The Hydrosphere:

Lecture 7: Evapotranspiration

Evapotranspiration

evapotranspiration summarizes all processes that return liquid water back into water vapor

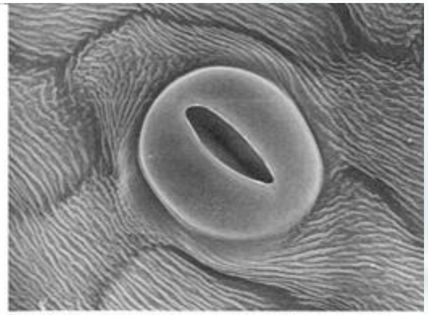
- **evaporation (E)**: direct transfer of water from open water bodies or soil surfaces
- **transpiration (T)**: indirect transfer of water from root-stomatal system
- Sublimation - process by which water passes directly from the solid phase to the vapor phase

of the water taken up by plants, ~95% is returned to the atmosphere through their stomata (only 5% is turned into biomass!)

Before E and T can occur there must be:

- A flow of energy to the evaporating or transpi
- A flow of liquid water to these surfaces, and
- A flow of vapor away from these surfaces.

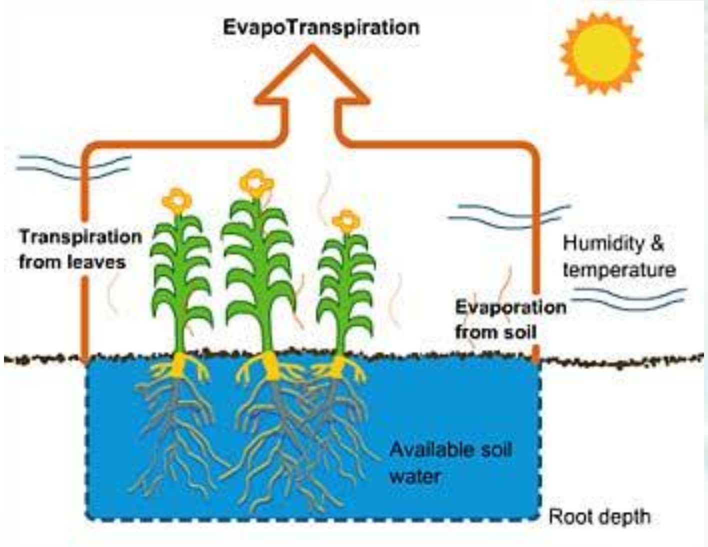
Total ET is change as a result of any changes
That happens to any of these 3.



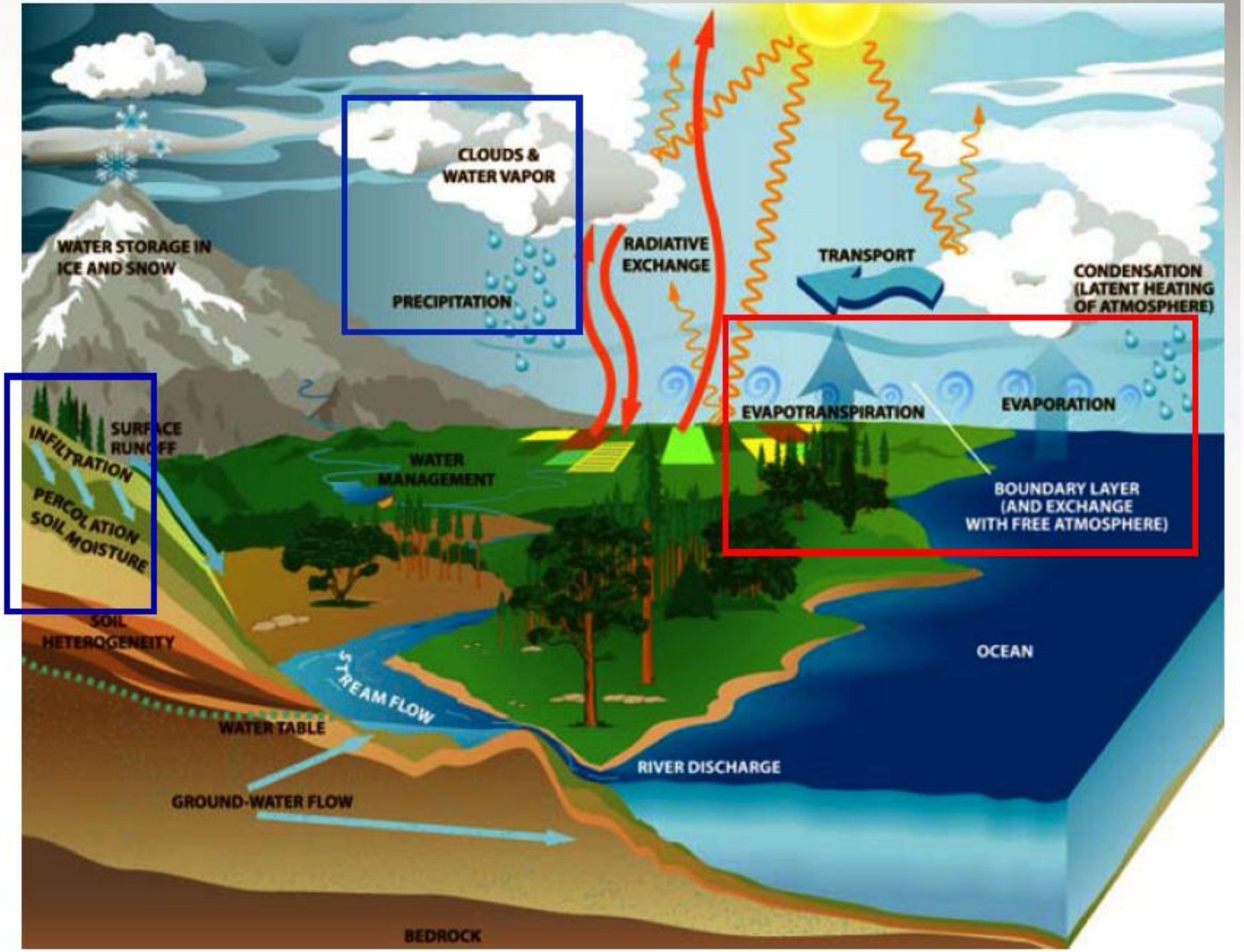
Photomicrograph of leaf surface showing one of the stomata. Dr. Jeremy Burgess/Science Photo library (after: Dingman, 1994)

Evapotranspiration

- Evapotranspiration is the process that returns water back to the atmosphere:
  - Evaporation from open water (e.g. oceans)
  - Evaporation from soils (deserts, mountains, agricultural, etc)
  - Transpiration from plants
- Evaporation can account for a large part of the hydrological cycle:
  - ET can be significant fraction of the total precipitation
  - ET/P ratio is called the aridity index
    - High ET/P imply desert conditions
    - Low ET/P imply humid conditions



ET


WATER STORAGE IN ICE AND SNOW
CLOUDS & WATER VAPOR
PRECIPITATION
RADIATIVE EXCHANGE
TRANSPORT
CONDENSATION (LATENT HEATING OF ATMOSPHERE)
EVAPOTRANSPIRATION
EVAPORATION
SURFACE RUNOFF
INFILTRATION
PERCOLATION
SOIL MOISTURE
SOIL HETEROGENEITY
WATER MANAGEMENT
BOUNDARY LAYER (AND EXCHANGE WITH FREE ATMOSPHERE)
STREAM FLOW
WATER TABLE
OCEAN
RIVER DISCHARGE
GROUND-WATER FLOW
BEDROCK

Evapotranspiration

$$ET = P – Q – \Delta S - \Delta D$$

ΔS= watershed storage variation (mm): $S_{end}–S_{beginning}$

P = Precipitation (mm)

Q = Stream flow (mm)

ΔD = Seepage out – seepage in (mm)

ET = evaporation and transpiration (mm)

Fluxes between stores

(note that the ocean area is about twice the land area)

Evaporation from ocean	117 cm/yr
Precipitation onto ocean	107 cm/yr
Precipitation onto land	74 cm/yr
Evaporation from land	49 cm/yr
Runoff from land	25 cm/yr

Over the ocean, E > P

Over land, P > E. Suggests that the storage of water on land causes some kind of “resistance” to evaporation, so that some of the precipitated water “escapes” evaporation and survives to run off the continents as streamflow (R).

Evapotranspiration

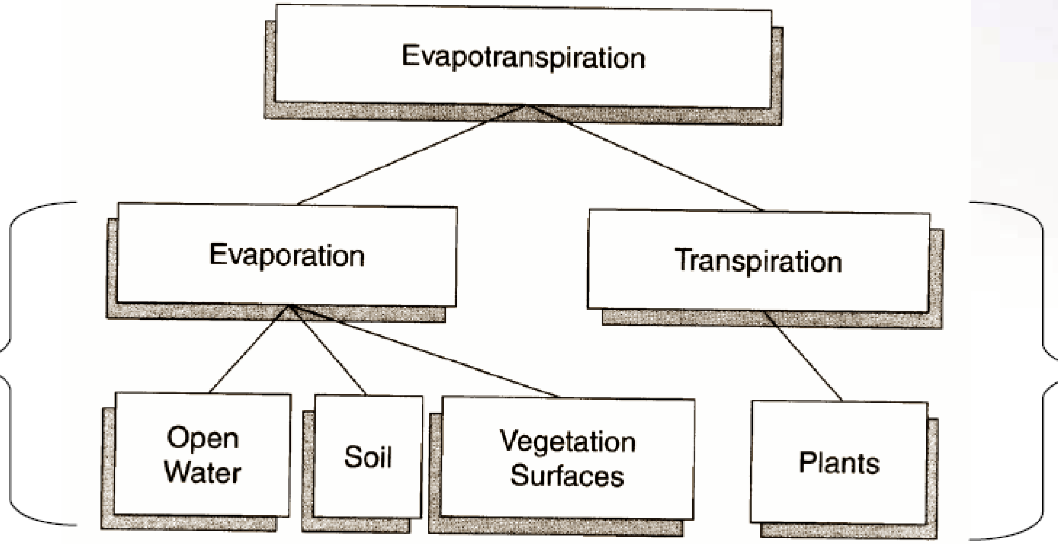
- More than 95% of 300mm in Arizona
- > 70% annual precipitation in the US
- In General: ET/P is
  - ~ 1 for dry conditions
  - ET/P < 1 for humid climates & ET is governed by available energy rather than availability of water

- For humid climates, vegetative cover affects the magnitude of ET and thus, Q (stream flow).
- In Dry climate, effect of vegetative cover on ET is limited.
- ET affects water yield by affecting antecedent water status of a watershed → high ET result in large storage to store part of precipitation

The linkage between water and energy budgets

- Is direct;
- the net energy available at the earth's surface is apportioned largely in response to the presence or absence of water.
- Reasons for studying it are:
  - To develop a better understanding of Hydrological cycle
  - Be able to quantify or estimate E and ET (soil, water or snowmelt)

- We classify the evapotranspiration process according to the surface condition:



Oceans, Lakes, Non-vegetated Land

Vegetated Land Surface

Evaporation Physics

- Basic physical principles
  - Conservation of Mass
  - Conservation of Energy
  - Ideal Gas Law related to water vapor
  - Latent heat of phase change
  - Turbulent transfer near the ground - (diffusion of momentum…)
- Diffusive process driven by a vapor pressure gradient

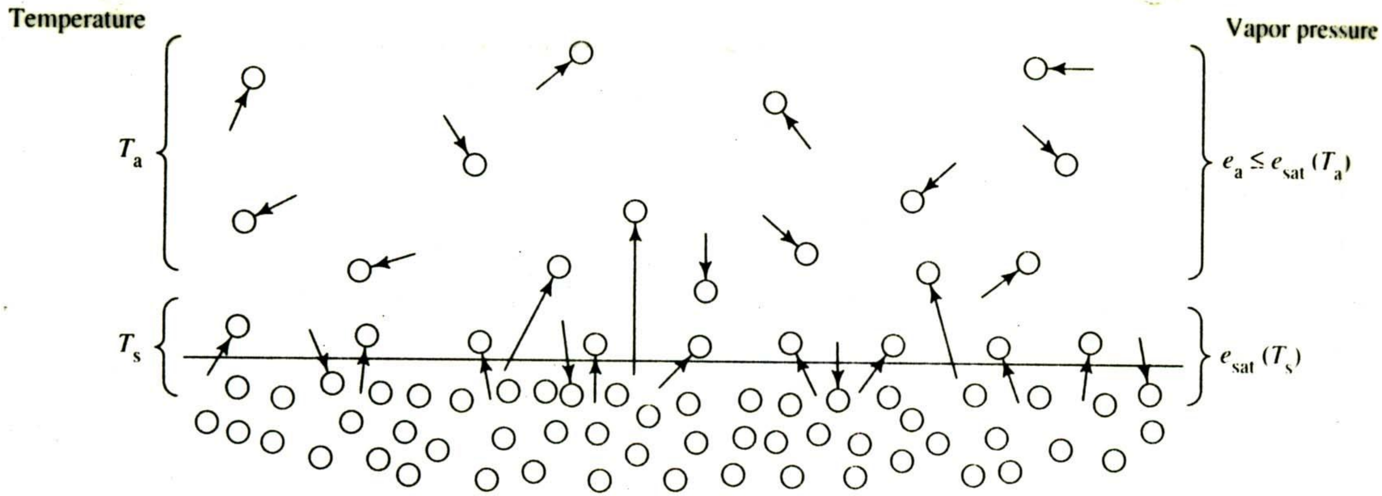


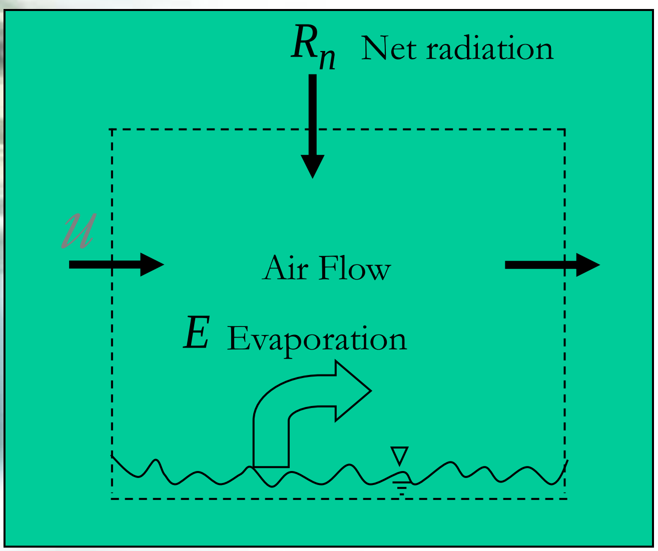
FIGURE D-4
Schematic diagram of flux of water molecules over a water surface. The vapor pressure at the surface is $e_{sat}(T_s)$; the vapor pressure of the overlying air is less than or equal to $e_{sat}(T_a)$. The rate of evaporation is proportional to $[e_{sat}(T_s) - e_a]$ [Equation (D-10)].

Evaporation Physics

- Dalton's Law $E \alpha (e_{sat(Ts)} - e_a)$
  - $e_{sat(Ts})$ is the vapor pressure of the liquid which is related to the temperature of the liquid
  - Evaporation occurs when the above relationship is positive.
  - Condensation occurs when the above relationship is negative.
  - What happens if RH is 100%, but $e_{sat(Ts)} > e_a$?

Factors affecting evaporation

- Heat energy to supply latent heat of vaporization (Net radiation, air temperature)
- Capacity to transport vapor away from evaporative surface (wind, humidity)
- Water available to supply evaporative moisture (soil water content)
- *Potential evaporation* is evaporation when water supply is not limiting



- So, there are 4 conditions necessary for evaporation to occur.
  - **Energy** available for phase change
  - **Water** available at the surface or in root zone
  - **Vapor pressure gradient**, or dry air
  - **Wind** – Capacity of the atmosphere to transport away moisture
  - **Conductance**

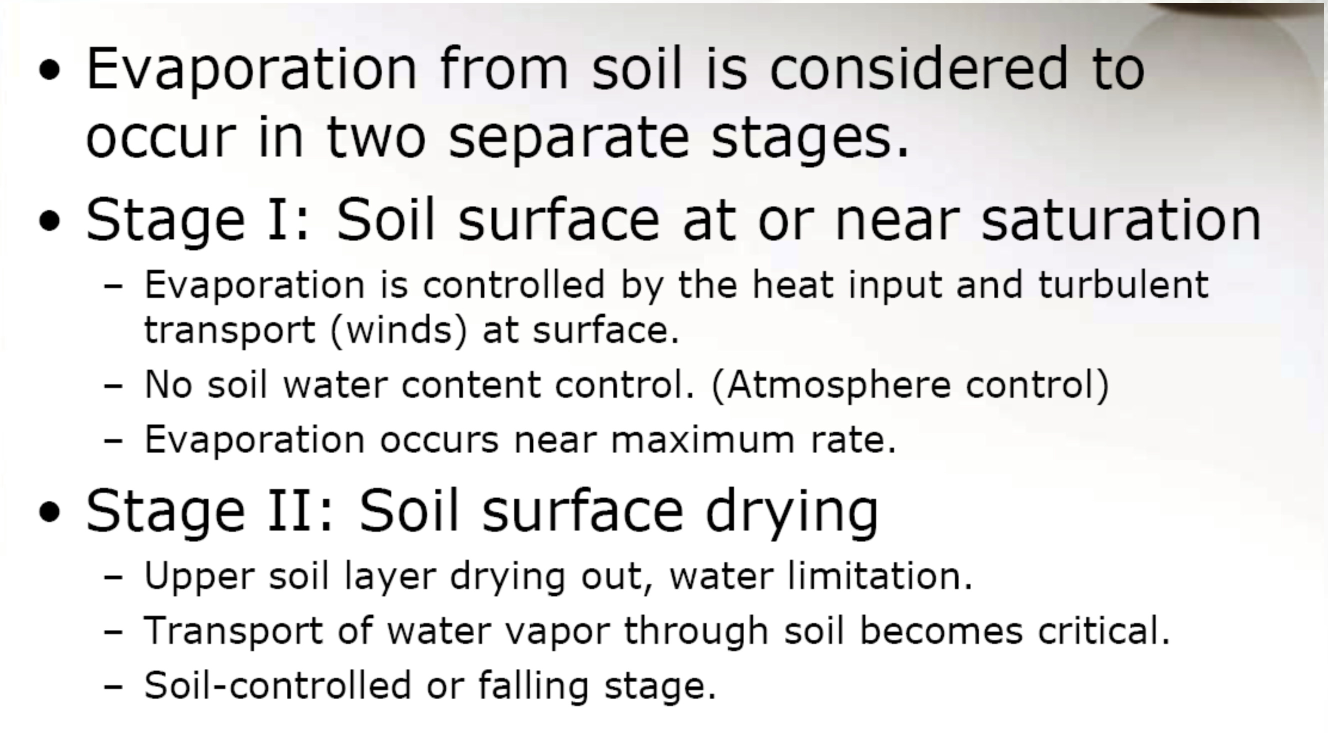
Wind as a Factor in Evaporation

- Wind has a major effect on evaporation, E
  - Wind removes vapor-laden air by convection
  - This Keeps boundary layer thin
  - Maintains a high rate of water transfer from liquid to vapor phase
  - Wind is also turbulent
    - Convective diffusion is several orders of magnitude larger than molecular diffusion

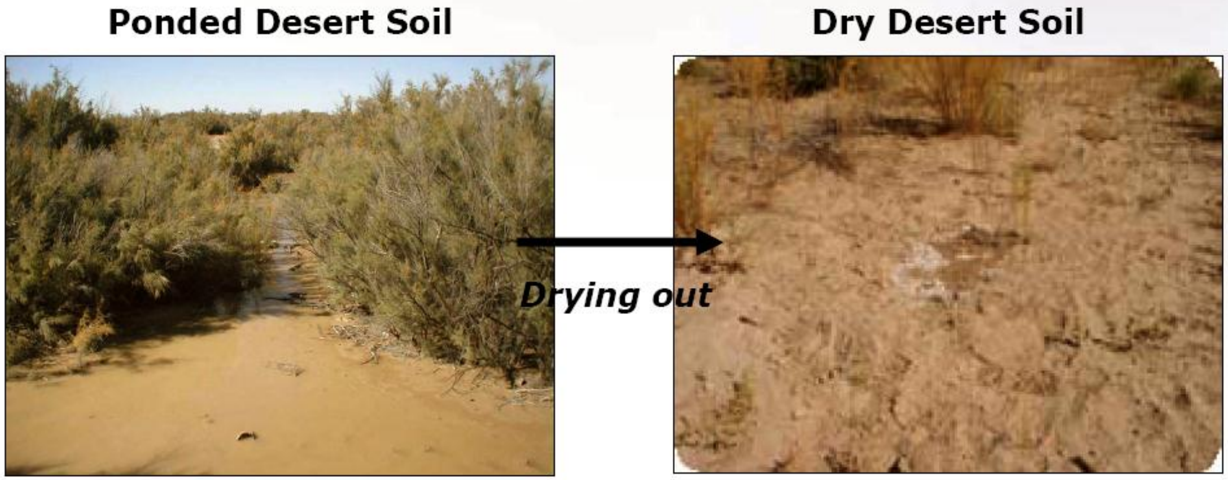
Open Water Evaporation

Figure 3. (left) Campbell Sci. CSAT3 3D sonic system, and (right) REBS Bowen ratio system.

Bare Soil Evaporation



- Evaporation from soil is considered to occur in two separate stages.
- Stage I: Soil surface at or near saturation
  - Evaporation is controlled by the heat input and turbulent transport (winds) at surface.
  - No soil water content control. (Atmosphere control)
  - Evaporation occurs near maximum rate.
- Stage II: Soil surface drying
  - Upper soil layer drying out, water limitation.
  - Transport of water vapor through soil becomes critical.
  - Soil-controlled or falling stage.



Stage I Evaporation

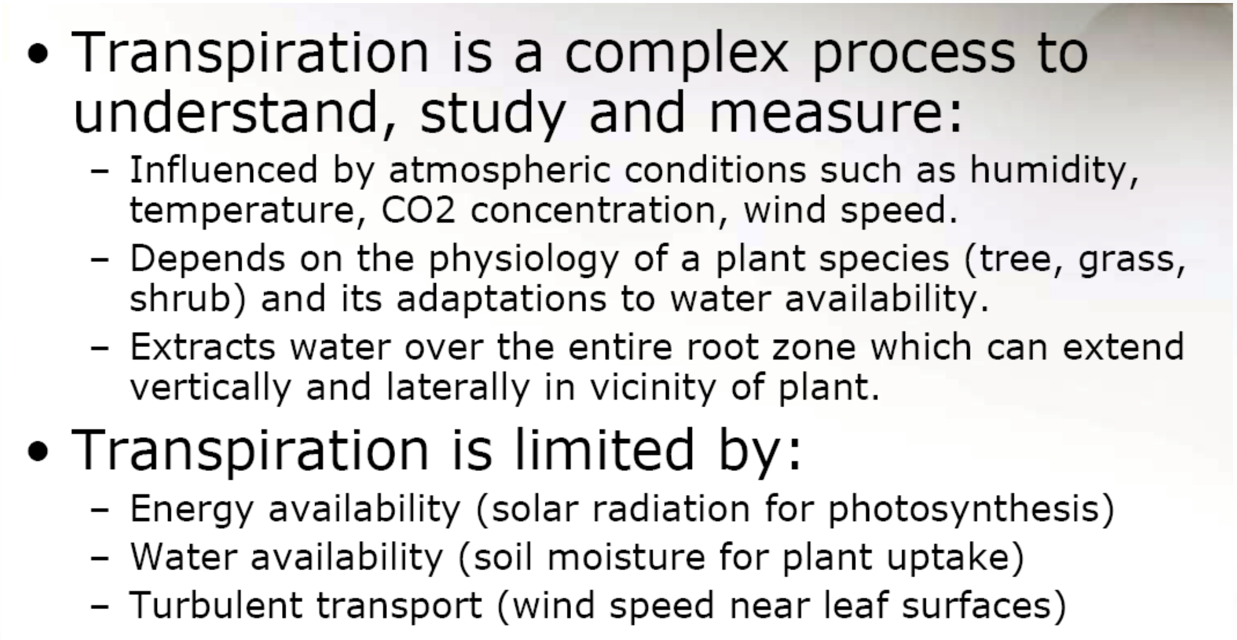
Stage II Evaporation

Transpiration

Evaporation of water from the vascular system of plants.

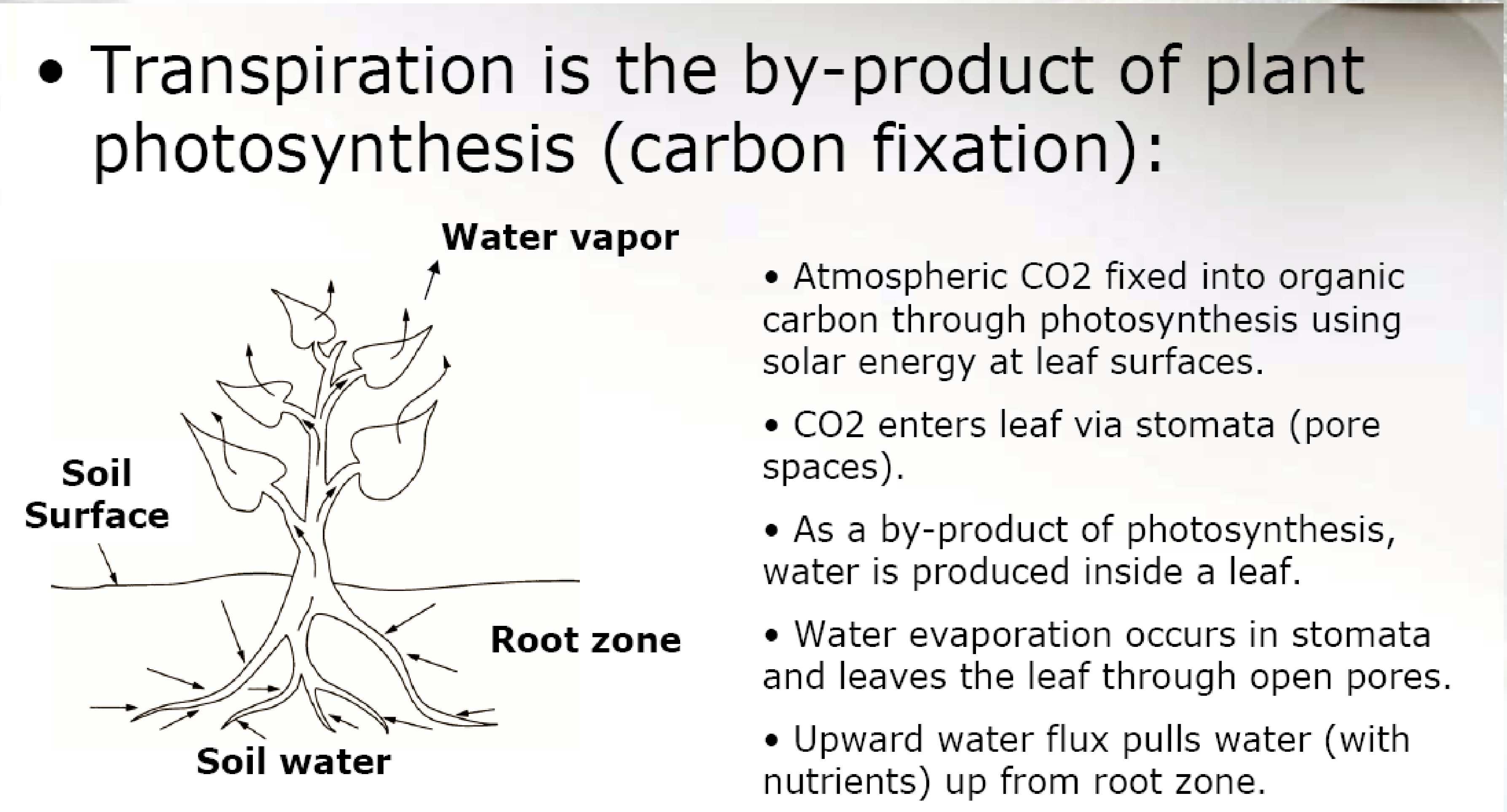
Process:

1. absorption into roots,
2. translocation to stomatal cavities,
3. evaporation



- Transpiration is a complex process to understand, study and measure:
  - Influenced by atmospheric conditions such as humidity, temperature, CO2 concentration, wind speed.
  - Depends on the physiology of a plant species (tree, grass, shrub) and its adaptations to water availability.
  - Extracts water over the entire root zone which can extend vertically and laterally in vicinity of plant.
- Transpiration is limited by:
  - Energy availability (solar radiation for photosynthesis)
  - Water availability (soil moisture for plant uptake)
  - Turbulent transport (wind speed near leaf surfaces)

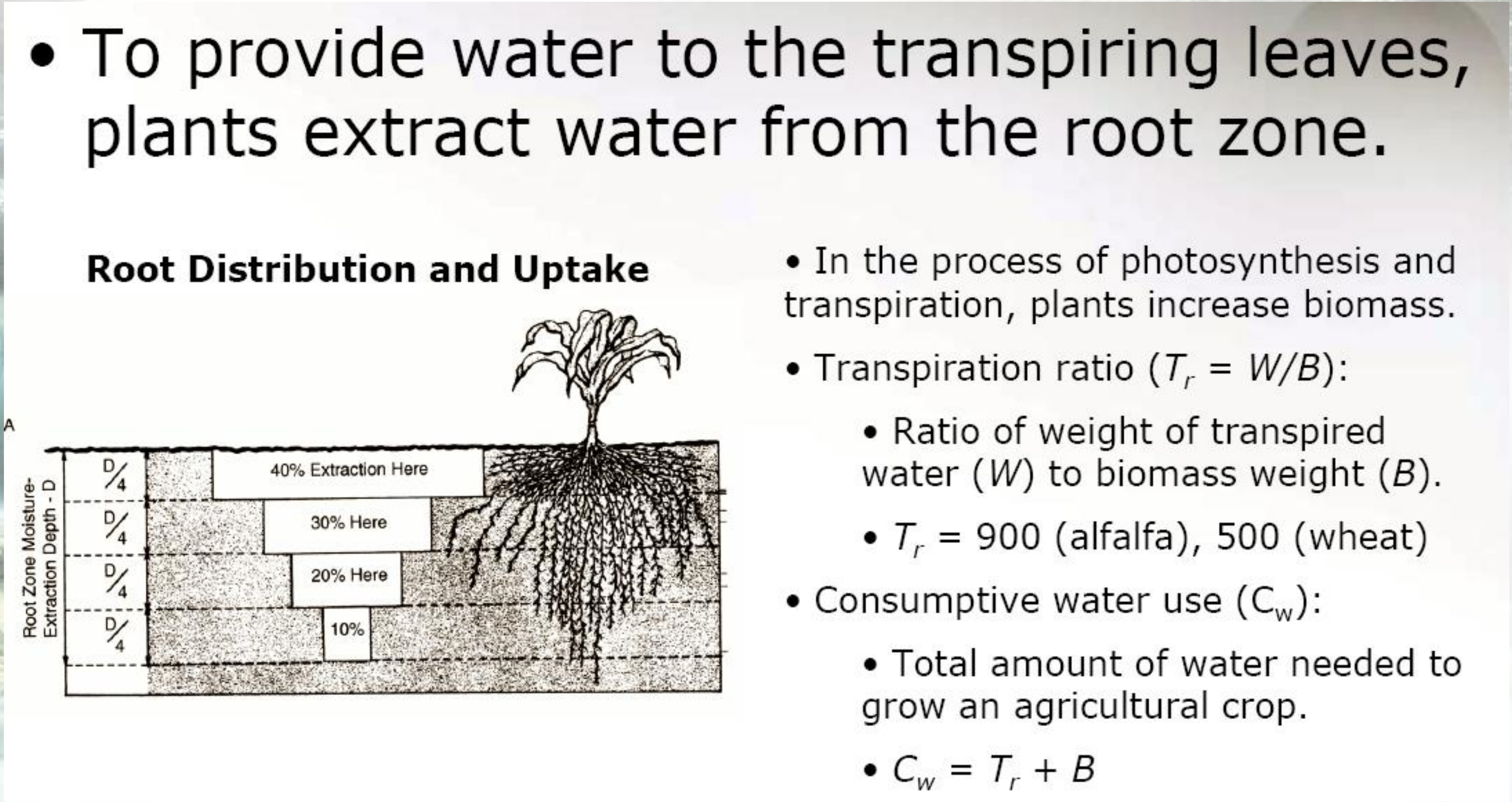
Transpiration



- Transcription is the by-product of plant photosynthesis (carbon fixation):

- Atmospheric CO2 fixed into organic carbon through photosynthesis using solar energy at leaf surfaces.
- CO2 enters leaf via stomata (pore spaces).
- As a by-product of photosynthesis, water is produced inside a leaf.
- Water evaporation occurs in stomata and leaves the leaf through open pores.
- Upward water flux pulls water (with nutrients) up from root zone.

Transpiration

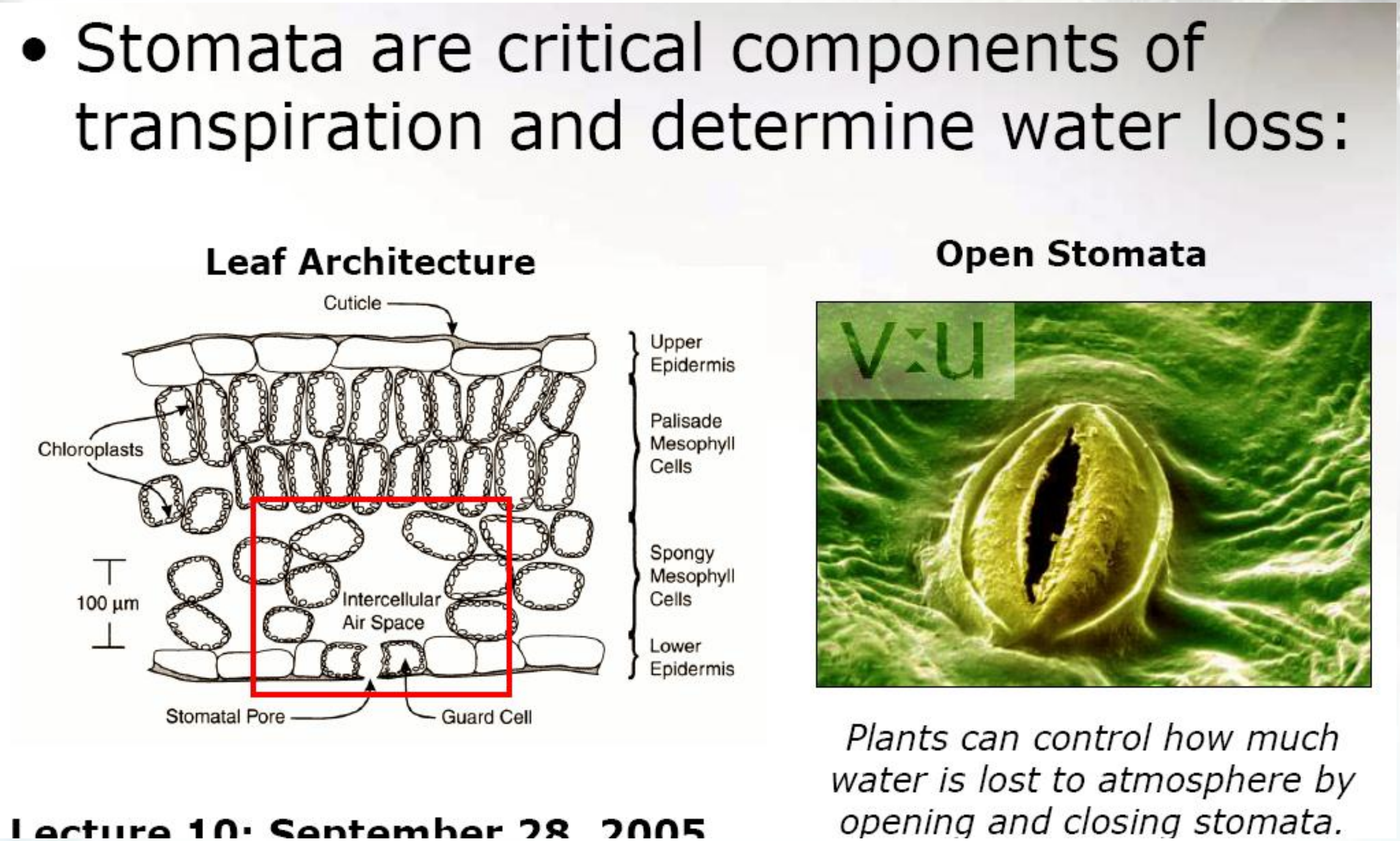


- To provide water to the transpiring leaves, plants extract water from the root zone.

Root Distribution and Uptake

- In the process of photosynthesis and transpiration, plants increase biomass.
- Transpiration ratio ($T_r = W/B$):
  - Ratio of weight of transpired water (W) to biomass weight (B).
  - T_r = 900 (alfalfa), 500 (wheat)
- Consumptive water use (C_w):
  - Total amount of water needed to grow an agricultural crop.
  - $C_w = T_r + B$

Transpiration



- Stomata are critical components of transpiration and determine water loss:

Leaf Architecture

Open Stomata

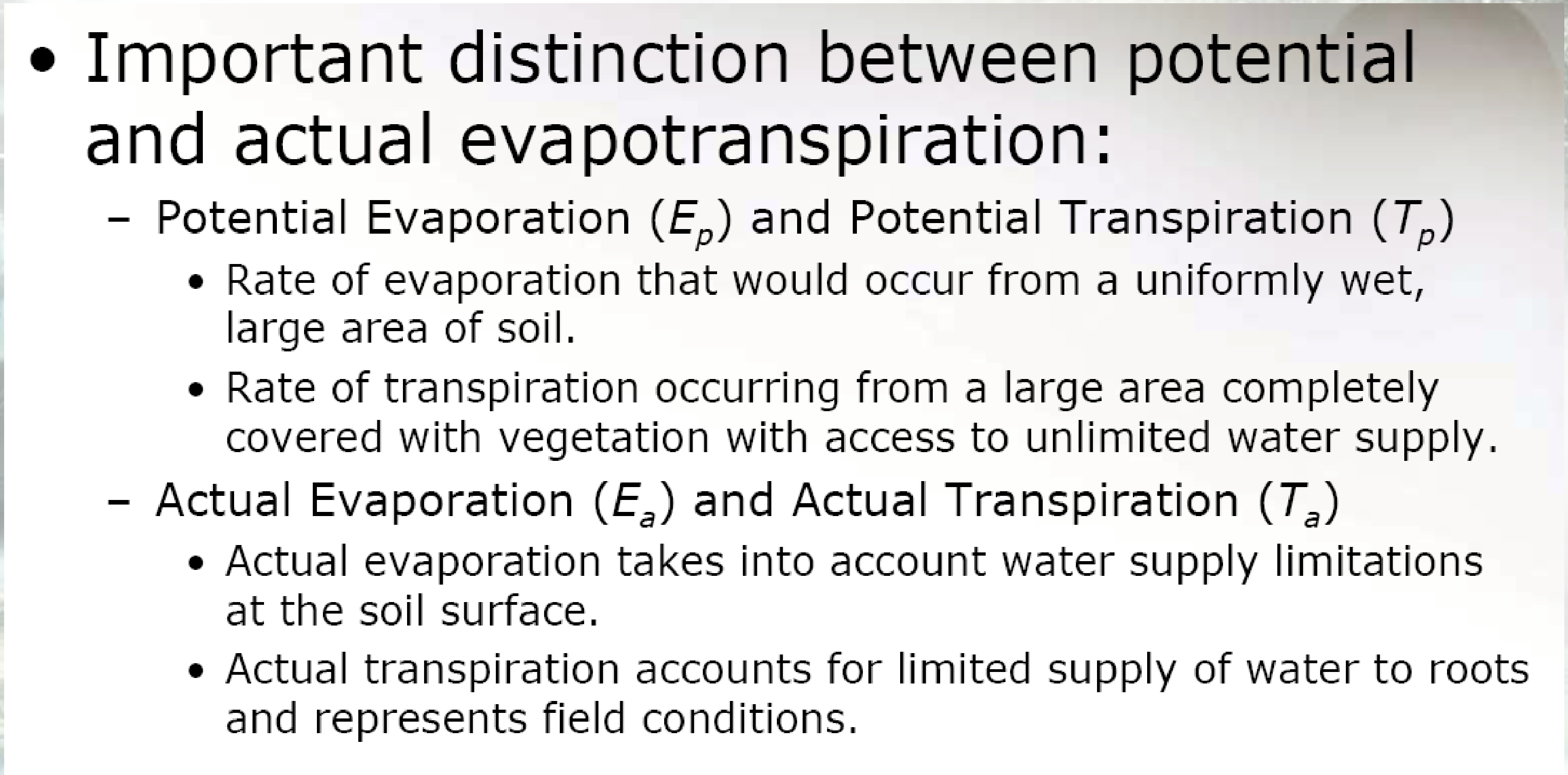
Plants can control how much water is lost to atmosphere by opening and closing stomata.

Lecture 10: September 28, 2005

Transpiration

- The physics of evaporation from stomata are the same as for open water. The only difference is the conductance term.
- Conductance is a two step process
  - stomata to leaf surface
  - leaf surface to atmosphere

Estimating Evaporation and ET

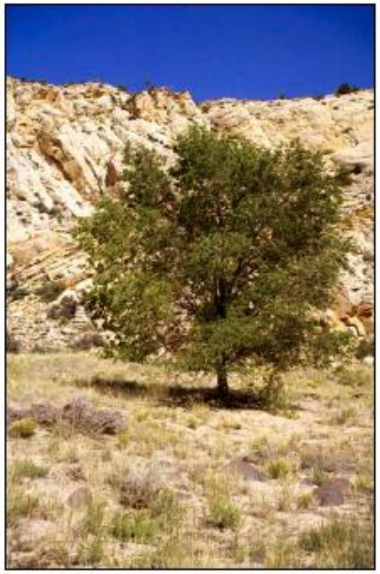


- Important distinction between potential and actual evapotranspiration:
  - Potential Evaporation (E_p) and Potential Transpiration (T_p)
    - Rate of evaporation that would occur from a uniformly wet, large area of soil.
    - Rate of transpiration occurring from a large area completely covered with vegetation with access to unlimited water supply.
  - Actual Evaporation (E_a) and Actual Transpiration (T_a)
    - Actual evaporation takes into account water supply limitations at the soil surface.
    - Actual transpiration accounts for limited supply of water to roots and represents field conditions.

PET can be considered a drying power

- Soil water content controls whether potential or actual transpiration occurs:

Desert Tree: Low Moisture



Actual Transpiration

Swamp Tree: High Moisture

Transpiration at Potential Rate

Estimating Evaporation, POT, and actual Evapotranspiration

- No good direct measurement method
- Methods
  - Pan
  - Water balance
  - Mass transfer approach
  - Energy balance approach
  - Combination – Penman Monteith
  - Eddy correlation
  - Temperate index – Thornthwaite
  - Radiation index – Priestley Taylor

Observe changes in water “level”

Calculate from weather data

Relate to an index

Pan method

Class A Pan

Standard at advanced weather stations

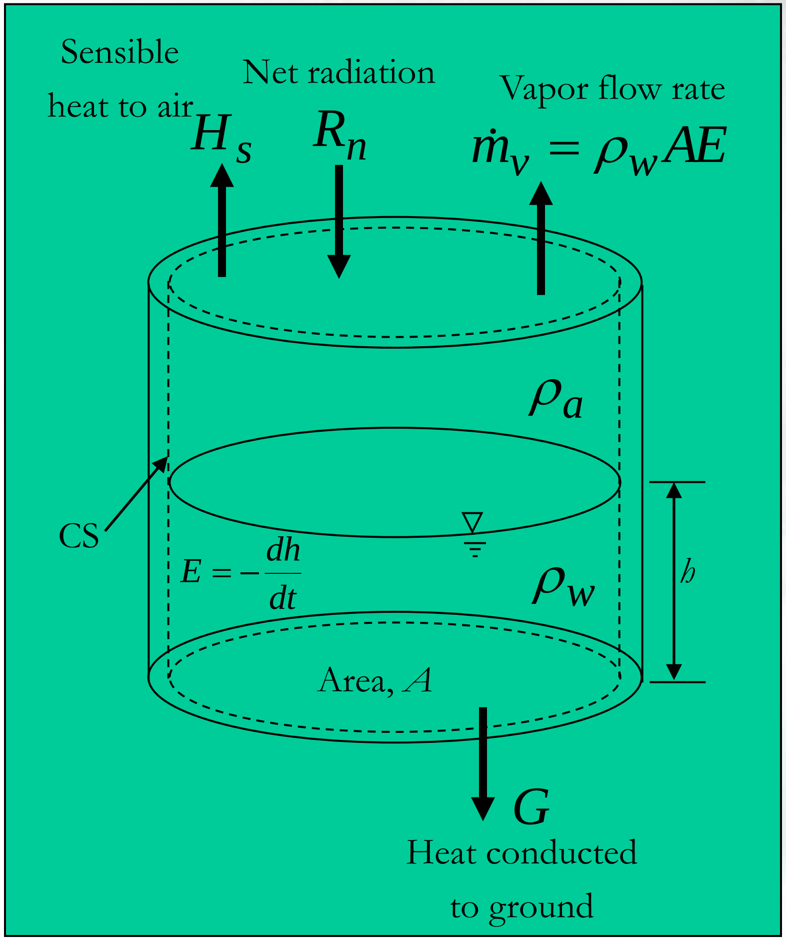
Must relate actual evaporation to pan with a coefficient

Can be used to estimate open water evaporation or POT

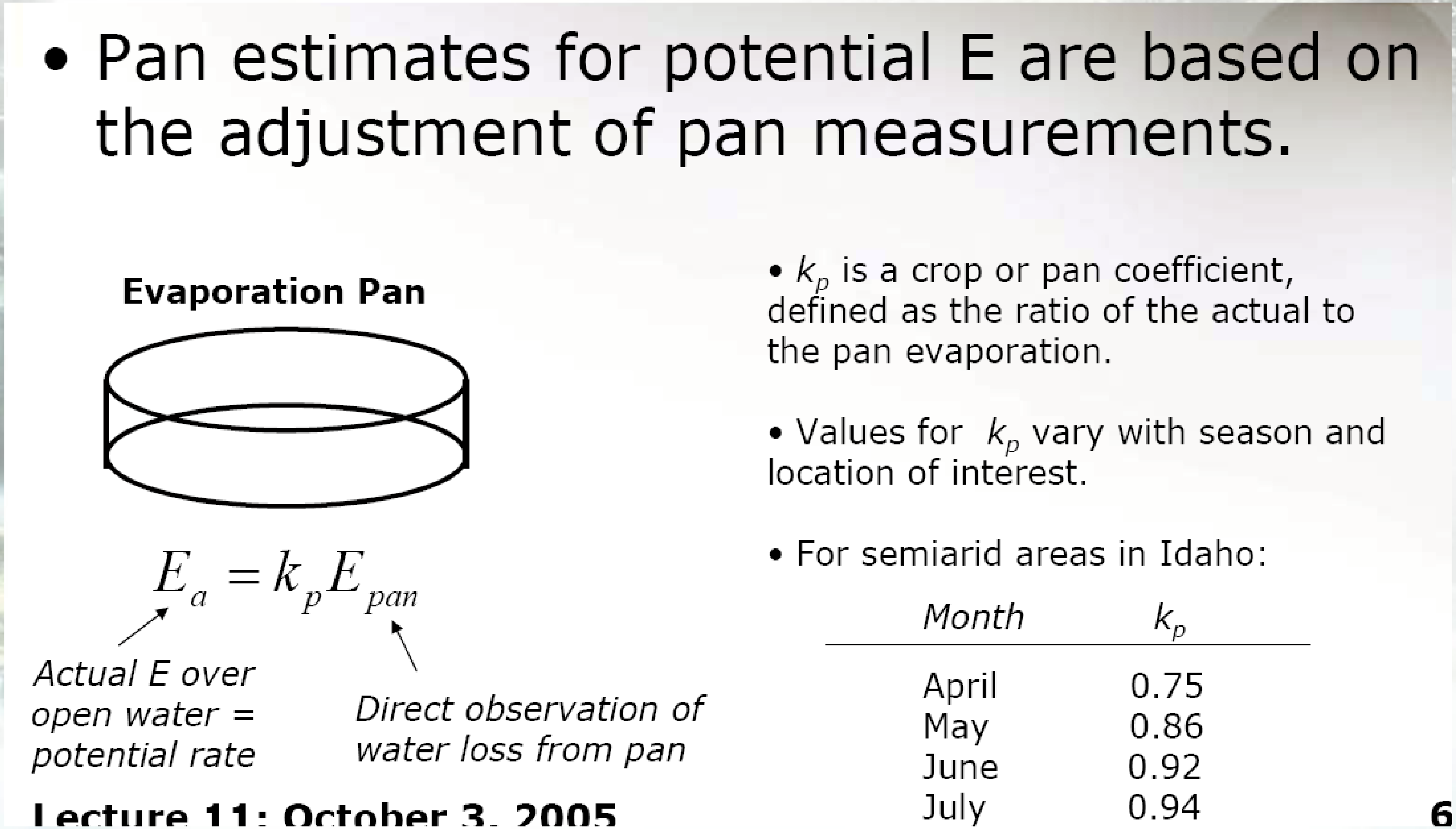
Why not actual evaporation or ET?

Evaporation from a Pan

- National Weather Service Class A type
- Installed on a wooden platform in a grassy location
- Filled with water to within 2.5 inches of the top
- Evaporation rate is measured by manual readings or with an analog output evaporation gauge



Pan Evaporation



- Pan estimates for potential E are based on the adjustment of pan measurements.

Evaporation Pan

$$E_a = k_p E_{pan}$$

Actual E over open water = potential rate

Direct observation of water loss from pan

- k_p is a crop or pan coefficient, defined as the ratio of the actual to the pan evaporation.
- Values for k_p vary with season and location of interest.
- For semiarid areas in Idaho:

Month	k_p
April	0.75
May	0.86
June	0.92
July	0.94

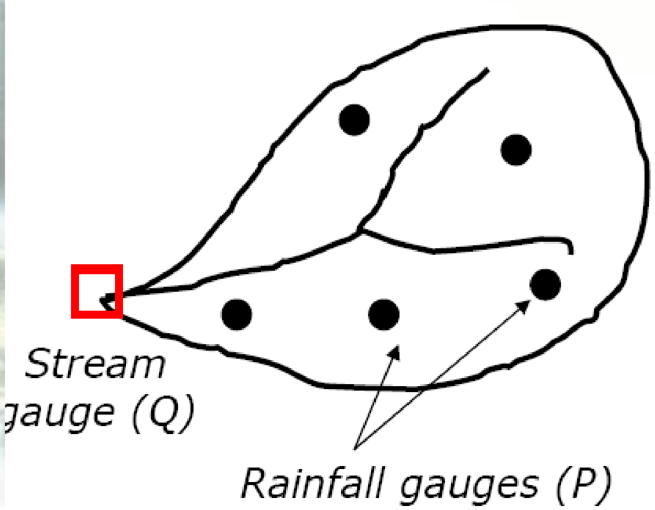
Lecture 11: October 3, 2005

Water Balance

- Evaporation or Actual Evapotranspiration can be calculated as the residual
  - in-out = ds
    - Can be written for any body of open water, watershed, soil, pan..
  - difficult to apply for large water bodies
  - accuracy increases as dt increases

- Watershed water balance method applied for large regions and long time periods.

Instrumented Watershed



- Measurements over a watershed can be used to estimate actual evaporation (ET_a) over large areas.

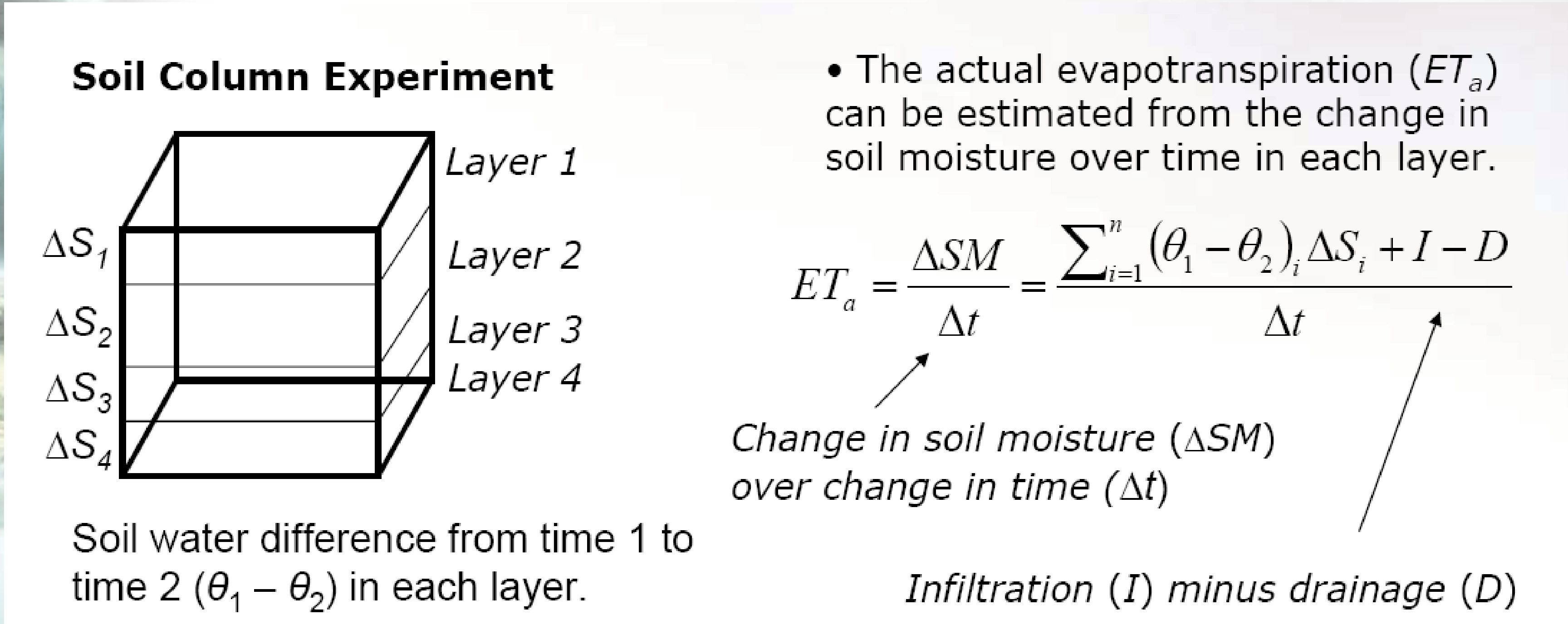
$$ET_a = P - Q \pm \Delta G \pm \Delta\theta$$

changes in groundwater (*G*) and soil water (*θ*)

- For long-term estimates with no changes in storage (*G* or *θ*):

$$ET_a = P - Q$$

Soil Water Balance



Soil Column Experiment

Soil water difference from time 1 to time 2 ($\theta_1 - \theta_2$) in each layer.

- The actual evapotranspiration (ET_a) can be estimated from the change in soil moisture over time in each layer.

$$ET_a = \frac{\Delta SM}{\Delta t} = \frac{\sum_{i=1}^{n} (\theta_1 - \theta_2)_i \Delta S_i + I - D}{\Delta t}$$

Change in soil moisture (ΔSM) over change in time (Δt)

Infiltration (I) minus drainage (D)

Energy Balance Approach

- Just like snowmelt calculations
- Solve the energy budget equation for everything except LE. LE is the residual, then convert to E
- Notice the addition of Aw. What is advected water energy?
- Again, the technique is difficult to apply –
  - Data intensive
  - Only good over small time intervals…
  - Need water surface temperature
- Bowen ratio is often used to eliminate the need to calculate sensible heat.