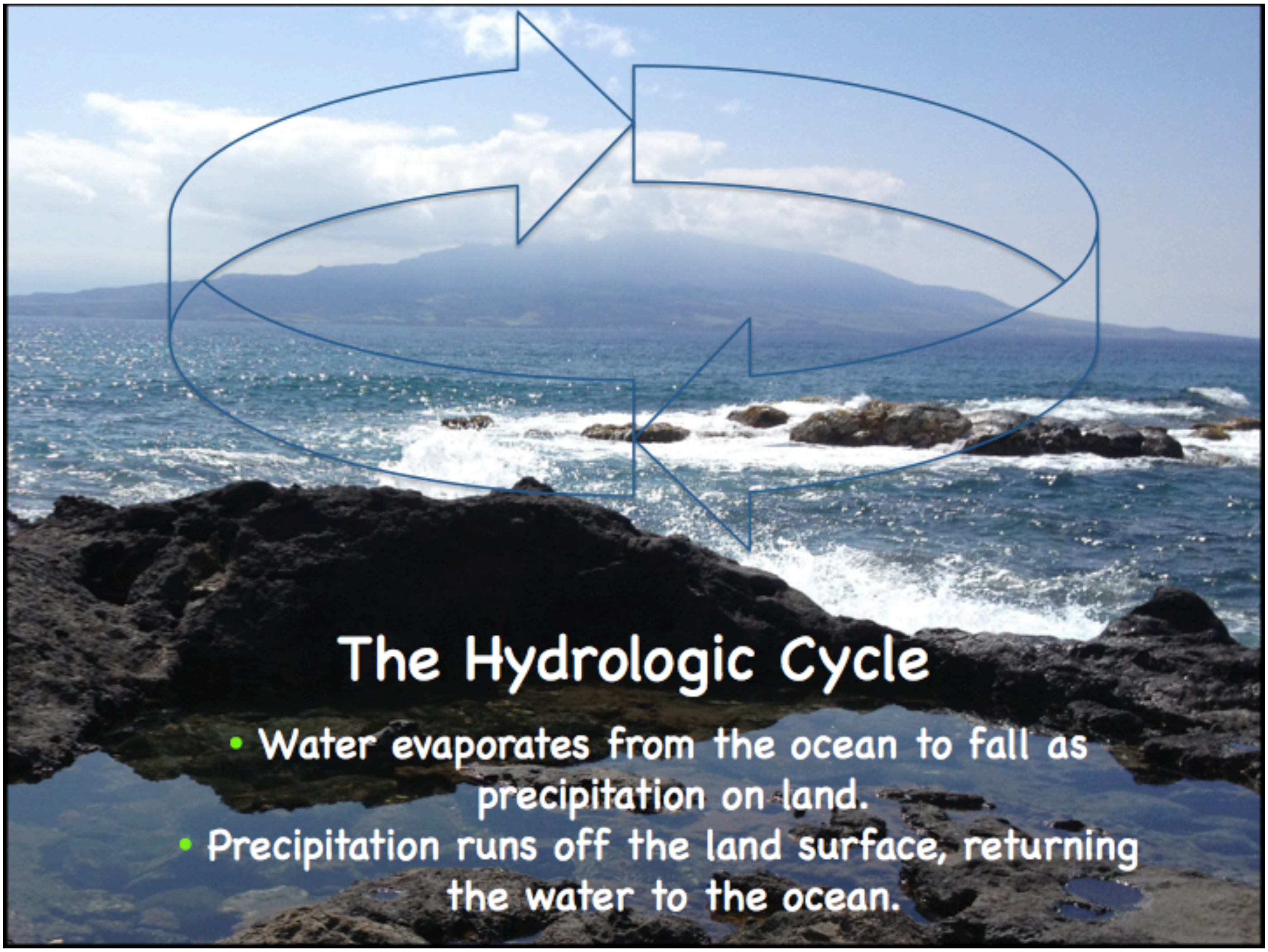
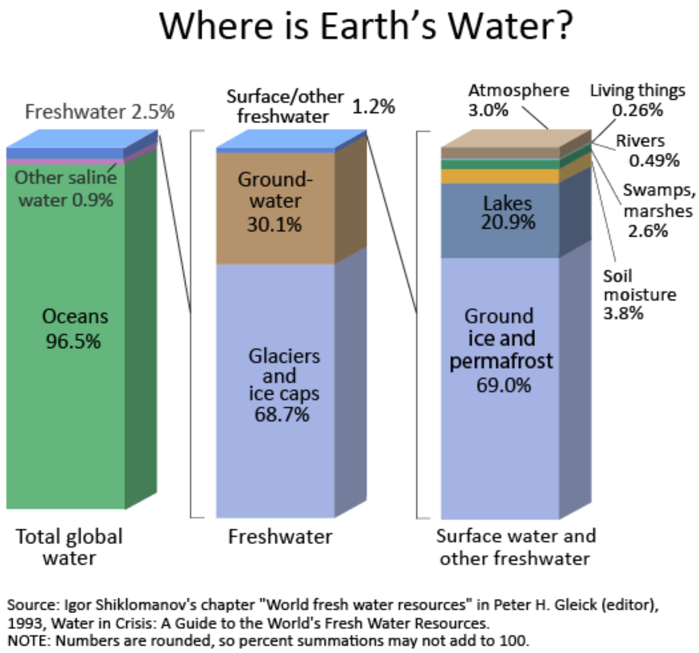
THE HYDROLOGIC CYCLE



Introduction

Water moves across the Earth surface, driven by solar energy and gravity. The statement in the figure above describes the three fundamental motions of the hydrologic cycle: evaporation, precipitation, runoff.

Of course there's a lot more to it than that. We can examine the locations where Earth's water is stored as well as the processes that move water from one location to another. Storage locations are termed *reservoirs*. Reservoir is a general term for any place where anything is stored – not just water – so we often study reservoirs of carbon, or nutrients, or genetic diversity. On Earth the largest water reservoir is the ocean, holding 97% of all water. The remaining 3% is fresh water, and is stored as glacial ice, in groundwater, surface waters, the atmosphere and biosphere.



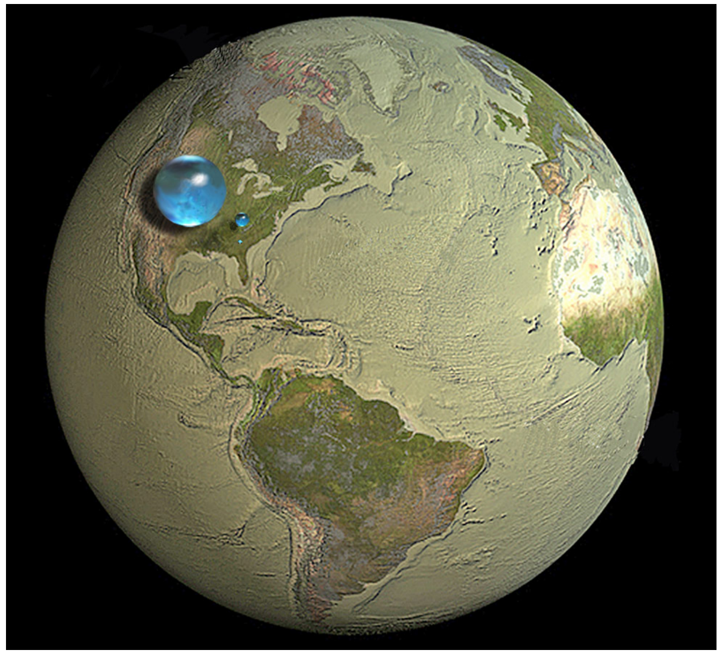


Figure 2: Two different representations of Earth's water reservoirs. The graph on the left is a set of bar graphs, where height is proportional to water volume. On the right, the blue spheres represent relative amounts of Earth's water in comparison to the size of the Earth. The largest sphere represents all of Earth's water. Its diameter is about 860 miles (the distance from Salt Lake City, Utah, to Topeka, Kansas) and has a volume of about 332,500,000 cubic miles (mi^3) (1,386,000,000 cubic kilometers (km^3)). This sphere includes all of the water in the oceans, ice caps, lakes, rivers, groundwater, atmospheric water, and biosphere. The blue sphere over Kentucky represents the world's liquid fresh water (groundwater, lakes, swamp water, and rivers). The volume comes to about 2,551,100 mi^3 (10,633,450 km^3), of which 99 percent is groundwater, much of which is not accessible to humans. The diameter of this sphere is about 169.5 miles (272.8 kilometers). The tiny bubble over Atlanta, Georgia represents fresh water in all the lakes and rivers on the planet. Most of the water people and life of earth need every day comes from these surface-water sources. The volume of this sphere is about 22,339 mi^3 (93,113 km^3). The diameter of this sphere is about 34.9 miles (56.2 kilometers) (USGS figure).

Because the ocean is so large we consider it to be the "home" of Earth's water, and we usually begin discussions of the hydrologic cycle in the ocean. Sunlight absorbed by seawater leads to evaporation; the phase change from liquid water to gaseous water vapor. Evaporation transports water from the ocean to the atmosphere. If the water vapor cools it condenses back to liquid (or sometimes solid snow or ice) and falls as precipitation. A simple cycle results when precipitation falls directly back into the ocean. But when precipitation falls on the terrestrial surface the cycle becomes more complex, as there are many different paths to return the water to the ocean.

Water on the Terrestrial Surface

The amount of fresh water available to human communities is small, thus we monitor it very closely. We have deployed a global network of rain gages, stream flow gages, well water gages, snow pack monitors – we even monitor the hydrologic cycle from space using sensors mounted on Earth-observing satellites. Satellites are very helpful for monitoring snow and ice, as cold regions are inaccessible and difficult to work in. This is important, as Figure 2 shows that glaciers and ice caps are the reservoir for 69% of Earth's fresh water.

All water arrives on the continents in the form of precipitation. We divide the landscape into *watersheds*; areas in which water flows to a common point. Rainfall can move through a watershed either on the land surface or in the subsurface.

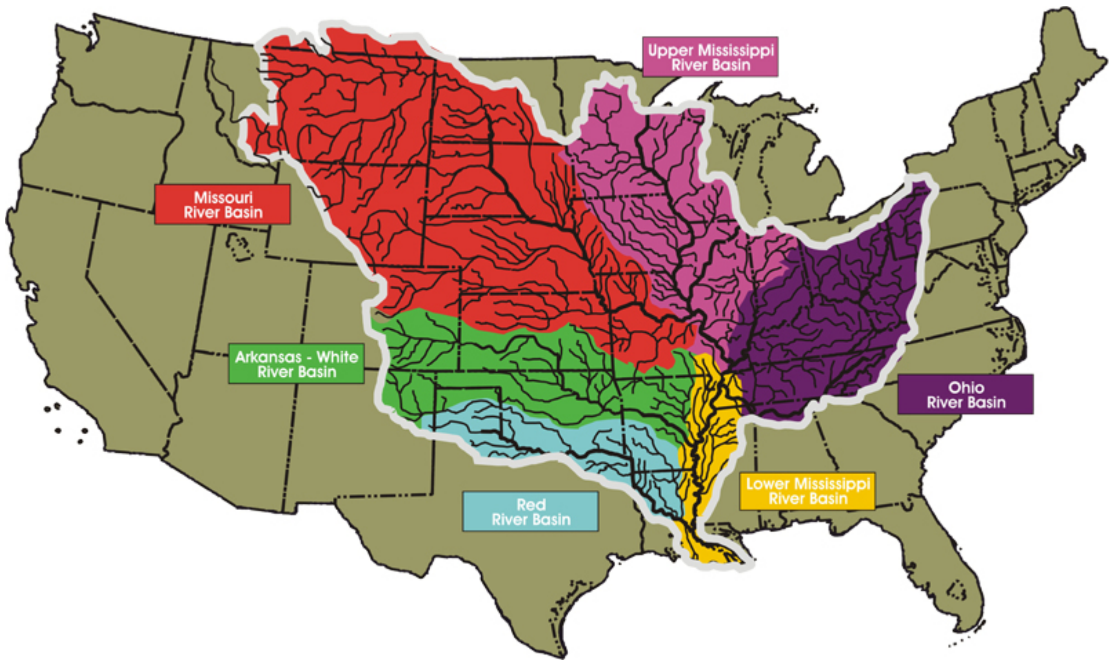


Figure 3: The Mississippi River watershed is comprised of the Mississippi River and many tributary streams that flow across more than 30 states. Here the four largest tributaries are shown: the Missouri River, the Arkansas River, the Red River and the Ohio River. All rainfall within this watershed flows to the ocean at the mouth of the Mississippi River, just downstream of the city of New Orleans (US Army map).

Rivers and streams are the most obvious expression of surface flow. Rainfall can move directly across the land surface as overland *runoff*, but this is uncommon. Water is usually channelized into rivulets and small streams that feed larger rivers. This network of *tributary* streams and larger rivers make up a watershed. Large rivers have many tributaries and large watersheds. Small tributary streams each flow through their own small watersheds.

Often rainfall *infiltrates* through the soil into the subsurface. Here too it flows toward river channels and eventually discharges into the ocean. We observe that rivers continue to flow even when there has been no recent precipitation, because the water moves slowly through the subsurface to supply the river channel year-round. Water can infiltrate into the deeper subsurface, filling the pore spaces of the rocky substrate and saturating the bedrock. This saturated subsurface zone is an *aquifer*. Water continues to move toward the ocean through aquifers, but very slowly.

On the land surface all living organisms require water for their survival. Biomass is a small reservoir for fresh water (Figure 2), yet organisms are important actors in moving water from one reservoir to another. Plants intercept precipitation as it falls and they pull water from the shallow subsurface and *transpire* it back to the atmosphere through their leaves. In this way plants take precipitation and move it directly back to the atmosphere, skipping the slower processes of infiltration or runoff.

Temporal Variation

Because sunlight powers the hydrologic cycle, the movement of water can vary a great deal from season to season. One of the most striking examples of seasonal variation is the *monsoon* rain cycle in south Asia. Summer rains are extreme, while winter is very dry. This is illustrated in Figure 4, the average monthly rainfall for the city of Cherrapunji, India. In January there is less than a half-inch of rain, while July sees nearly 11 feet of rainfall. For comparison, New York City gets a uniform 3-4 inches or rain per month.

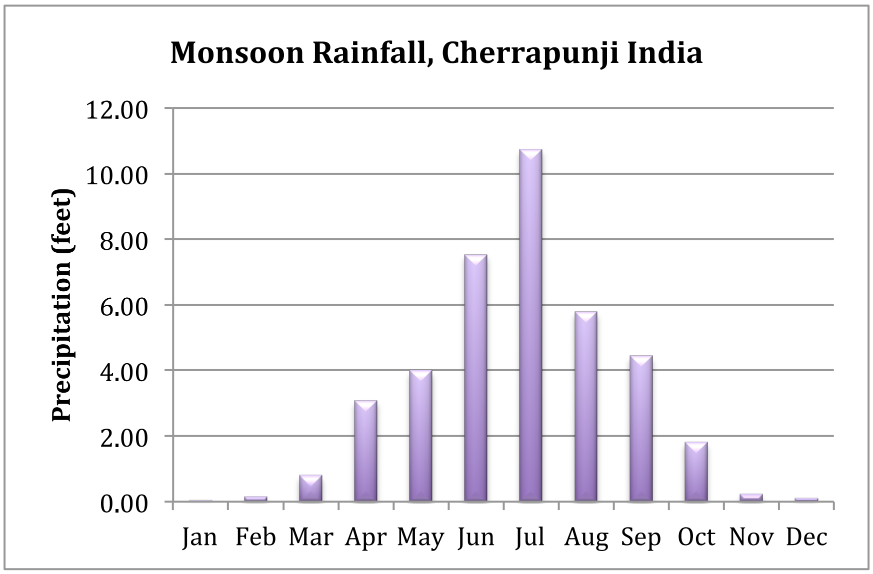


Figure 4: Seasonal monsoon rains in Cherrapunji, India show distinct wet and dry periods (NOAA data).

Seasonality is also important for precipitation that falls as snow or ice. Winter temperatures keep the water in solid form, until the increased sunlight of spring warms the atmosphere and land surface enough to cause melting. This produces a significant delay between the arrival of precipitation and subsequent runoff in river systems. Similarly, landscapes dominated by *deciduous* vegetation also show a seasonal signal. Trees that are dormant in winter do not pump water. When plants grow leaves, flowers and fruit they have much higher water demands and move water at a greater rate.

Dramatic hydrologic cycle variations are observed over the much longer time scale of *glacial* and *interglacial* periods. Because continental *ice sheets* are large, the volume of water transferred from the ocean to ice sheets is also large. During the last glacial period, ice sheets expanded when water evaporated from the ocean and precipitated on land. Because this precipitation remained frozen there was little or no runoff to return it to the ocean. Thus when ice sheets expand sea level falls, as more and more ocean water is stored on the land surface. This is shown in the record of sea level change from the last ice age (Figure 5b). Eighteen thousand years ago sea level was 125 meters (400 ft) lower than it is now because an immense amount of seawater was moved into storage as frozen continental ice sheets. As the ice sheets eventually melted, sea level rose to its present position. Modern coastal nations are very concerned about continued sea level rise. Large ice sheets remain on Greenland and Antarctica. The current melt-rate is increasing due to human-induced climatic warming, causing increasingly rapid sea level rise. If all of Earth's ice sheets melt, sea level will increase by more than 70 meters (230 feet).

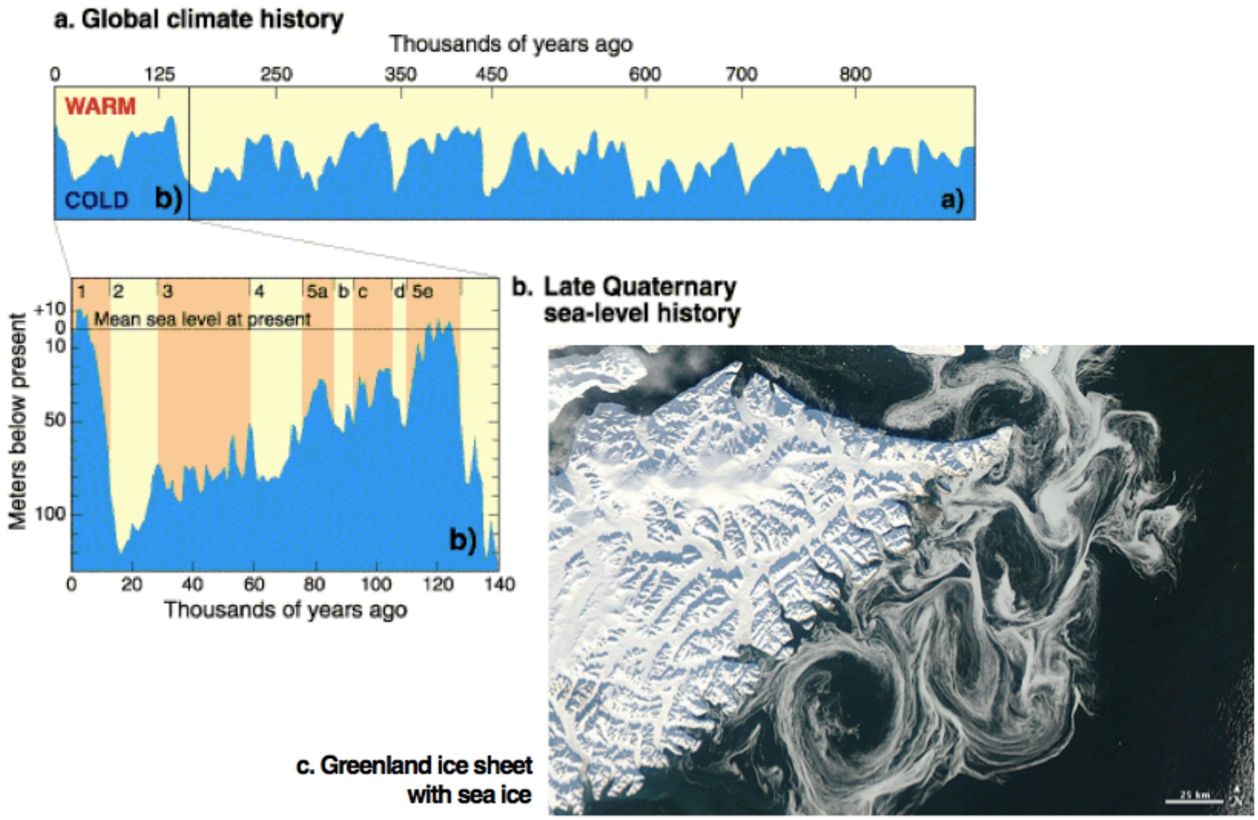


Figure 5: Ice storage on continents removes water from the ocean. (a) Record of global warm and cool periods. (b) Global sea level fall and rise during and after the last ice age. (c) NASA satellite image of the Greenland ice sheet (left) and swirls of floating sea ice released by melting (right).

Vocabulary

Aquifer: An underground zone of rock saturated with water. The rocks of an aquifer are both porous (contain empty pore spaces) and permeable; where pores are connected so that water can flow.

Condensation: The change of the physical state of matter from a gas phase into a liquid phase. It is the reverse of evaporation.

Deciduous vegetation: Deciduous means "to fall off," and is typically used to refer to trees or shrubs that lose their leaves seasonally (most commonly during autumn); also to the shedding of other plant structures such as petals after flowering or fruit when ripe. In tropical regions deciduous plants often lose their leaves during the dry season.

Evaporation: The process of liquid water becoming water vapor, including vaporization from water surfaces, land surfaces, and snow fields.

Glacial period: An interval of time (thousands of years) marked by colder temperatures and glacier advances. The last glacial period ended about 12,000 years ago.

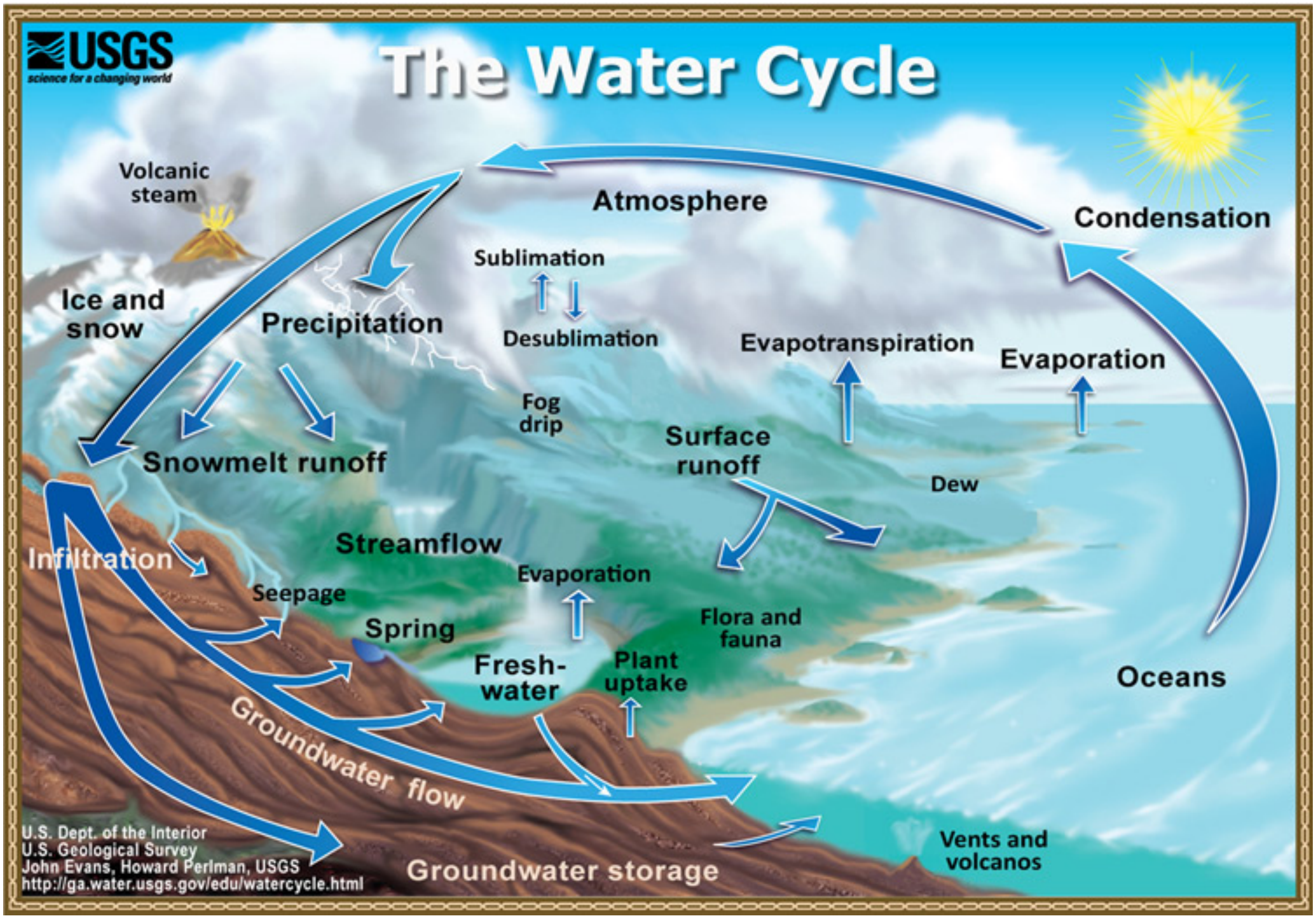


Figure 6: The Hydrologic Cycle.

Ice sheet: An ice sheet is a mass of glacial land ice extending more than 50,000 square kilometers (20,000 square miles). The two ice sheets on Earth today cover most of Greenland and Antarctica. During the last ice age, ice sheets also covered much of North America and Scandinavia. Ice sheets form in areas where snow that falls in winter does not melt entirely over the summer. Over thousands of years, the layers of snow pile up into thick masses of ice, growing thicker and denser as the weight of new snow and ice layers compresses the older layers.

Infiltration: The flow of water from the land surface into the subsurface.

Interglacial period: A geological interval of warmer global average temperature lasting thousands of years that separates consecutive glacial periods within an ice age. The current Holocene interglacial began about 12,000 years ago.

Monsoon: A seasonal change in atmospheric circulation and precipitation associated with the uneven heating of land and sea. Usually, the term monsoon is used to refer to the rainy phase of the seasonally changing pattern.

Precipitation: Any product of the condensation of atmospheric water vapor that falls under gravity; rain, snow, hail, sleet, dew, and frost.

Reservoir: A site for storage of a resource of interest. Ocean, atmosphere, and biosphere are examples of natural reservoirs of water.

Runoff: The part of the precipitation, snowmelt, or irrigation water that appears in surface streams, rivers, or artificial channels. Runoff may be classified according to source as surface runoff or groundwater runoff. Runoff can also defined as the depth to which a drainage area would be covered if all of the runoff for a given period of time were uniformly distributed over it.

Transpiration: The process by which water that is absorbed by plants, usually through the roots, is evaporated into the atmosphere from the plant surface, such as leaf pores.

Tributary stream: A smaller river or stream that flows into a larger river or stream. Usually, a number of smaller tributaries merge to form a river.

Watershed: The land area that drains water to a particular stream, river, or lake. It is a land feature that can be identified by tracing a line along the highest elevations between two areas on a map, often a ridge. Large watersheds, like the Mississippi River basin contain thousands of smaller watersheds.

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