Water exists in liquid, solid and gaseous forms. All play roles in the biosphere.

Why can't we drink sea water?

Water, water, every where,
And all the boards did shrink;
Water, water, every where,
Nor any drop to drink.

Rime of the Ancient Mariner, Samuel Coleridge
Outline

- Physical properties
- Water at cell level
  - Water potential
- Water at Plant level
  - Adhesion Cohesion theory
  - Transpiration
  - Hydraulic lift
- Water at Ecosystem/Watershed Level
  - Evaporation
- Water Balance at Continental/Global Level
Reasons why water is important to life...and if we assume life evolved in the sea it is important for the origin of life, too.

Water, Life and the Biosphere

• Water is a highly effective solvent for salts, sugars, gases, acids and alkalis
• It is transport medium for nutrients to cells
• Provides turgidity for cell growth and expansion
• It provides electrons in photochemical reactions that lead to carbon reduction
• Plays role in weathering rock and forming soil
Is water less or more dense at 0°C. Key points include the facts that water can be in liquid, gas and solid forms across the range of climate conditions the biosphere experiences. The large latent heat of vaporization has major effects on weather, climate, rain and storms. Its high heat capacity gives water bodies much thermal inertia.

The dielectric constant of water is distinct. It enables us to use time domain reflectometers, essentially cable testers, to measure moisture as the time of flight is dependent on the dielectric constant and the value for dry soil is so much different.
Salvucci and latent heat exchange.

1 car 1000 kg lifted 1 m

9.8 m s\(^{-2}\) * 1000 kg * 1 m = 9800 kg m\(^{2}\) s\(^{-2}\)

Latent energy in 1 kg water, 2,442, 000 J (kg m\(^{2}\) s\(^{-2}\))

1 kg water is 10 cm by 10 cm by 10 cm

1 g water is 1 cm by 1 cm by 1 cm

It possesses 2,442 J of energy and can lift a car 0.4 m
Network of water transport through the soil-plant-atmosphere continuum. While it is conventional wisdom that water moves ‘downhill’ here is a case where it moves upward. The point is it moves down hill energetically. Hence it is important to consider the case of water potential.

In this SPAC the nodes are water in the soil, which is the least negative, towards nodes across resistors associated with the roots, xylem, stem, leaves and atmospheric boundary layer. The demand is set by the highly negative water potential of the atmosphere.
It Takes Energy to Move Water, the Concept of Water Potential

- Water Potential is the Thermodynamic Capacity for a Unit of Water to do Work
- Work is Force times Distance
- It Takes Energy to do Work
- Water Potential has units of Pressure
  - Pressure is Energy per unit volume, or Force per unit Area

Unit, Pa: kg m\(^{-1}\) s\(^{-2}\)
The water potential of pure water is zero. It is important to know the various components of water potential. These are associated with Pressure, with Gravity, or head, that induced by solutes and that with the Matrix surrounding water molecules.
We use a Scholander pressure ‘bomb’ to measure total leaf water potential. The leaf is placed in a sturdy metal chamber and the pressure of air is increased. At equilibrium sap will start to exude out the cut petiole. Domestic plants tend to wilt when the water potential is below -1.5 MPa, or -15 atmospheres. Drought adapted oaks can function as low as -6.0 MPa.
Pressure, or Hydrostatic, Water Potential

Pressure exerted by an overlying water column on an infinitesimal cube of water.

Pressure potential can be positive or negative. Think of the case of the stomatal guard cells, the movement of water into these cells makes the turgid as pressure potential is positive. This leads to their opening. In the reverse case, they can experience negative pressure potential as they become water leaves and they become flaccid. The actual potential of a sample of pure water in water is defined as zero.
Solutes in water reduce its free energy and make its water potential more negative.
Matric water potential is exerted on water in soils, as well as in cells and the plant xylem.
A Sponge is a Good Example, or Analog, for Matrix potential

It Takes Work, Energy, to squeeze the Sponge to Release Water
We are most associated with gravitational potential. Its value depends on the position relative to a reference, known as head
How does a Straw work? Does Paris suck the water out of the glass? The technical answer is no. Sucking evacuates the atmospheric pressure acting on the water column under the straw. With it evacuated of air pressure, the pressure on the water exposed in the glass pushes it up the straw to a new equilibrium.

\[ P_{\text{atmos}} = -\psi_g = \rho_w gh = 101300 \text{ Pa} \]
What are the Limits on Pumping Water from a Well?
How deep can the Water Table Be?

This is an important limit as it also establishes the limit of lifting ground water with a suction pump. If you are interested in doing work for the Peace corp and bring water to underserved people you should know this fact. It is a reason companies like Jacuzzi develop submersible pumps.
A redwood tree needs to lift water up 90 m or so, this imposes a negative water potential of about -0.88 MPa, or nearly 9 atmospheres of negative pressure. Remember by suction alone one can only lift a column of water 10.3 m. So how does this tree beat physical limits?
The idea of matric water potential enables the adhesion-cohesion theory to lift water up the column of xylem cells. Water is polar, so bonds allow adjacent water molecular cohesion with one another, tied together like a long string. Adhesion with the surface of vessels and tracheids in the xylem enable the string of water to work its way upward to the demand by the atmosphere.
Stomata are the gatekeepers of water in the plant biosphere. They enable plants to not succumb to potential demand of evaporation by the atmosphere and regulate water use for carbon gain. No understanding of evaporation can proceed without due attention to stomata.
The movement of cations (K+) and anions (Cl-) with a charge balance of H+ out changes the solute water potential of guard cells. This promotes movement of water into those cells. It increases the turgor pressure, which bows the shape of the stomata and causes a pore to open.
Key Points

- Again We see the role of water potential for describing the movement of water.
- Water moves downhill energetically, allowing it to move uphill physically through the stem of plants.
- We described the Soil-Water-Plant-Atmosphere Continuum, SPAC.
- Stomata play a key role in regulating water loss by plants.
List of moisture variables of interest in studying the state of the atmosphere and weather. We show how much water the atmosphere is able to hold and how this holding capacity increases with Temperature.
Saturation Vapor Pressure

- When a pool of water is at constant temperature in a closed container, some water molecules are leaving the liquid and others are condensing and returning to the liquid. Molecules in the head space exert a partial pressure on the system.
- The equilibrium vapor pressure that occurs is called the saturation vapor pressure.
- It is a function of temperature and is independent of pressure.

Saturation vapor pressure is one measure of humidity
The saturation vapor pressure-temperature curve tells us how much water the atmosphere can hold. The vapor pressure is greater at high temperatures, associated with tropical forests, than cold temperatures associated with tundra. This plays a role why the hydrological cycle is intense in the warm and wet tropics and why rainfall in the tundra matches that of a desert.

If you know the saturated vapor pressure-temperature curve you can assess humidity by knowing the dew point temperature. It also tells you when water boils at a given altitude.

What is boiling? It is the temperature when the saturation vapor pressure equals atmospheric pressure. This is why water boils at lower temperatures in the high mountains than at sea level. By definition the saturation vapor pressure equals 101.3 kPa at 100 °C.
Simple definition. Estimate the vapor pressure from the dew point. Compute saturation vapor pressure for the air temperature. This is a way you can measure humidity in your kitchen. All you need is a glass, ice, water and a thermometer. And patience. When humidity reaches 100% it condenses forming dew or water droplets. Latent heat is released by this phase change.
Here we will delve into the water cycle and focus on evaporation, rain, pools and stores of water, runoff, etc..

At global scales we close the water budget by defining precipitation as the sum of evaporation, runoff and storage.
Water can be divided into blue water, that we don’t access and which flows into the ocean, vs green water, that which cycles through plants and produces ecological and human services, like food and fiber.

Green water stocks and flows are controlled by biological processes.
Fresh water is a scarce commodity. It is only 3% of the Earth’s water. The water we drink is even scarcer. Of freshwater, only 30% is in ground water or surface water. Of freshwater, only about 0.3% is surface water, in lakes, swamps and rivers.
Flows and pools of water... 113k km³ of precipitation leads to about 753 mm of rain on land; 373k km³ of precipitation over oceans leads to about 1036 mm of rain over sea
Ocean precipitation is less than evaporation, and this imbalance is met with runoff. Hence, salts build up in the oceans was fresh water readily evaporates and as air masses move fro sea to land, much of this water is deposited over land. The runoff of water from land to sea carries minerals and increases and reinforces the sea’s saltiness.
Get a sense of the amount of annual precipitation in major geographical regions. It may come in handy when you travel overseas and decide to bring a rain coat, or not.
Coldest regions are driest. Hottest regions can be both wet or dry. Upper limits of rainfall exceed 4000 mm.
Fun fact on the wettest places and amounts on earth, over 11 meters.
How the Biosphere Uses Water
Evaporation

- Evaporation is the “physical process by which a liquid or solid is converted to a gaseous state” (Glossary of Meteorology).

- Plant canopies introduce water vapor into the atmosphere via transpiration and the evaporation of water from the soil and free water on the leaves and stems.
Measuring Evaporation

- Pan
- Eddy Covariance
- Sap Flow
- Lysimeter

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The most obvious would seem to measure evaporation from a pond or pan. Sounds simple enough, but it is not the right metric. Evaporation from a well-irrigated grass is greater than an open pan. Sounds counter-intuitive? First, the grass has a leaf area index > 3, so there may be more than 3 meters of evaporation leaf area per meter of ground. In contrast, the surface area of the pan is 1 meter squared per meter squared. Second the leaf is moist. We assume the vapor pressure at the leaf is equal to its saturation vapor pressure at its surface temperature, the same as for a pan. Third, the water is transparent, so the water body may absorb less energy than a thick vegetated canopy. Finally the grass is aerodynamically rougher than a smooth water body, so its boundary layer resistance is less.
One aspect of this class is to have basic fundamentals to challenge conventional wisdom with back of the envelop calculations. Search the web, check a textbook and you will find that a tree may evaporation 40,000 gallons of water. As someone who measures evaporation, but uses different units, I had to test this idea. First was where the data came from? The citations are from 1960, but my colleagues and I were not even measuring forest evaporation until the 1980s. So this number had to have some flaws as being derived from the residual of the water balance, evaporation ~ precipitation minus runoff.

USGS Primer on Water (Leopold and Langbein, 1960) Says:

a Large Oak Tree can Transpire 40,000 gallons.

Can we Believe this number?
So let’s convert gallons to metric volume, and assuming the size of a tree covert to the depth of water evaporated. This yields over 1500 mm of evaporation. We just saw in previous slides that an upper limit of 1400 mm may be plausible in only the wettest and warmest regions, if there is enough sunlight, and that these systems become energy limited because clouds limit sunlight. And we find most temperate forests evaporate < 500 mm/year
How Much Water Does a Tree Evaporate?:
Case Study at Tonzi Ranch

Stand Transpiration: 230 mm/y = 2300 m³/ha-y
Trees Density: 144 #/ha
Evaporation ~ 15.9 m³/tree-year = 4216 gallons per tree-year

Using data from annual evaporation measurements and tree density at our savanna site, we come up with about ~4000 gallons per tree. Granted this is a water limited system.
So let’s consider a forest in Tennessee that is not water limited. Here, the tree density is greater. And we come up with less than 10,000 gallons per tree if we focus only on the upper storey emergent trees. We obtain a number about ¼ the classic, conventional wisdom.
The is an ecosystem view on evaporation and transpiration. You are starting to see connections between previous lectures on carbon cycle, energy balance, structure and function and biosphere-atmosphere interactions come together to provide a more mechanistic understanding of evaporation. Many of these processes are indeed coupled. Here the amount of evaporation will depend on leaf area index, which affects light interception and the amount of available light energy. LAI determines the surface area of transpiring leaves. Stomatal conductance depends on factors like photosynthetic pathway, soil moisture and the nitrogen status of leaves.
The relationship between potential evaporation, temperature and available energy helps us understand better the slow water cycling of the tundra vs the tropics. It also helps us understand that the highest rates can only be achieved with evergreen forests, not deciduous ones.
When potential evaporation ($f(R_{net})$) is less than precipitation ($\text{PET}/P$) is less than one, evaporation is energy limited, as in tropical forests; not during the ‘dry’ season daily evaporation can increase due to fewer clouds and more sunlight. When potential evaporation is less precipitation actual evaporation is water limited, and reaches an asymptote.
Budyko Distilled

- Water Limited
- Hot Dry, Sunny California
- Potential Evaporation ~ 1200 mm/y
- Rainfall ~ 500 mm/y
- Actual Evaporation < Rainfall (~300 mm/y) << Potential Evaporation

- Energy Limited
- Rainy, Cloudy Tennessee
- Potential Evaporation, 1050 mm/y
- Rainfall, 1400 mm/y
- Actual evaporation 550 mm/y
This histogram gives you a clue on the amount of water that is evaporated from forests. Most are below 1000 mm/y
Newer estimates of global ET put it at 63,000 km³/y rather than 73,000 km³/y, 14% difference
Areas of highest evaporation are in the tropics. Amazon, Congo, Southeast Asia
How Accurate is the Global Estimate of Land Evaporation?

Budget reports: 73,000 km$^3$

ET tends to be deduced by Residual, the Difference between Precipitation (113k km$^3$) and Runoff (40k km$^3$) using ‘Back of Envelope’ calculations

Textbook estimates of global evaporation, determined by residual of the water budget, are being challenged with newer bottom up integration of measurements and Earth system models.
Map showing the spread of evaporation rates across the US. The Southeast is hot and humid with highest evaporation rates. Range of evaporation is from about 100 mm to 1000 mm per year.
All that rain has to go somewhere, hence the key rivers of the world. The Amazon, Mississippi, Nile, Ganges, Indus, Yangtze, Congo are among the largest and Iconic. What Rivers drain the Sierra Nevada in California?
For those of you new to California, here are our major rivers.
Map gives a sense where runoff is greatest, or nil. What is the runoff of the Great Basin of North America?

Mean annual combined runoff field.

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Key Points

- Evaporation and Transpiration vary with Temperature, Available Energy and Available Soil Moisture
- New Earth Observation Systems enable us to measure and synthesize local to global evaporation and runoff.
Human Water Use
Irrigation is rising with human population. Yet there are questions to the sustainability of irrigation, especially when and where it mines ground water and when and where salts build up. Agriculture accounts for over 80 of consumptive water use, globally (Gleick, + Field and Michalak).
Rivers and ground water provide water for irrigations to many of the world’s bread baskets. 33% of crop production comes from 25% of land that is irrigated.

Global irrigation map..where are the hot spots? Central Valley of California, Nile Delta, Aral Sea, Great Plains, middle East, Northern India, Po Valley Italy, Spain/Portugal, eastern China.
<table>
<thead>
<tr>
<th>Food product</th>
<th>Water consumption (gal/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>356</td>
</tr>
<tr>
<td>Wheat</td>
<td>160</td>
</tr>
<tr>
<td>Corn</td>
<td>109</td>
</tr>
<tr>
<td>Soybeans</td>
<td>214</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>21</td>
</tr>
<tr>
<td>Eggs</td>
<td>400</td>
</tr>
<tr>
<td>Milk</td>
<td>119</td>
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<td>Cheese</td>
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<td>Beef</td>
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</tr>
<tr>
<td>Pork</td>
<td>582</td>
</tr>
<tr>
<td>Sheep</td>
<td>736</td>
</tr>
<tr>
<td>Chicken</td>
<td>269</td>
</tr>
</tbody>
</table>

GRACE involves a pair of satellites, whose gravitational attraction varies with mass of the earth, which can vary with stored water.
Data from GRACE Satellite...It shows the year to year variation in stored water in major river basins. What do you distill from this figure? Is Storage Nill, or trending??
**Mixed picture.** Between 2003 and 2012, GRACE data show water losses in agricultural regions such as California’s Central Valley (1) (−1.5 ± 0.1 cm/year) and the Southern High Plains Aquifer (2) (−2.5 ± 0.2 cm/year), caused by overreliance on groundwater to supply irrigation water. Regions where groundwater is being depleted as a result of prolonged drought include Houston (3) (−2.3 ± 0.6 cm/year), Alabama (4) (−2.1 ± 0.8 cm/year), and the Mid-Atlantic states (5) (−1.8 ± 0.6 cm/year). Water storage is increasing in the flood-prone Upper Missouri River basin (6) (2.5 ± 0.2 cm/year). See fig. S1 for monthly time series for all hot spots. Data from (15) and from GRACE data release CSR RL05.
GRACE is being used to study ground water in California
Groundwater is the source of irrigation water for many of the fruits, nuts, and vegetables you like to eat. Groundwater storage is declining and soils in the San Joaquin Valley are subsiding.
Evidence of land subsidence in the San Joaquin Valley...Lesson: We cannot mine our ground water indefinitely.
Irrigation of the Aral Sea for cotton to support the Soviet era agricultural economy has led to its immense shrinkage.
I first became aware of the Aral Sea reading National Geographic at home. It is an issue that resonated with me, so I show you what is happening
Picture of the Aral Sea today..
Lakes and Wetlands

Why are most of the Wetlands in the Sub Arctic?: Isn’t it a Desert?

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Reinforces why evaporation near the poles is so low... despite long summer days with 24 hours of sunlight.
Water from Himalaya glaciers are critical for feeding the rivers that are the source of water for over 2 billion people in southern Asia.

Oliver Schell’s editorial NY Times
Mountain glaciers are shrinking with warming
Whiskey is for Drinking; Water is for fighting over

Quote attributed to Mark Twain, but not proven
Water has multiple stakeholders, many with divergent interests. How do we share water? Part of the problem is our water laws were based on English Law and ideas like Riparian rights were given during years of ample rain, low populations and water demand.
Take Home Points

- Water Flows Down Hill Energetically
- The Global Water Balance, Precipitation is balanced by evaporation, runoff and storage
- Clean, Fresh Drinking Water is Extremely Scarce
  - Only 3% of the World’s Water is Fresh
  - Only 0.3% of Fresh Water is Surface Water
- 30% of Freshwater is Groundwater, but it is being rapidly depleted in an unsustainable manner.
Discussion Topics

- What are some Solutions to Stop and Reverse the loss of Ground Water in California?
Mean Global Mixing Ratio of Humidity of the Atmosphere

Mass Atmosphere: $5.28 \times 10^{18}$ kg

Volume of Water in Atmosphere: 12,900 km$^3$

Density of Water: 1000 kg m$^{-3}$

Mass of Water: $1.29 \times 10^{16}$ kg

Mean Global Mixing Ratio: 2.44 g/kg $\approx 0.244\%$
Values near the surface may not reflect the integrated atmosphere
Managing Water in California
CIMIS ET Map

ESPM 111 Ecosystem Ecology
Green water is a much, much smaller fraction of blue water. Many wars and regional disputes tend to be over resources like available water and more will occur in the future.
Saltwater
97.5%
1 365,000,000 km³

0.3% Lakes and river storage
30.0% Groundwater, including soil moisture, swamp water
and permafrost
60.0% Glaciers and permanent snow cover


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Water on Earth

- Earth Area: $5.1 \times 10^{14}$ m$^2$
- Ocean Area: $3.6 \times 10^{14}$ m$^2$ (70%)
- Land Area: $1.5 \times 10^{14}$ m$^2$ (30%)

This section is on the Earth's water budget and pools
Note on water movement through soils. Flux rates of saturated flow depend upon the head and the hydraulic conductivity of the soil. Sand is more conductive than clays.
Precipitation = Evaporation + Runoff + Storage

Annual Runoff

Data taken from CMAP ISCCP Composite Runoff Trends v1.2

Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin-Madison

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How humid is the atmosphere and where is it humid?

NH Winter:
- RH: ~80% over oceans
- RH: 30-80% over land

NH Summer:
- RH: ~80% over oceans
- RH: 30-80% over land