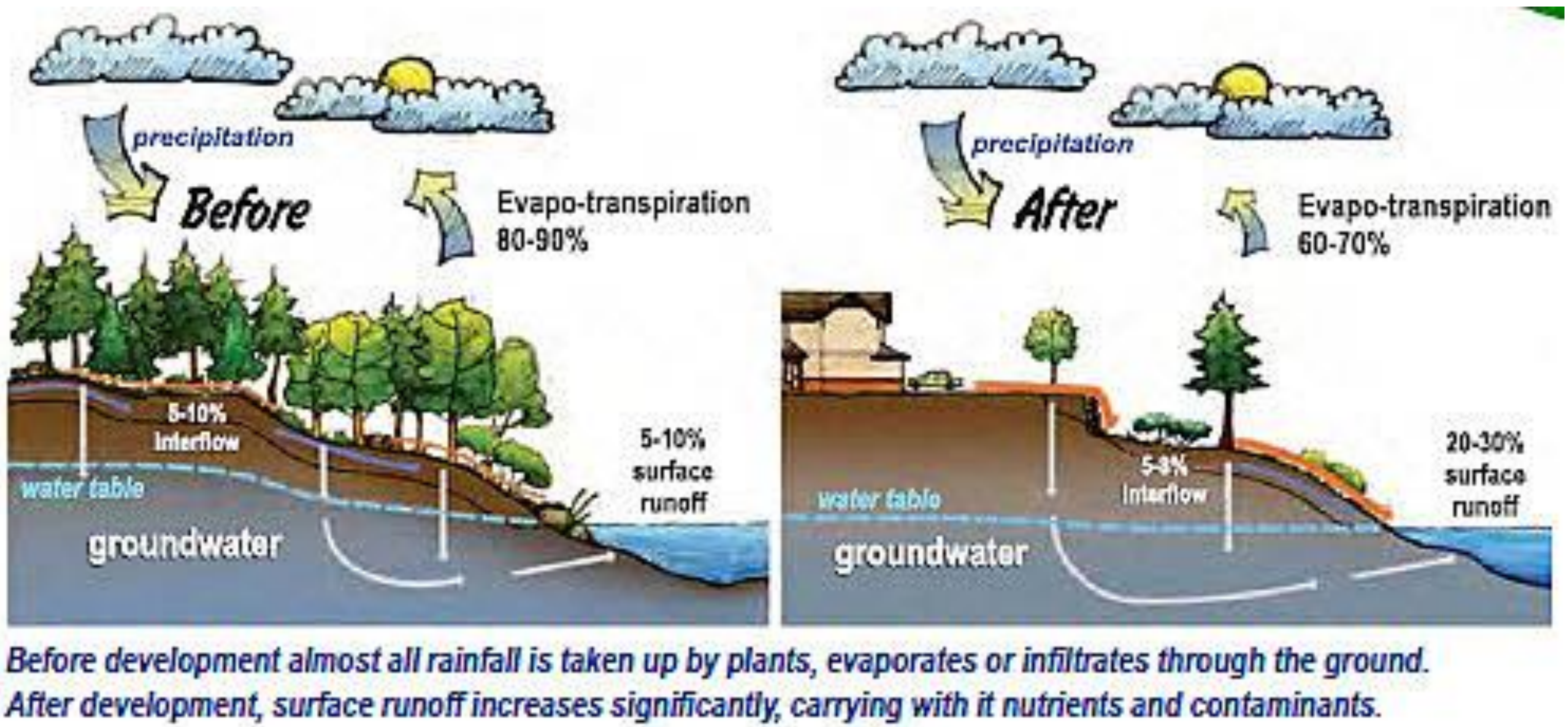
Water loss from leaves is controlled by the evaporative potential of the air, the water supply from the soil, and the stomatal conductance of leaves

Plants adjust the size of stomatal openings to regulate the loss of water from leaves

It's all a balancing act

Water Losses from Ecosystems

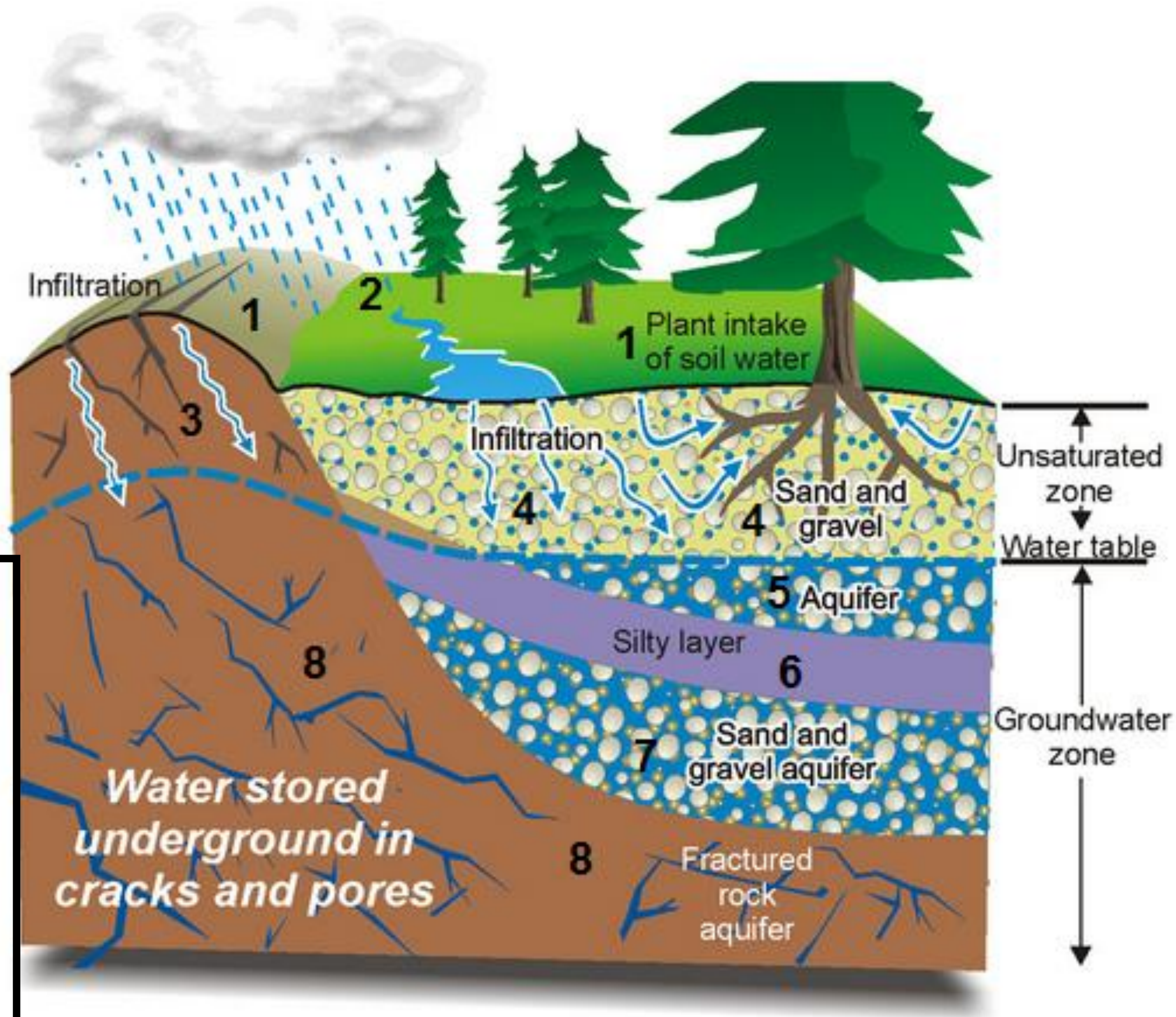
The water loss from ecosystems is by evapotranspiration, runoff, and changes in storage



Changes in Storage

Water **inputs that exceed outputs** is stored in soil and groundwater

When ET exceeds precipitation, stored water allows ET to continue



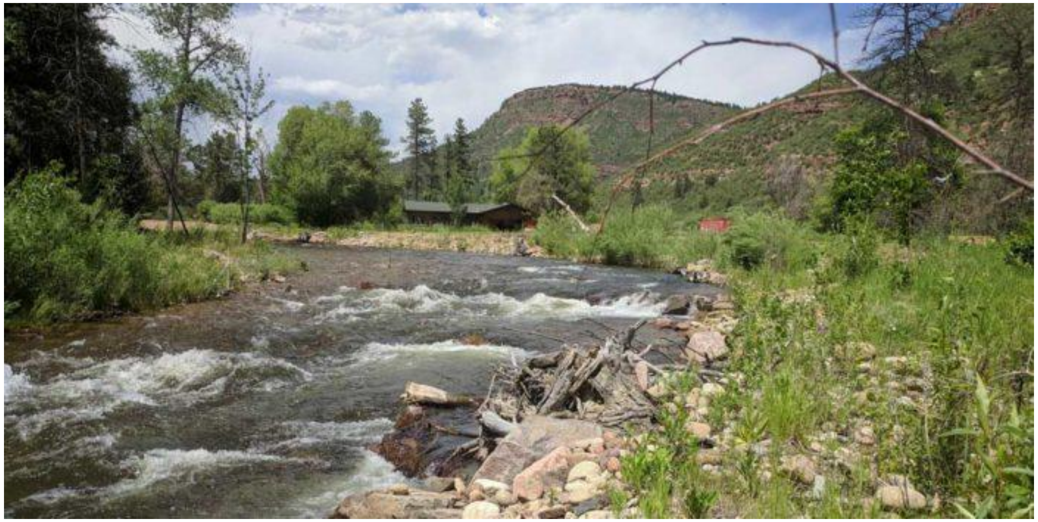
Runoff (Discharge)

Runoff from terrestrial ecosystems is the difference between:

- **precipitation inputs**,
- **changes in storage**, and
- **losses to evapotranspiration**

Average runoff depends primarily on precipitation and ET (long-term changes in storage are usually negligible)

When soils are dry, the recharge of soil moisture prevents large increases in **streamflow** after a rain



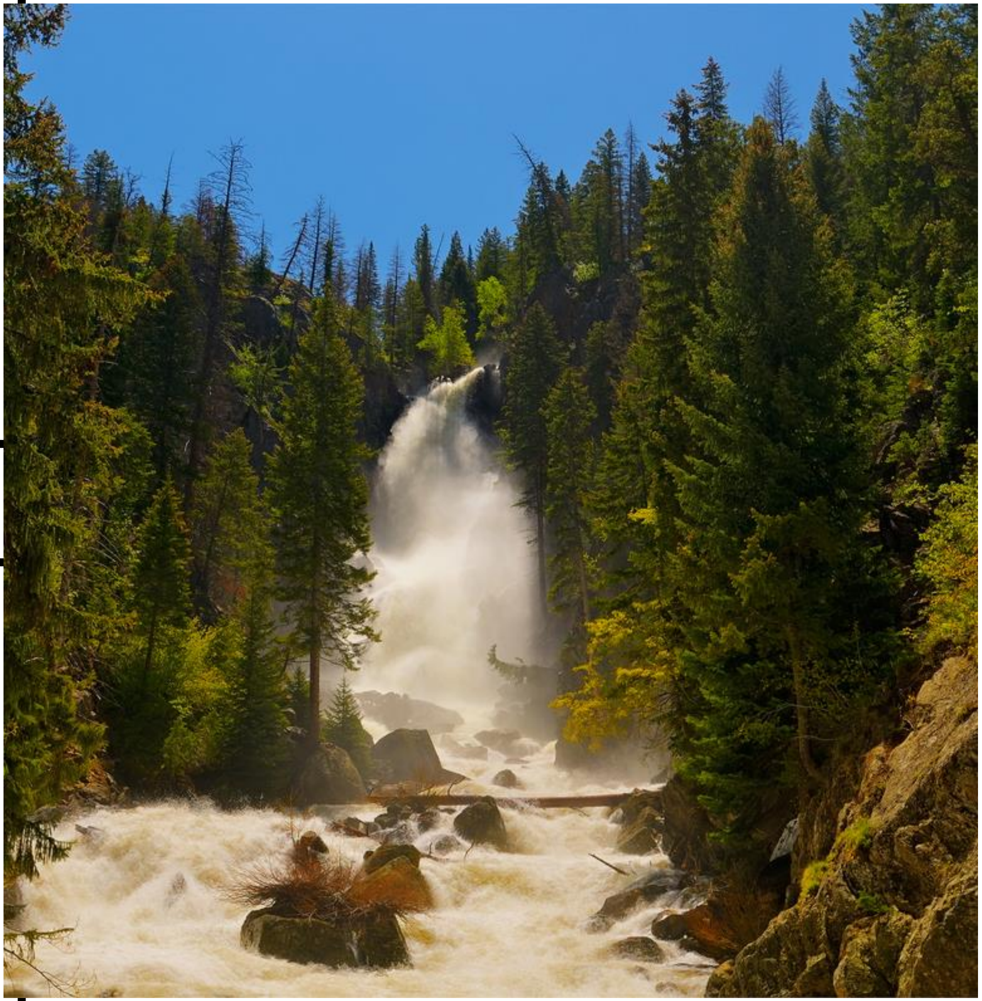
South St. Vrain, Lyons, CO Sept. 2018

Streamflow may increase rapidly after a storm when **soils are wet or shallow**

South St. Vrain, Lyons, CO Sept. 2013

In ecosystems that develop a snowpack in winter, precipitation inputs are stored in the ecosystem during winter

During spring snowmelt, this stored water recharges aquifers or moves directly to streams, causing large spring runoff events



Fish Creek Falls, near Steamboat Springs, CO

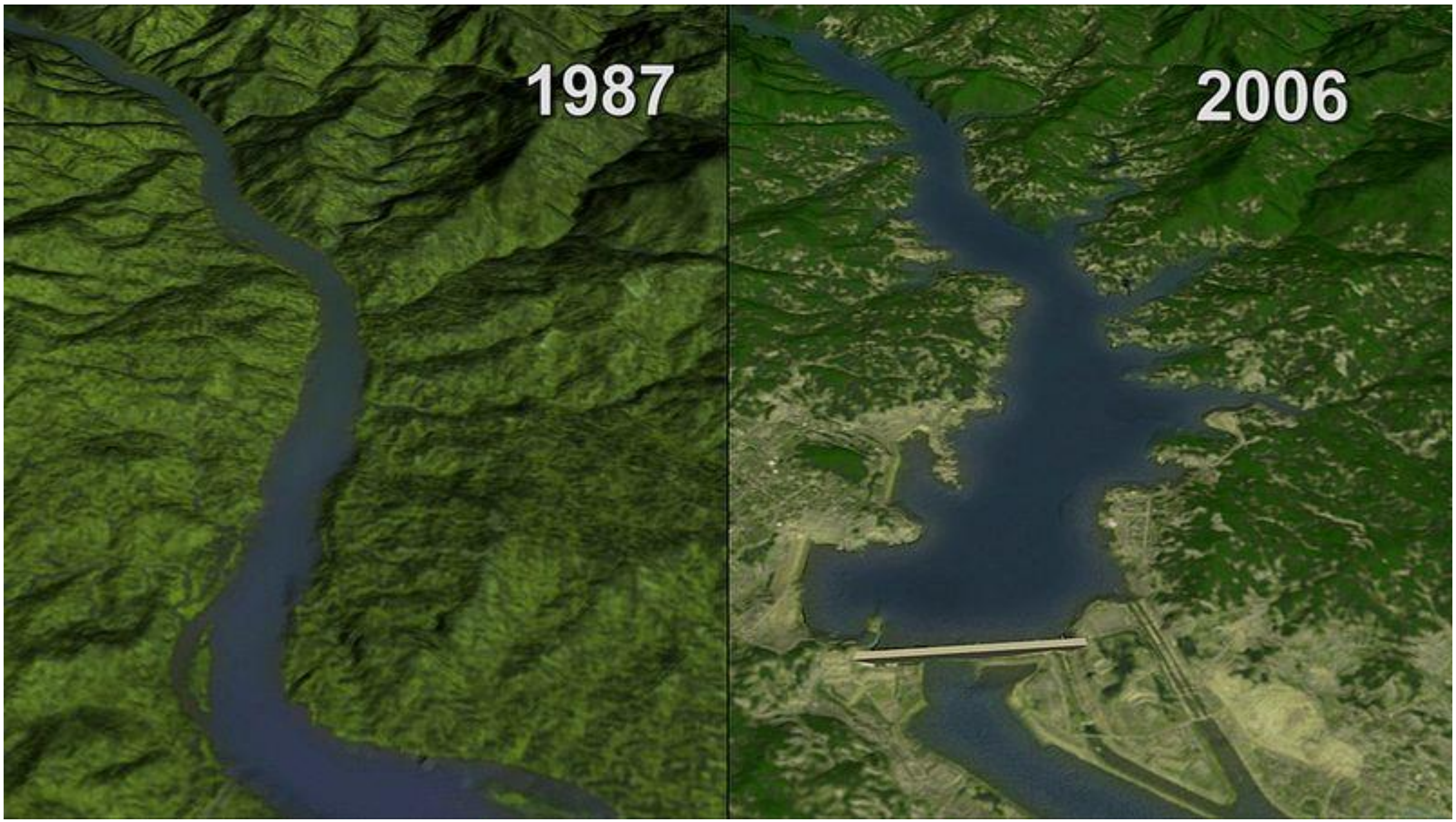
When **climate warming changes snowfall to winter rains**, this increases winter runoff and reduces the spring snowmelt pulse and summer runoff, which are **important water sources for many cities**

River flow integrates the precipitation, evapotranspiration, and changes in storage throughout the drainage basin

Yampa River, CO-UT

In undammed rivers, high flow events may lead to predictable patterns of bank erosion and deposition…. river biota are adapted to a natural flow regime

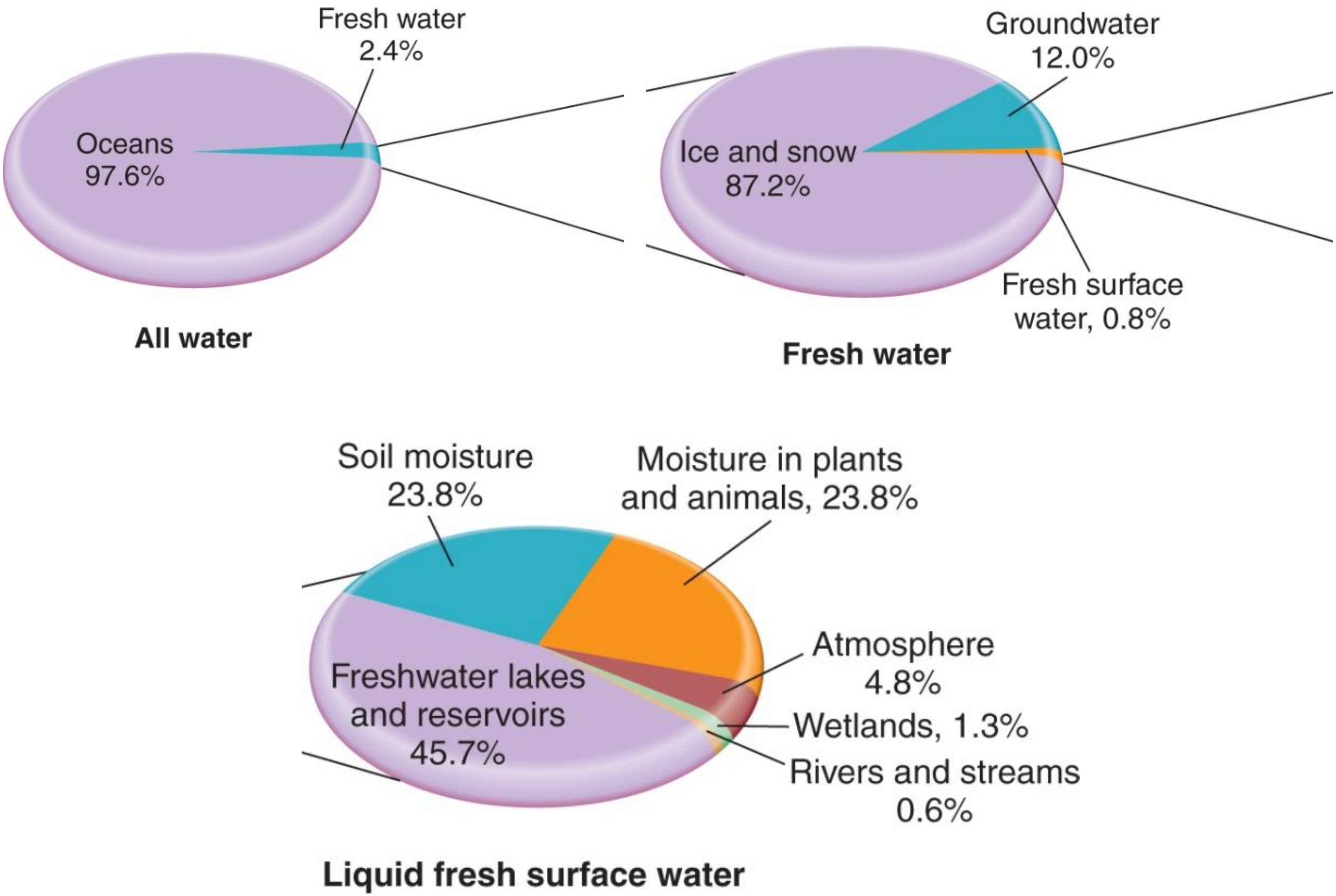
Dams that reduce the intensity or seasonality of high-flow events dramatically alter the natural disturbance regime and functioning of freshwater ecosystems



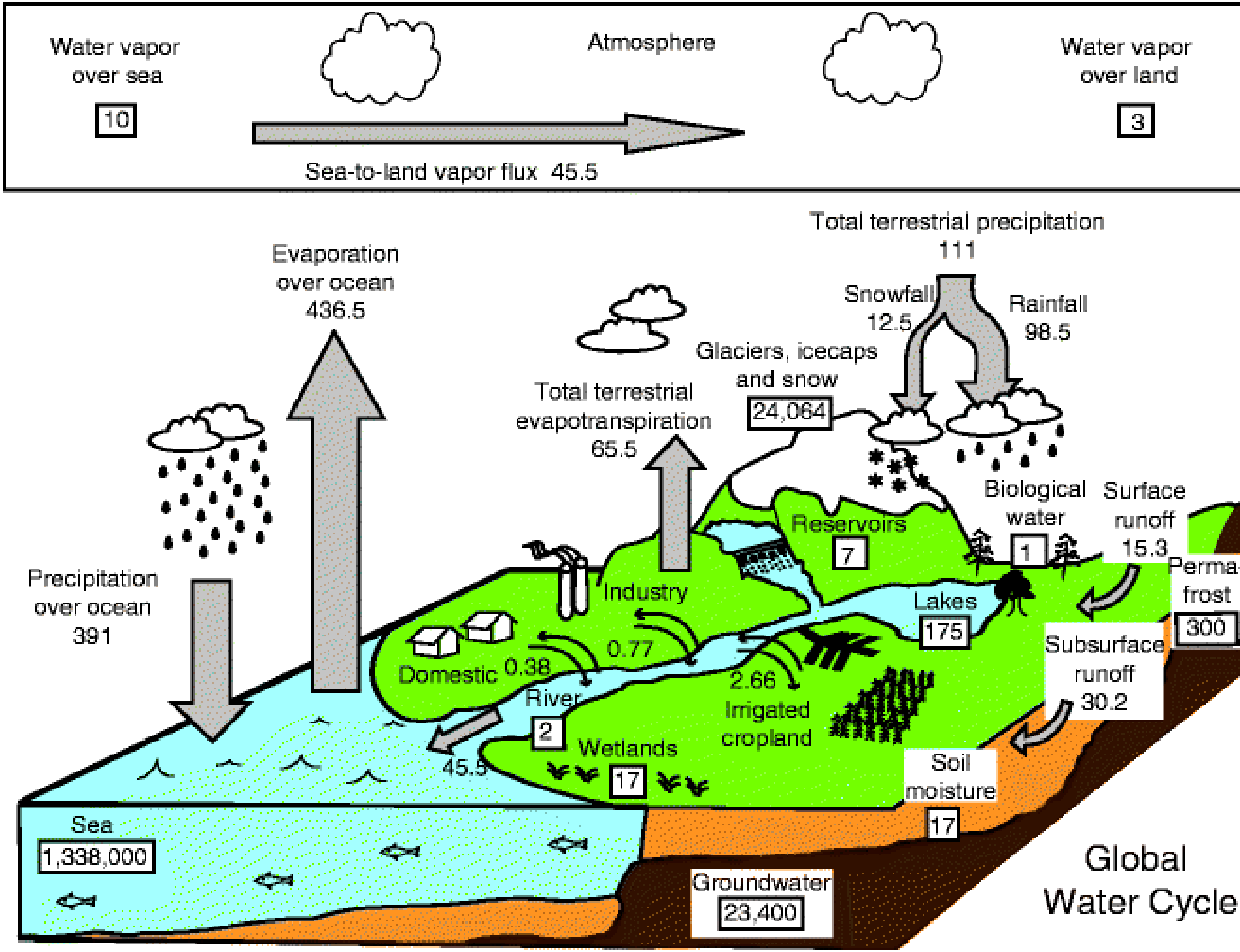
Three Gorges Dam, China

Human Impacts on the Global Water Cycle

Where is Earth's water?



Fresh water
2.4%
Oceans
97.6%
All water
Groundwater
12.0%
Ice and snow
87.2%
Fresh surface
water, 0.8%
Fresh water
Soil moisture
23.8%
Moisture in plants
and animals, 23.8%
Freshwater lakes
and reservoirs
45.7%
Atmosphere
4.8%
Wetlands, 1.3%
Rivers and streams
0.6%
Liquid fresh surface water



Water vapor over sea
10
Atmosphere
Water vapor over land
3
Sea-to-land vapor flux 45.5
Total terrestrial precipitation 111
Evaporation over ocean 436.5
Snowfall 12.5
Rainfall 98.5
Glaciers, icecaps and snow
24,064
Total terrestrial evapotranspiration 65.5
Precipitation over ocean 391
Biological water
1
Surface runoff 15.3
Reservoirs
7
Perma-frost
300
Industry
Lakes
175
0.77
Domestic 0.38
Subsurface runoff 30.2
River
2
2.66
Irrigated cropland
Wetlands
17
45.5
Soil moisture
17
Sea
1,338,000
Groundwater
23,400
Global Water Cycle

Anthropogenic climate warming has accelerated the global water cycle:

- ↑ **evapotranspiration**
- ↑ **precipitation**

Note: Warm air holds more moisture….

THUS: Wet areas may become wetter….

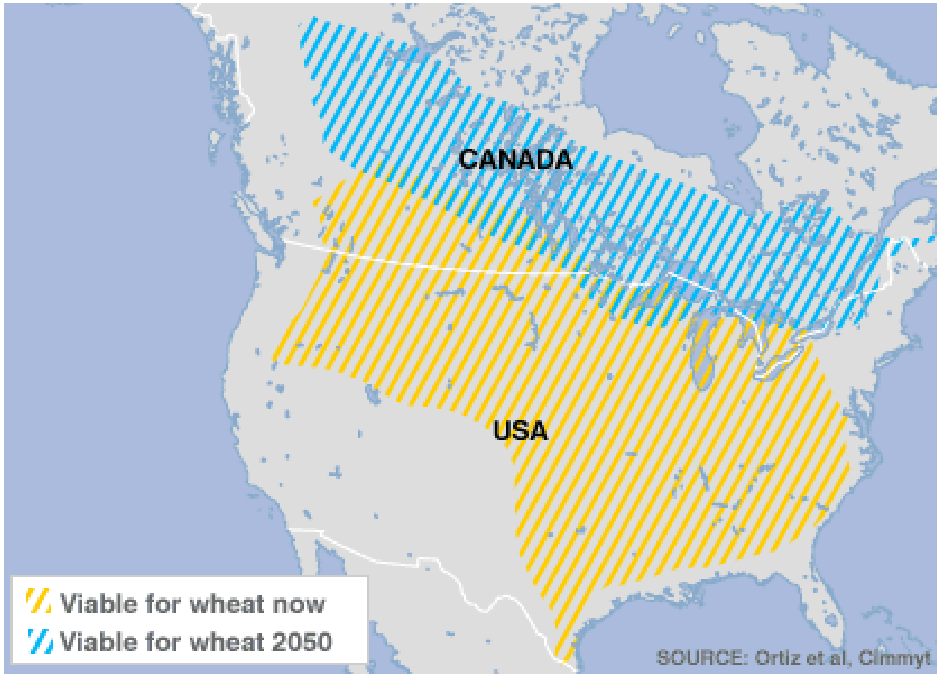
BUT: Dry areas may become drier…

Anthropogenic land use changes alter the water cycle…

Ex: Tropical rainforest → pasture

Current agricultural areas may be prone to future drought

Grain-producing regions may shift toward the poles

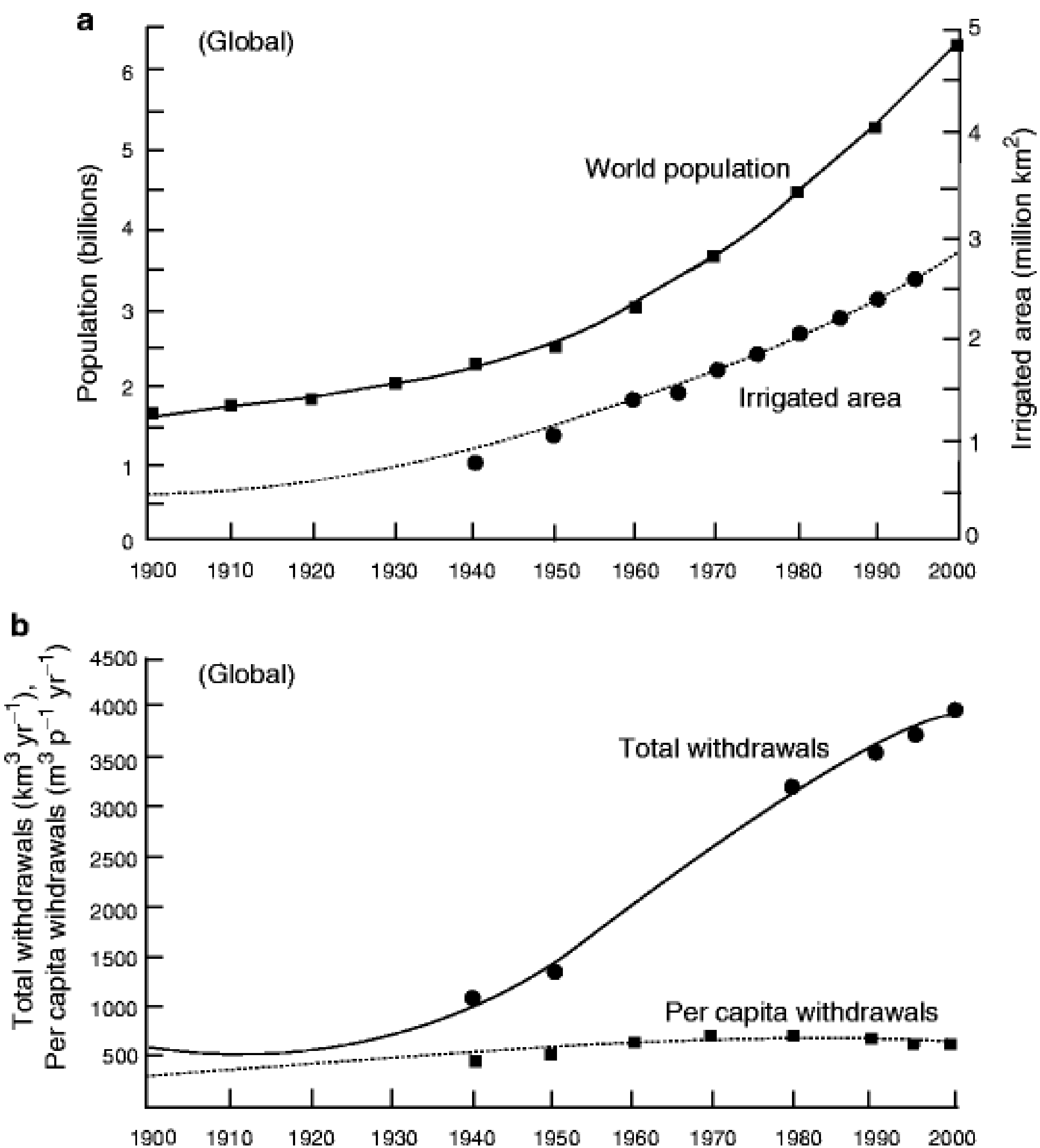


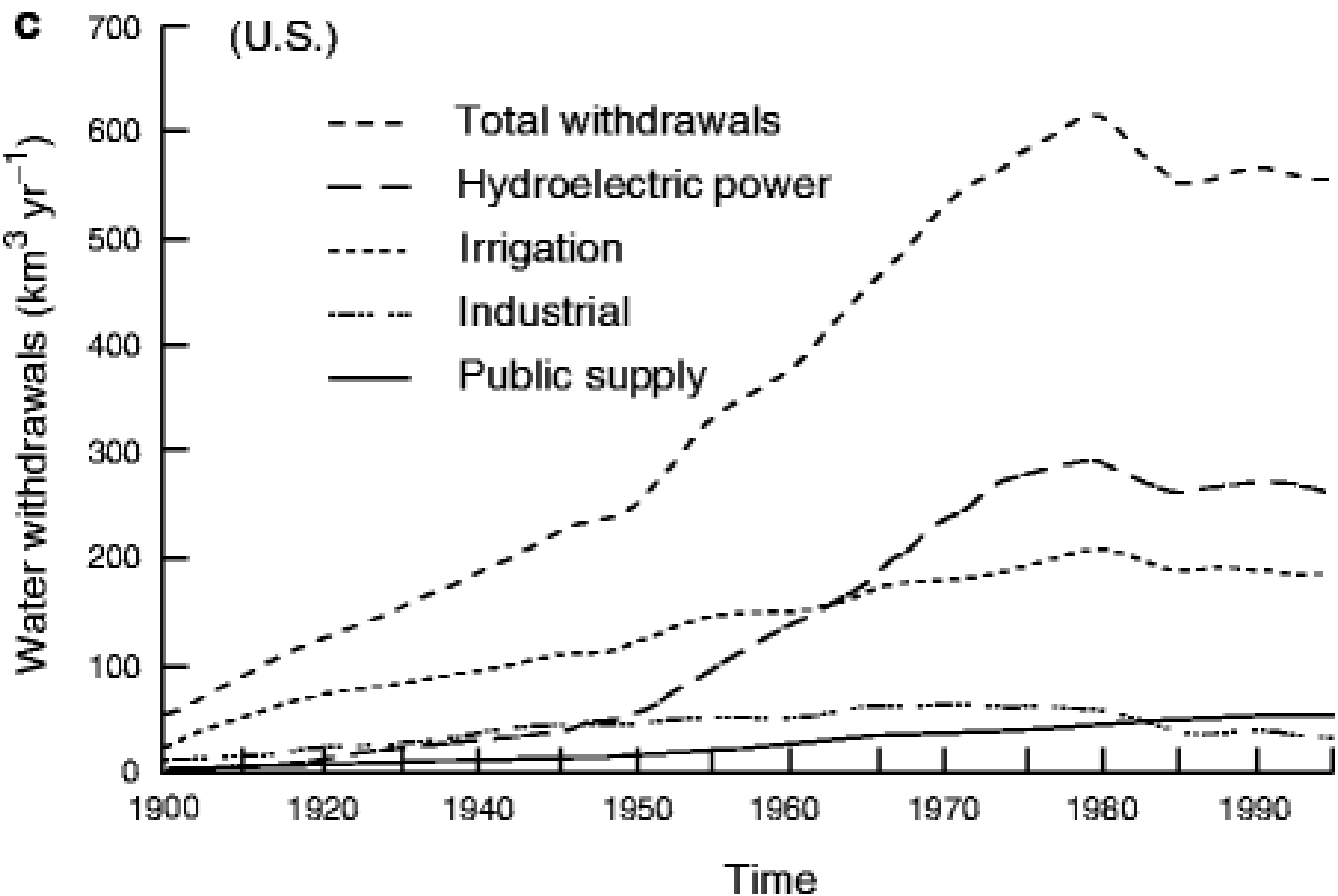
Regional and national economic and societal impacts

Non-irrigated croplands rely on soil moisture from precipitation….

…Irrigated croplands have increased five-fold during the 20th century

Trends in (a) world population, (b) water withdrawals for human activities, per capita



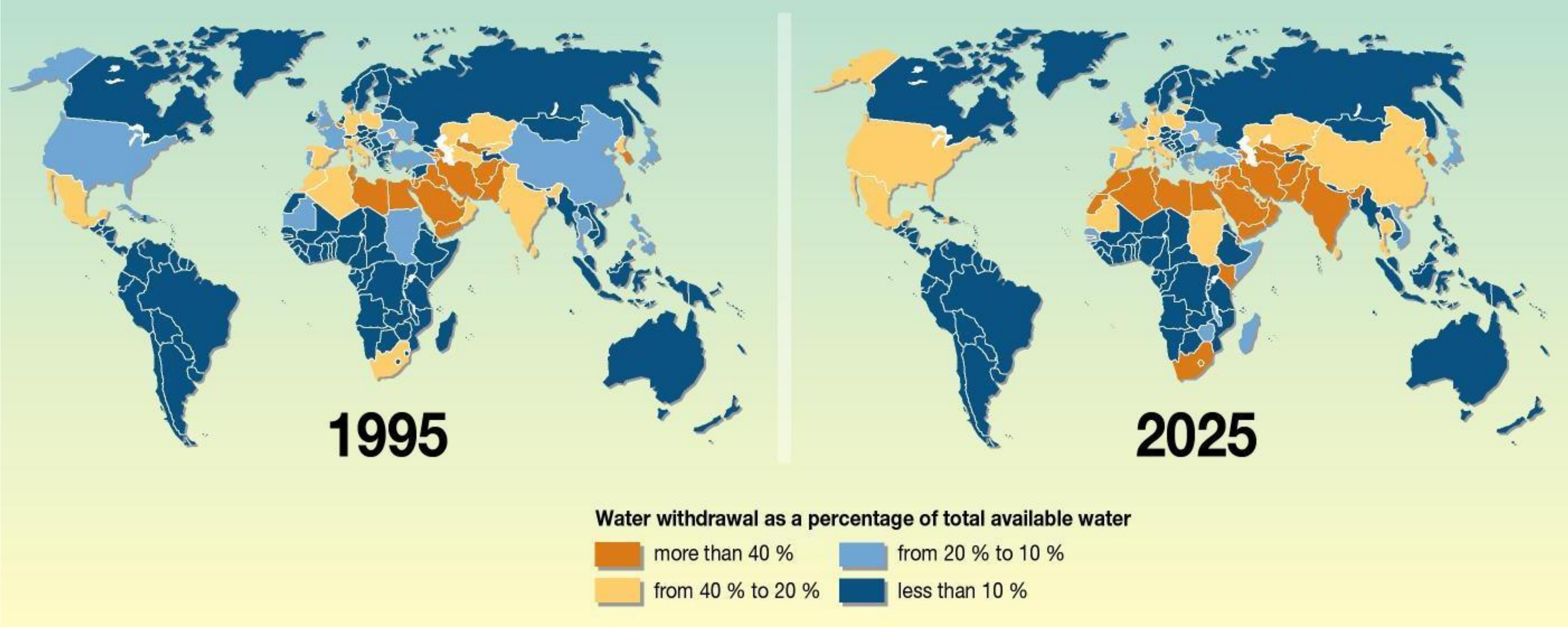


Trends in (c) water withdrawals in the U.S. by economic sector

During the past 100 years, human water use increased 8-fold

Agriculture uses 70% of the global fresh water supply

By 2025, two-thirds of the world's people may be living in water-stressed countries (consumption of more than 10% of renewable freshwater resources)



Diversion projects redistribute water

- **Dams** and **canals** store and redistribute water for agriculture and cities

The All-American Canal, the main water conduit from the Colorado River into the Imperial Dam, flows through the Imperial Valley, Calif.

More than half of the world's largest rivers have been damned or diverted