REFERENCE

THE WATER CYCLE

By Steve Graham, Claire Parkinson, and Mous Chahine

Introduction
As seen from space, one of the most unique features of our home planet is the water, in both liquid and frozen forms, that covers approximately 75% of the Earth's surface. Believed to have initially arrived on the surface through the emissions of ancient volcanoes, geologic evidence suggests that large amounts of water have likely flowed on Earth for the past 3.8 billion years, most of its existence. As a vital substance that sets the Earth apart from the rest of the planets in our solar system, water is a necessary ingredient for the development and nourishment of life.

Earth from space. (Image courtesy of NASA Jet Propulsion Laboratory.)

Water, Water, Everywhere
Water is everywhere on Earth and is the only known substance that can naturally exist as a gas, liquid, and solid within the relatively small range of air temperatures and pressures found at the Earth's surface. In all, the Earth's water content is about 1.39 billion cubic kilometers (331 million cubic miles) and the vast bulk of it, about 96.5%, is in the global oceans. Approximately 1.7% is stored in the polar icecaps, glaciers, and permanent snow, and another 1.7% is stored in groundwater, lakes, rivers, streams, and soil. Finally, a thousandth of 1% exists as water vapor in the Earth's atmosphere.

One estimate of global water distribution:

"WATER IS A NECESSARY INGREDIENT FOR THE DEVELOPMENT AND NOURISHMENT OF LIFE."

The Water Cycle

	Volume (1000 km^3)	Percent of Total Water	Percent of Fresh Water
Oceans, Seas, & Bays	1,338,000	96.5	-
Ice caps, Glaciers, & Permanent Snow	24,064	1.74	68.7
Groundwater	23,400	1.7	-
Fresh	(10,530)	(0.76)	30.1
Saline	(12,870)	(0.94)	-
Soil Moisture	16.5	0.001	0.05
Ground Ice & Permafrost	300	0.022	0.86
Lakes	176.4	0.013	-
Fresh	(91.0)	(0.007)	.26
Saline	(85.4)	(0.006)	-
Atmosphere	12.9	0.001	0.04
Swamp Water	11.47	0.0008	0.03
Rivers	2.12	0.0002	0.006
Biological Water	1.12	0.0001	0.003
Total	1,385,984	100.0	100.0

Source: Gleick, P. H., 1996: Water resources. In *Encyclopedia of Climate and Weather,* ed. by S. H. Schneider, Oxford University Press, New York, vol. 2, pp.817-823.

Estimates of groundwater are particularly difficult and vary widely amongst sources, with the value in this table being near the high end of the range. Using the values in this table, groundwater constitutes approximately 30% of fresh water, whereas ice (including ice caps, glaciers, permanent snow, ground ice, and permafrost) constitute approximately 70% of fresh water. With other estimates, groundwater is sometimes listed as 22% and ice as 78% of fresh water.

next: A Multi-Phased Journey

The Water Cycle

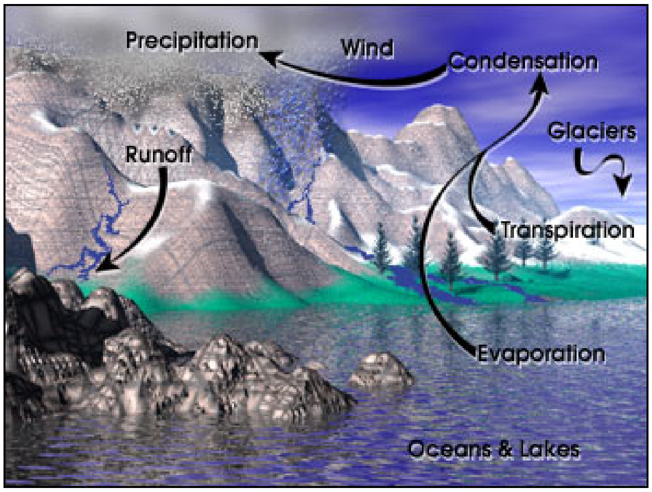
A Multi-Phased Journey

The hydrologic cycle describes the pilgrimage of water as water molecules make their way from the Earth's surface to the atmosphere, and back again. This gigantic system, powered by energy from the sun, is a continuous exchange of moisture between the oceans, the atmosphere, and the land.

"Roughly one-third of the Earth's annual precipitation that falls on the continents runs off into the oceans."

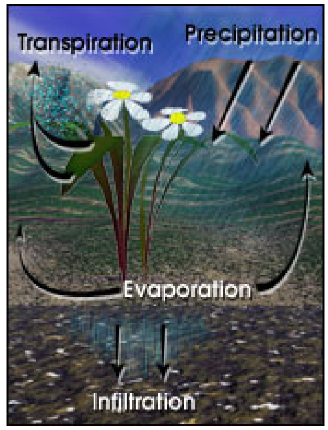
The Water Cycle

[The Aqua Spacecraft](#)
[References](#)



In the hydrologic cycle, individual water molecules travel between the oceans, water vapor in the atmosphere, water and ice on the land, and underground water. (Image by Hailey King, NASA GSFC.)

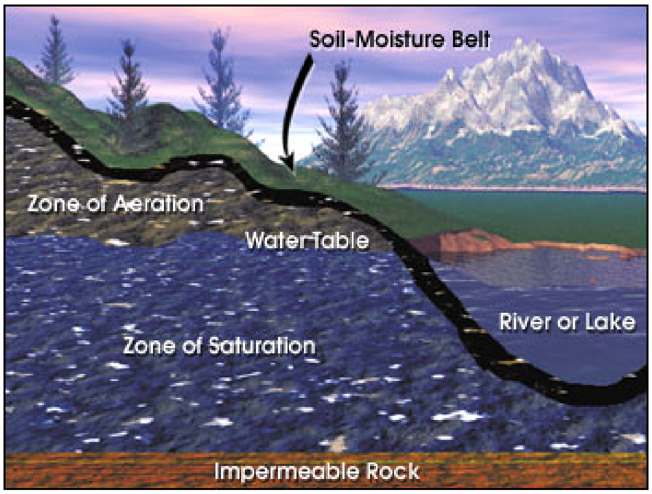
Studies have revealed that the oceans, seas, and other bodies of water (lakes, rivers, streams) provide nearly 90% of the moisture in our atmosphere. Liquid water leaves these sources as a result of evaporation, the process by which water changes from a liquid to a gas. In addition, a very small portion of water vapor enters the atmosphere through sublimation, the process by which water changes from a solid (ice or snow) to a gas. (The gradual shrinking of snow banks, even though the temperature remains below the freezing point, results from sublimation.) The remaining 10% of the moisture found in the atmosphere is released by plants through transpiration. Plants take in water through their root systems to deliver nutrients to their leaves, then release it through small pores, called stomates, found on the undersides of their leaves. Together, evaporation, sublimation, and transpiration, plus volcanic emissions, account for all the water vapor in the atmosphere. While evaporation from the oceans is the primary vehicle for driving the surface-to-atmosphere portion of the hydrologic cycle, transpiration is also significant. For example, a cornfield 1 acre in size can transpire as much as 4000 gallons of water every day.



Plants return water to the atmosphere through transpiration. In this process, water evaporates from pores in the plant's leaves, after being drawn, along with nutrients, from the root system through the plant. (Image by Hailey King, NASA GSFC.)

After the water enters the lower atmosphere, rising air currents carry it upward, often high into the atmosphere, where the air cools and loses its capacity to support water vapor. As a result, the excess water vapor condenses (i.e., changes from a gas to a liquid) to form cloud droplets, which can eventually grow and produce precipitation (including rain, snow, sleet, freezing rain, and hail), the primary mechanism for transporting water from the atmosphere back to the Earth's surface.

When precipitation falls over the land surface, it follows various routes. Some of it evaporates, returning to the atmosphere, and some seeps into the ground (as soil moisture or groundwater). Groundwater is found in two layers of the soil, the "zone of aeration," where gaps in the soil are filled with both air and water, and, further down, the "zone of saturation," where the gaps are completely filled with water. The boundary between the two zones is known as the water table, which rises or falls as the amount of groundwater increases or decreases. The rest of the water runs off into rivers and streams, and almost all of this water eventually flows into the oceans or other bodies of water, where the cycle begins anew (or, more accurately, continues). At different stages of the cycle, some of the water is intercepted by humans or other life forms.



The water table is the top of the zone of saturation and intersects the land surface at lakes and streams. Above the water table lies the zone of aeration and soil moisture belt, which supplies much of the water needed by plants. (Image by Hailey King, NASA GSFC.)

Even though the amount of water in the atmosphere is only 12,900 cubic kilometers (a minute fraction of Earth's total water supply that, if completely rained out, would cover the Earth's surface to a depth of only 2.5 centimeters), some 495,000 cubic kilometers of water are cycled through the atmosphere every year, enough to uniformly cover the Earth's surface to a depth of 97 centimeters. Because water continually evaporates, condenses, and precipitates, with evaporation on a global basis approximately equaling global precipitation, the total amount of water vapor in the atmosphere remains approximately the same over time. However, over the continents, precipitation routinely exceeds evaporation, and conversely, over the oceans, evaporation exceeds precipitation. In the case of the oceans, the routine excess of evaporation over precipitation would eventually leave the oceans empty if they were not being replenished by additional means. Not only are they being replenished, largely through runoff from the land areas, but, over the past 100 years, they have been over-replenished, with sea level around the globe rising by a small amount. Sea level rises both because of warming of the oceans, causing water expansion and thereby a volume increase, and because of a greater mass of water entering the ocean than the amount leaving it through evaporation or other means. A primary cause for increased mass of water entering the ocean is the calving or melting of land ice (ice sheets and glaciers).

Throughout the hydrologic cycle, there are an endless number of paths that a water molecule might follow. Water at the bottom of Lake Superior may eventually fall as rain in Massachusetts. Runoff from the Massachusetts rain may drain into the Atlantic Ocean and circulate northeastward toward Iceland, destined to become part of a floe of sea ice, or, after evaporation to the atmosphere and precipitation as snow, part of a glacier. Water molecules can take an immense variety of routes and branching trails that lead them again and again through the three phases of ice, liquid water, and water vapor. For instance, the water molecules that once fell 100 years ago as rain on your great grandparents' farmhouse in Iowa might now be falling as snow on your driveway in California.

next: The Water Cycle and Climate Change
back: Introduction

The Water Cycle

The Water Cycle and Climate Change

Amongst the highest priorities in Earth science and environmental policy issues confronting society are the potential changes in the Earth's water cycle due to climate change. The science community now generally agrees that the Earth's climate will undergo changes in response to natural variability, including solar variability, and to increasing concentrations of greenhouse gases and aerosols. Furthermore, agreement is widespread that these changes may profoundly affect atmospheric water vapor concentrations, clouds, and precipitation patterns. For example, a warmer climate, directly leading to increased evaporation, may well accelerate the hydrologic cycle, resulting in an increase in the amount of moisture circulating through the atmosphere. Many uncertainties remain, however, as illustrated by the inconsistent results given by current climate models regarding the future distribution of precipitation.

"A WARMER CLIMATE, DIRECTLY LEADING TO INCREASED EVAPORATION, MAY WELL ACCELERATE THE HYDROLOGIC CYCLE."

The Water Cycle

The Persian Gulf from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite. Arid regions like this may face increasingly severe water shortages as global climate changes. (Image by Brian Montgomery, Earth Observatory, and Mark Gray, MODIS Atmosphere Group, NASA GSFC.)

next: The Aqua Mission and the Water Cycle
back: A Multi-Phased Journey

The Water Cycle

The Aqua Mission and the Water Cycle

As mentioned earlier, the hydrologic cycle involves evaporation, transpiration, condensation, precipitation, and runoff. NASA's Aqua satellite will monitor many aspects of the role of water in the Earth's systems, and will do so at spatial and temporal scales appropriate to foster a more detailed understanding of each of the processes that contribute to the hydrologic cycle. These data and the analyses of them will nurture the development and refinement of hydrologic process models and a corresponding improvement in regional and global climate models, with a direct anticipated benefit of more-accurate weather and climate forecasts.

Aqua's contributions to monitoring water in the Earth's environment will involve all six of Aqua's instruments: the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit (AMSU), the Humidity Sounder for Brazil (HSB), the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), the Moderate Resolution Imaging Spectroradiometer (MODIS), and Clouds and the Earth's Radiant Energy System (CERES). The AIRS/AMSU/HSB combination will provide more-accurate space-based measurements of atmospheric temperature and water vapor than have ever been obtained before, with the highest vertical resolution to date as well. Since water vapor is the Earth's primary greenhouse gas and contributes significantly to uncertainties in projections of future

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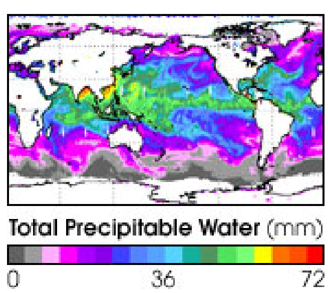
The Water Cycle



Total precipitable water from the Advanced Microwave Sounding Unit (AMSU) aboard the NOAA 15 satellite.

global warming, it is critical to understand how it varies in the Earth system.

The water in clouds will be examined with MODIS, CERES, and AIRS data; and global precipitation will be monitored with AMSR-E. The cloud data will include the height and areal coverages of clouds, the liquid water content, and the sizes of cloud droplets and ice particles, the latter sizes being important to the understanding of the optical properties of clouds and their contribution to the Earth's albedo (reflectivity). HSB and AMSR-E, both making measurements at microwave wavelengths, will have the ability to see through clouds and detect the rainfall under them, furthering the understanding of how water is cycled through the atmosphere.

Frozen water in the oceans, in the form of sea ice, will be examined with both AMSR-E and MODIS data, the former allowing routine monitoring of sea ice at a coarse resolution and the latter providing greater spatial resolution but only under cloud-free conditions. Sea ice can insulate the underlying liquid water against heat loss to the often frigid overlying polar atmosphere and also reflects sunlight that would otherwise be available to warm the ocean. AMSR-E measurements will allow the routine derivation of sea ice concentrations in both polar regions, through taking advantage of the marked contrast in microwave emissions of sea ice and liquid water. This will continue, with improved resolution and accuracy, a 22-year satellite record of changes in the extent of polar ice. MODIS, with its finer resolution, will permit the identification of individual ice floes, when unobscured by clouds.

AMSR-E and MODIS will also provide monitoring of snow coverage over land, another key indicator of climate change. Here too, the AMSR-E will allow routine monitoring of the snow, irrespective of cloud cover, but at a coarse spatial resolution, while MODIS will obtain data with much greater spatial detail under cloud-free conditions.

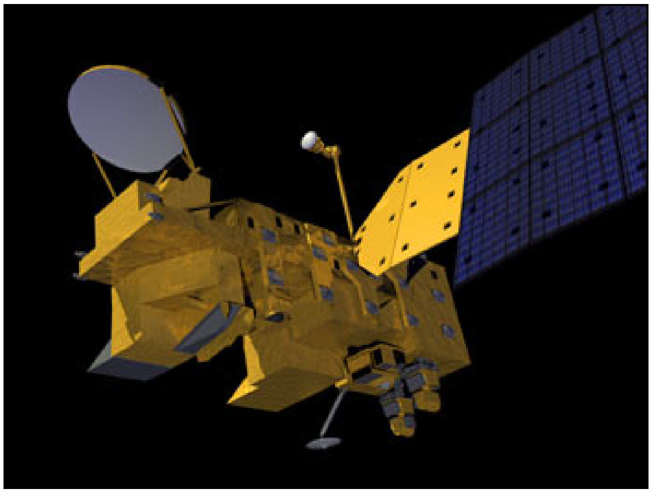
As for liquid water on land, AMSR-E will provide an indication of soil moisture, which is crucial for the maintenance of land vegetation, including agricultural crops. AMSR-E's monitoring of soil moisture globally should permit, for example, the early identification of signs of drought episodes.

next: The Aqua Spacecraft
back: The Water Cycle and Climate Change

The AMSU instrument aboard the Aqua satellite will complement NOAA's AMSU instruments, resulting in a better understanding of the Earth’s water cycle. (Image courtesy of NOAA.)

The Aqua Spacecraft

Aqua is a major mission of the Earth Observing System (EOS), an international program centered in NASA's Earth Science Enterprise to study the Earth in detail from the unique vantage point of space. Focused on key measurements identified by a consensus of U.S. and international scientists, EOS is further enabling studies of the complex interactions amongst the Earth's land, ocean, air, ice and biological systems.



The Aqua Spacecraft. Aqua's instruments are on the underside of the spacecraft, pointing towards Earth. (Image by Jesse Allen, Visualization Analysis Lab, NASA GSFC, from material provided by the Aqua Project.)

The Aqua spacecraft will circle the Earth in an orbit that ascends across the equator each day at 1:30 p.m. local time and passes very close to the poles, complementing the 10:30 a.m. measurements being made by Terra, the first of the EOS spacecraft, launched in December 1999. The instrument complement on Aqua is designed to provide information on a great many processes and components of the Earth system, including cloud formation, precipitation, water vapor, air temperature, cloud radiative properties, sea surface temperature, surface wind speeds, sea ice concentration and temperature, snow cover, soil moisture, and land and ocean vegetation. The individual swaths of measurements will be compiled into global images, with global coverage of many variables being obtained as frequently as every two days or, with the help of numerical models, combined every 6 or 12 hours into comprehensive representations of the Earth's atmospheric circulation and surface properties. In combination with measurements from other polar orbiting satellites, Aqua measurements will also provide accurate monthly-mean climate assessments that can be compared with and assimilated into computer model simulations of the Earth's climate.

"The Aqua spacecraft will circle the Earth in an orbit that ascends across the equator each day at 1:30 p.m. local time."

The Water Cycle

The Earth Observing System has three major components: the EOS spacecraft, an advanced ground-based computer network for processing, storing, and distributing the collected data (the EOS Data and Information System); and teams of scientists and applications specialists who will study the data and help users in universities, industry, and the public apply it to issues ranging from weather forecasting and climate prediction to agriculture and urban planning.

next: References
back: The Aqua Mission and the Water Cycle

The Water Cycle

Print References

Ahrens, C. Donald. *Meteorology: An Introduction to Weather, Climate, and the Environment.* St. Paul: West Publishing Company, 1994.

Chahine, Moustafa T. "The hydrological cycle and its influence on climate," *Nature* 359 (1992): 373-380.

Lutgens, Frederick K., and Edward J. Tarbuck. *The Atmosphere: An Introduction to Meteorology.* Upper Saddle River: Prentice Hall, 1998.

Moran, Joseph M., and Michael D. Morgan. *Meteorology: The Atmosphere and the Science of Weather.* Upper Saddle River: Prentice Hall, 1997.

Schneider, Stephen H., ed. *Encyclopedia of Climate and Weather.* New York: Oxford University Press, 1996.

back: The Aqua Spacecraft
return: Introduction

The Water Cycle