Climate Science

GLOBAL WATER CYCLE/WATER VAPOR FLUX AND TOPOGRAPHICAL RELIEF

MONITORING DROUGHT

Background:

Drought continued across the Plains and the West through the 2013 agricultural season following the hot and dry summer of 2012. The summer of 2012 can be considered to have had one of the nation's worst droughts in the last 80 years, which resulted in significant monetary losses across the nation due to lost crops, numerous wildfires and diminished barge traffic on the Mississippi River. Welcome winter precipitation along with spring and early summer rains helped ease or eliminate drought conditions in many areas of the Plains. However, many areas across the nation's midsection suffered from a lack of precipitation in mid to late summer, resulting in a return to drought conditions across the region. One could inspect the tables of monthly precipitation (in hundredths of an inch) that are furnished by the National Weather Service several days after the conclusion of each month for nearly 250 selected U.S. cities. Many of the cities across the upper and mid-Mississippi Valleys along with the Southeast had monthly precipitation totals in September 2013 that were below "normal" (or the averages from the 1981-2010 climatological reference interval). Sections of the Pacific Northwest, the southern Rockies and the western Gulf Coast reported above average September precipitation totals.

What constitutes a drought? The answer depends upon whom you ask. At least four types of drought can be defined. To the farmer, an *agricultural drought* represents an extended interval with a serious soil moisture deficiency during critical crop growth periods. A hydrologist would classify a *hydrological drought* as an extended interval containing abnormally low stream flow, lake levels and ground water reservoirs. Most meteorologists would consider a *meteorological drought* to occur when the accumulated precipitation is well below a prescribed amount that would depend upon the region or season. A fourth type would be *socioeconomic drought*, where the shortage of water affects humans, typically in terms of economic activities. Economic goods that may be affected may include water, agricultural food products and hydroelectric power.

Typically, the severity of a drought depends upon the lack of soil moisture, which is influenced by one or more of the following factors to include a lack of precipitation, low atmospheric humidity, high air temperature, strong winds, a lack of clouds and intense sunlight. In addition, the drought severity depends upon its duration and the size of the affected area.

The start of a drought usually is subtle in that few can tell when a spell of dry weather really constitutes the incipient phase of a drought. Similarly, the end of a drought is also difficult to assess, since one rain event does not necessarily "break a drought". The National Weather Service uses several indices to assess the severity of a drought. One of the most frequently used drought indices is the Palmer Drought Severity Index developed by Wayne Palmer in the 1960s. This Palmer Index, with unit-less values ranging from below -4 (severe drought) to above +4 (extremely moist),. incorporates temperature and rainfall information in a formula to determine abnormal dryness or wetness over prolonged time intervals, such as a month to years. The National Weather Service and U.S. Department of Agriculture jointly compute the Drought Index weekly for each of 344 climatological divisions across the United

States. A map of the current Drought Index is available that shows those divisions experiencing drought with negative index values and varying shades of red, while those regions with excess precipitation have positive values and varying shades of green.

The most recent map (weekly index values ending 28 September 2013) shows a widespread region of moderate to extreme drought across the West, primarily in California and Nevada and across Wyoming, southeastern Idaho and central Montana. Moderate to severe drought conditions were also indicated across sections of the upper and mid-Mississippi Valleys, along with the central and southern Plains. On the other hand, a few scattered areas across the West, especially over the interior Northwest, the southern Rockies and the northern Plains had unusually moist to very moist conditions. Additional areas that experienced unusually moist to very moist conditions were found across the Southeast and the Northeast. Near normal soil moisture conditions prevailed over the remainder of the nation.

Beginning in 2000, the National Drought Mitigation Center, a group consisting of several governmental agencies along with the University of Nebraska-Lincoln, has maintained a US Drought Monitor site that provides weekly updates of current drought information and forecasts of the potential for drought across the nation. Their current summary map of drought conditions attempts to improve upon the Palmer Drought Severity Index and synthesize five other indices, together with a certain amount of subjectivity to arrive at six drought severity categories. They attempt to show the short-term impacts of the drought upon agriculture and wildfire potential and long-term impacts on hydrology and ecology. (A description of the categories used in the drought classification scheme appearing on the National Drought Monitor map is available.) Their most recent map (1 October 2013) shows scattered areas of severe to extreme drought across a large section of the nation, extending from the Mississippi Valley westward across the Plains, the central Rockies and the Great Basin into central and southern California. Pockets of exceptional drought continued across sections of the southern high Plains in southwestern Oklahoma, north Texas and southeastern Colorado, along with the Great Basin in west central Nevada. While some areas of the Midwest were experiencing short-term drought conditions, the drought across many areas of the Plains and the Far West in Nevada and California would have both short and long-term consequences. Short-term drought that would typically have durations of less than six months affect agriculture and grasslands, while long-term drought exceeds six months and would affect rivers, lakes and groundwater (or "hydrology"), along with trees and other natural perennial vegetation (or "ecology"). An accompanying narrative entitled "National Drought Summary" also provides a five-day forecast and a 6- to 10-day outlook for precipitation and temperature across the country. This site also includes animated Drought Monitor maps for the prior six and twelve weeks. The *Drought Impact Reporter* is an interactive tool that permits exploration of the reported drought impacts across the nation. The goal is to help in risk management that could ultimately help shape drought related policy at the state and federal levels.

The US Seasonal Drought Outlook (released on 19 September 2013 by the Climate Prediction Center and valid through December 2013) indicates that the current drought conditions across most of the nation extending from the Midwest to the Pacific Coast should persist. However, limited improvements in drought conditions could occur across sections of the Mid-South, the northern Rockies in Montana and the northern California coast that are currently experiencing drought. Several areas of northern Idaho and southwestern Oregon could be removed from drought conditions by the end of the calendar year.

Source:

Palmer, W.C., 1988 (12 Jul): The Palmer Drought Index: When and how it was developed. *Weekly Weather and Crop Bulletin, 75* (28), 5.

GLOBAL WATER CYCLE

Driving Question: *How does the global water cycle link the principal components of the Earth system?*

Educational Outcomes: To describe how unique properties of water place it in a major role establishing the boundary conditions and variability of climate. To explain how water cycles throughout the Earth system and impacts climate on all spatial and time scales, as well as how it transports heat globally as part of the never-ending drive towards a uniform distribution of energy.

Objectives: In the holistic Earth system perspective, Earth is composed of many interacting subsystems including the atmosphere, geosphere, hydrosphere, cryosphere, and biosphere. Earth's climate system encompasses aspects of these same components because their mutual interactions and responses to external influences determine climate on local, regional, and global scales.

After completing this investigation, you should be able to:

- Describe the components of the global water cycle within Earth's climate system.
- Explain ways in which the global water cycle links the various subsystems of Earth's climate system through flows of mass and energy.
- Explain the steady-state global water budget with more precipitation than evaporation occurring over land and more evaporation than precipitation taking place over ocean being balanced by the excess water on land dripping, seeping, and flowing back to sea.

The Global Water Cycle

In this investigation, some of the roles of water in shaping climate are explored, particularly as water participates in the complex redistribution of energy and mass by Earth's coupled atmosphere/ocean system.

Figure 1 is a depiction of the water cycle in terms of mass and mass flows between oceanic, terrestrial, atmospheric, and biospheric reservoirs. It provides a view of the water cycle already familiar to most people. What it does not display is the essential reason why water cycles through its reservoirs, namely, the accompanying energy flow. **The mass flow of water as portrayed in the figure is basically a response to the non-uniform distribution of energy in the Earth system.** Water's coexistence in three different phases, its high specific heat and latent heats, and the relative ease with which it changes phase within the temperature and pressure ranges on Earth, makes it the working fluid that absorbs, transports, and releases heat within the Earth system.

Water is the primary mover of energy from where there is relatively too much energy, to where there is too little energy. Winds transport water vapor to every location on Earth, including the highest mountain peaks. Changing back to liquid or solid within the atmosphere, water begins its gravity-driven return trip to Earth's surface and eventually flows into the ocean. Ocean currents also transport energy as warm waters flow to higher latitudes and cold waters to lower latitudes. Development of a more complete and authentic depiction of the global water cycle, including both mass and energy flows, is an integral part of Earth's climate system.

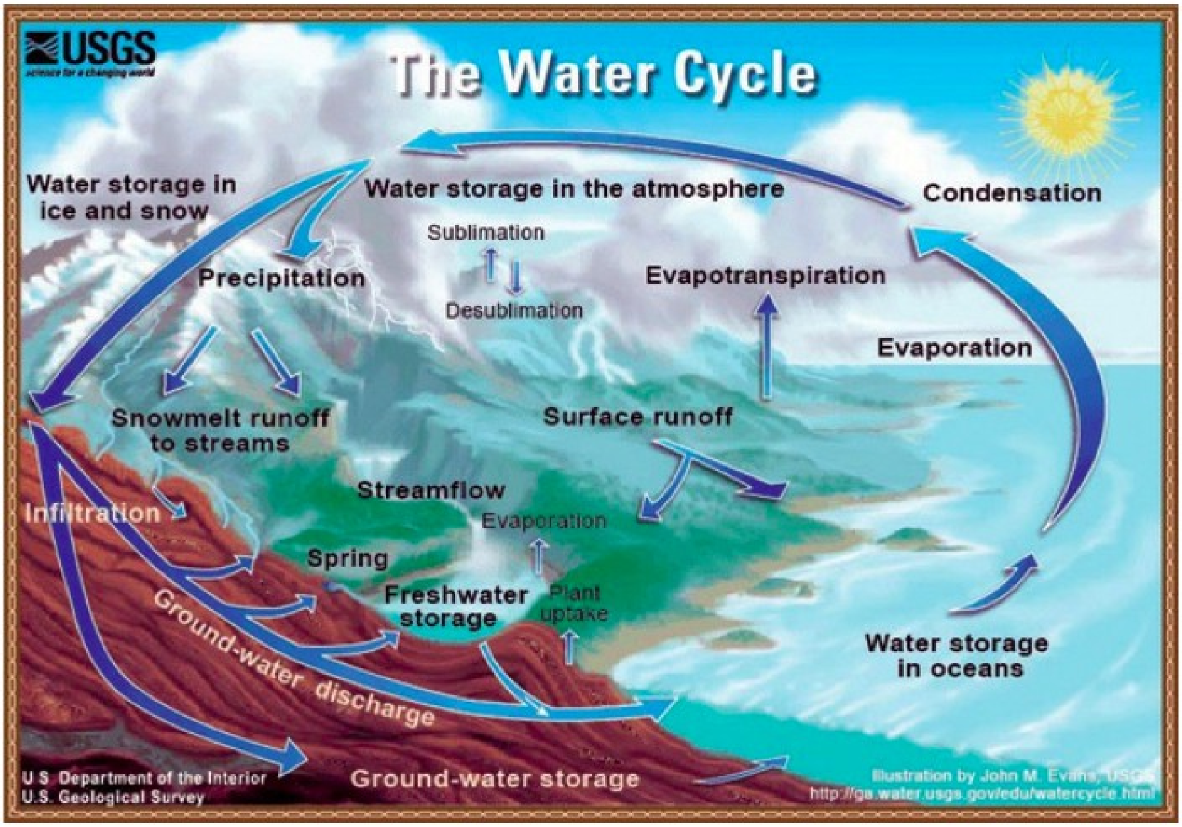


Figure 1.
The Water Cycle [USGS]

Water flow in the atmosphere is the essential heat-driven ***uphill*** component of the water cycle that lifts water as vapor to great altitudes and transports it around the globe. The atmospheric water vapor flow embodied in the water cycle is invisible to our eyes because water vapor is transparent. However, special infrared sensors aboard weather satellites can detect the presence of water vapor (and clouds) in the atmosphere above altitudes of about 3000 m (10,000 ft).

You can view an animation of real Earth perspective full-disk GOES East water vapor imagery for the last day at: *http://www.ssec.wisc.edu/data/geo/index.php?satellite=east&channel=vis&coverage=fd&file=jpg&imgoranim=8&anim_method=jsani (QR Code)*. At the SSEC Geostationary Satellite Images site, click on Imager Channel: Water Vapor 6.5 µm to view the most recent full-disk atmospheric water vapor.

To examine an animated full global composite view covering the past week, go to: *http://www.ssec.wisc.edu/data/comp/wv/wvmoll.mpg.*

In the atmospheric water vapor imagery bright white patches represent the relatively cold tops of high clouds. Clouds occur where there are significant upward atmospheric motions. Medium gray regions depict mainly water vapor. These gray regions would probably appear clear on visible and ordinary infrared satellite images. Streaks and whirls of gray are common patterns in the water vapor images at the middle and higher latitudes. Dark areas are relatively dry portions of the middle atmosphere resulting from the sinking of low humidity air from higher altitudes.

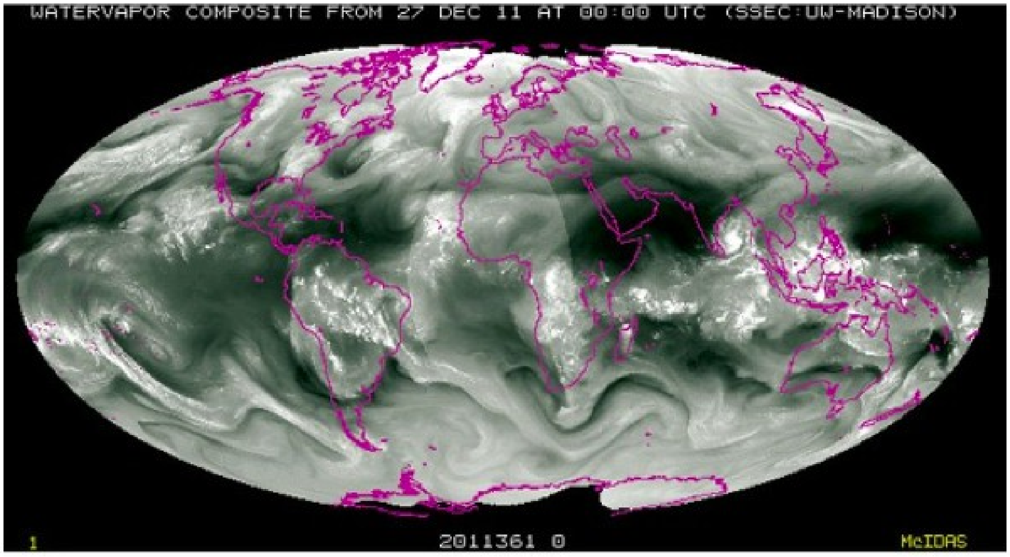
1. Viewed in animation, the cloud patterns in the tropics and the curving swirls of water vapor in middle latitudes of the Northern and Southern Hemisphere portions of the images reveal that atmospheric motions **[(*do*)(*do not*)]** transport water vapor horizontally over great distances within the atmosphere.

2. Examine the general motion in the middle latitudes of the Northern and Southern Hemispheres. [To better analyze motions, consider using the control button to step forward through successive images.] In the middle latitudes, the dominant horizontal motion in both hemispheres is from **[(*higher to lower latitude*)(*east to west*)(*west to east*)]**.

3. Examine the motion seen in the tropical latitudes. The numerous bright white cloud patches at these latitudes signify upward convection currents and thunderstorms. These tropical clouds embedded in air with relatively high water vapor concentrations generally mark the ***Intertropical Convergence Zone (ITCZ).*** Here, intense solar energy arriving at Earth's surface heats near-surface air, promoting evaporation (and transpiration, especially in tropical rainforests) and upward vertical motions. The dominant horizontal motion in the ITCZ is from **[(*east to west*)(*west to east*)]**.

Figure 2 displays two composite images acquired one day apart. The upper image is from 0000 UTC 27 DEC 2011 (7:00 pm EST on the 26th) and the lower image is 24 hours later, 0000 UTC 28 DEC 2011. During this time period a winter storm system delivering considerable precipitation traveled up the U.S. East Coast packing strong winds that downed trees and power lines leading to delays in post-holiday travel.

4. Note on the upper image the broad band of light gray extending from the tropical Pacific Ocean across central Mexico to the Southeastern states. The brightest area in that band centered northwest of Florida corresponds to the major winter storm that brought high winds and heavy rains across a broad area of the country while traveling up the East Coast. Such midlatitude swirls are storm systems that transport warm humid air poleward to be replaced by colder drier polar air moving equatorward. Such storm motions transfer **[(*water mass*)(*heat energy*)(*both*)]** within the Earth system.



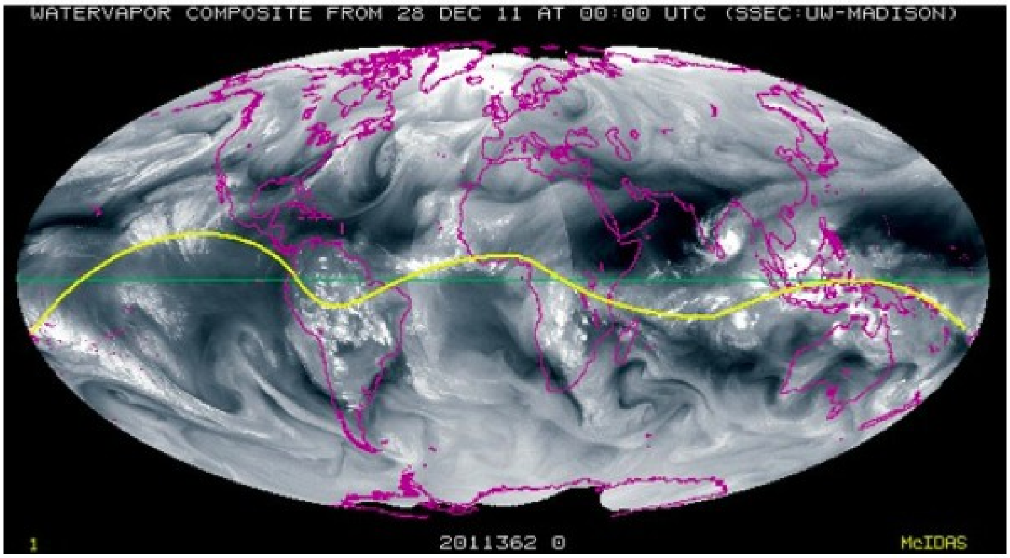


Figure 2.
Composite satellite images displaying the distribution of water vapor in the middle levels of the atmosphere at 0000 UTC 27 December 2011 (upper view) and 0000 UTC 28 December 2011 (lower view). The lower view has lines signifying the positions of the equator (green) and average December position of the Intertropical Convergence Zone (ITCZ) in yellow. [SSEC-UW]

5. Based on what you learned about midlatitude atmospheric motions (generally west to east) from the animated images, it appears that the plume of water vapor fueling the winter storm system described above originated primarily (upper image) from the **[(*Pacific Ocean*)(*Atlantic Ocean*)]**. It is evident from a global water cycle perspective, that water evaporated from ocean surfaces was incorporated in the overlying air and transported to areas above land surfaces where significant quantities then precipitated as rain, freezing rain (icing), and snow.

6. Now examine the lower image in Figure 2 showing atmospheric water vapor distribution one day after the upper image. Focus in on the U.S. East Coast area. It is evident from the two images that the winter storm had moved generally towards the **[(*east*)(*west*)]**. This movement, combined with north or south components, is commonly characteristic of midlatitude storm systems. The patterns and frequency of such storm systems have major impacts on local and regional climate at places in their paths.
7. A straight green line has been drawn across the midsection of the lower image in Figure 2 to represent the equator. The yellow curve approximates the center of the average December position of the Intertropical Convergence Zone (ITCZ). The ITCZ is a relatively narrow, irregular band of convective clouds and thunderstorms roughly parallel to the equator in which huge quantities of water vapor enter the atmosphere from underlying warm surface ocean waters and tropical rainforests (e.g., Amazon Basin). Note the general agreement between the brightest clouds surrounded by light gray shadings and the average December ITCZ position. They show that at this time of the year the ITCZ is largely **[(*north*)(*south*)]** of the equator. Six months later, the ITCZ is found almost entirely on the opposite side of the equator.

8. In Figure 2, two darker irregular bands surrounding Earth and located north and south of the equator indicate the presence of **[(*dry*)(*humid*)]** air. These are broad regions of relatively high surface air pressure and associated sinking air which produce relatively persistent clear skies

and fair-weather conditions, which in turn have major impacts on local and regional climates.

9. The flow of atmospheric water vapor is a major energy transport mechanism in Earth's climate system. The energy flow starts with the evaporation of water from ocean and land surfaces or transpiration by vegetation transferring energy **[(from air to water and land surfaces or vegetation) (from water and land surfaces or vegetation to air)].**

10. Atmospheric water vapor is often carried great distances before it condenses to liquid or solid cloud particles, thereby transporting huge quantities of **[(*sensible*)(*latent*)]** heat energy from one place to another.

11. Assume that much of the heat energy added to the environment by the late December 2011 Southeastern U.S. winter storm depicted in Figure 2 was carried in the water vapor plume shown flowing generally northeastward into the storm. The heat energy carried by the plume in the lower image was now originating most directly from the **[(*Pacific Ocean*)(*Atlantic Ocean*)]**. In combination with Item 5, it is evident that the global water cycle embodies both mass and energy flow.

The global water cycle's transport of mass (and, indirectly, energy) can be traced via NASA's Tropical Rainfall Measuring Mission's (TRMM) rainfall animations. TRMM provides estimates of rainfall between about 40 degrees N and 40 degrees S using sensors on a satellite.

Go to: *http://trmm.gsfc.nasa.gov/publications_dir/global.html* and click on A WEEK of Rainfall "Medium Quicktime" or "Medium Mpeg" to observe rainfall patterns for the previous seven days.

12. The TRMM Rainfall patterns during the past week, when generalized, show evidence of **[(*passage of storm systems from ocean to land and from land to ocean*)**
(*general eastward motion of midlatitude storms*)
(*general westward motion of tropical storms*)(*all of these*)].

At the same NASA TRMM website, click on A WEEK of Rainfall ACCUMULATION "Medium Quicktime" or "Medium Mpeg" to observe accumulated rainfall patterns for the previous seven days.

13. Broad areas in the TRMM global accumulated rainfall pattern for the past week that exhibited evidence of little or no rainfall generally **[(*show no relationship to*)(*coincide with*)]** the dark areas in the animated global views of atmospheric water vapor you viewed at the beginning of this investigation. As you recall, the dark areas denoted low water vapor content.

Summary: Water cycles throughout the Earth system. Water vapor flow in the atmosphere is the essential heat-driven ***uphill*** component of the water cycle that lifts water as vapor to great altitudes and transports it around the globe. The atmospheric energy flow embodied in the water cycle is largely invisible to our eyes but special infrared sensors aboard weather satellites enable us to monitor it. The atmosphere delivers water vapor globally and impacts climate on all spatial and time scales, acting as a major agent transporting heat in a never-ending drive towards a more uniform distribution of energy.

WATER VAPOR FLUX AND TOPOGRAPHICAL RELIEF

Driving Question: *Do precipitation amounts on windward and leeward sides of mountains differ?*

Educational Outcomes: To investigate the role of elevation as a boundary condition of climate. To examine the influence of topographical relief on precipitation. To explain the differences in precipitation patterns on the windward and leeward slopes of mountain ranges.

Objectives: The flow of air in the atmosphere forced vertically by changes in the elevation of Earth's surface plays major roles in determining climates, particularly in regions exhibiting significant topographical relief. After completing this investigation, you should be able to:

- Compare precipitation amounts at locations on the windward and leeward sides of a mountain range.
- Explain how and why precipitation totals vary on the windward and leeward slopes of a mountain range.
- Describe the implications of topographically-induced variations in precipitation for activities that depend on the fresh water supply.

Orographic Precipitation

Vertical motions in the atmosphere forced by changes in the elevation of Earth's surface play major roles in determining climates, particularly in regions exhibiting significant topographical relief. ***Orographic*** lifting is an important boundary-condition mechanism that can bring air to saturation and subsequently cause cloud formation and precipitation. Air flowing up the windward slopes of a mountain range is subjected to decreasing air pressure, which brings on expansion and cooling. With sufficient ascent and cooling, the air becomes saturated, clouds form, and precipitation usually develops. Air flowing down the leeward slopes of a mountain range is compressed by the increased air pressure and warms. With warming, existing clouds vaporize in the descending air. Once the clouds have vaporized, the relative humidity decreases as the sinking air continues to warm by compression.

Where large-scale winds blow persistently toward a prominent mountain range, the climate of the windward slope can be much wetter than the climate of the leeward slopes. And, in fact, the region of reduced cloudiness and precipitation downwind may extend great distances from the mountain range. In this so-called ***rain shadow***, meager precipitation coupled with frequent sunny skies that promote evaporation means agricultural activity is likely to be limited without irrigation.

1. The topographic influence on precipitation is especially evident across the U.S. Pacific Northwest where the large-scale atmospheric circulation across the region is fairly consistent. For a view of the recent flow of water vapor over that region, go to:? *http://www.wrh.noaa.gov/satellite/*. Scroll down to the table and its "Water Vapor" section. In its "Western US" coverage, click on the 16-km resolution "Animation." The general flow of water vapor at the U.S. Pacific Northwest latitudes is
towards the **[(*west*)(*east*)]**.

Prevailing winds deliver relatively humid air masses from their Pacific Ocean source regions. North-south oriented mountain ranges provide barriers to the humid flow, forcing it upward or around the topographical obstacles. In winter the region's weather is often dominated by a procession of storm systems from over the Pacific Ocean. In summer, storm systems are less frequent and accompanied by less precipitation.

Figure 1 below is a colorized relief map of Washington State and adjacent areas with near sea-level elevations of the land in green. North is to the top of the map. The Cascade Mountains trend north-south through the center of Washington with the Olympic Mountains in the west and the Coast Range to the southwest into Oregon.

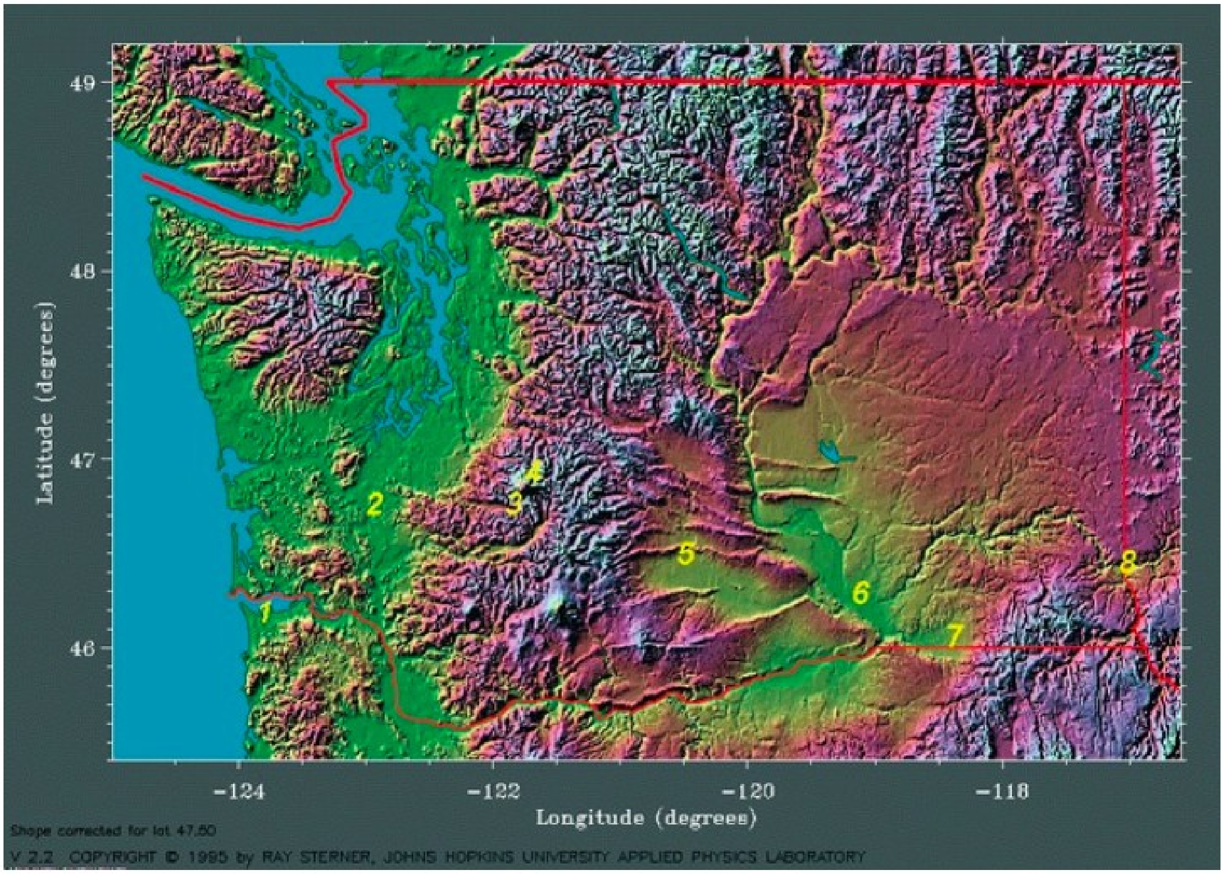


Figure 1.
Relief map of Washington State. [Modified from map by Ray Sterner, Johns Hopkins University Applied Physics Laboratory]

Numbers plotted on the map identify locations listed in **Table 1** below. Table 1 gives the elevation (in feet above mean sea level), and mean seasonal and annual precipitation (in inches of rain plus liquid equivalence of snow) for eight stations. The seasons are defined by meteorological convention: winter (December - February), spring (March - May), summer (June - August), and autumn (September -November). Examine the climatic information in the Table.

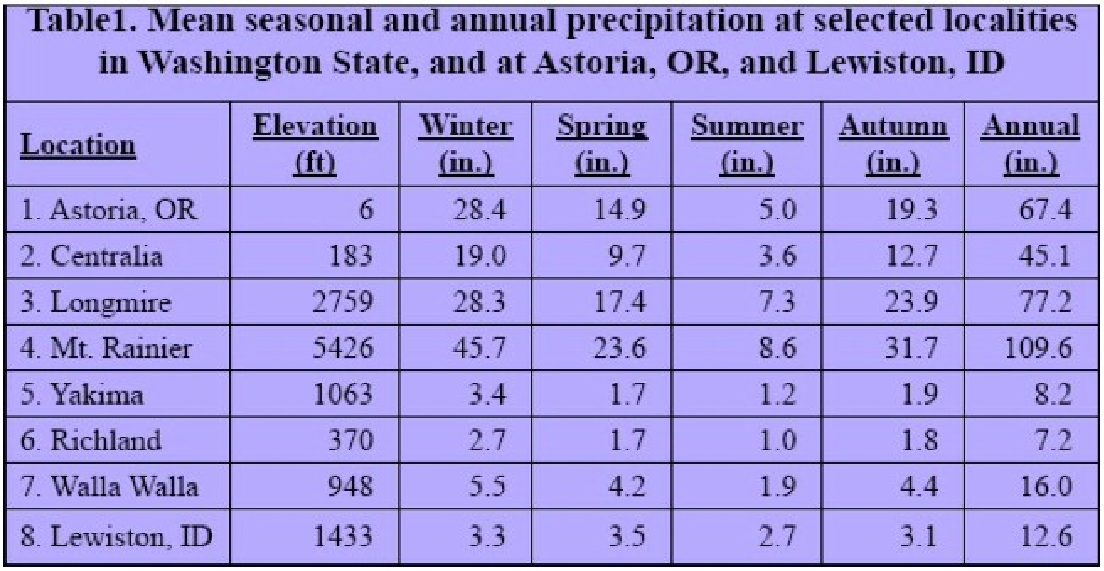


Table1. Mean seasonal and annual precipitation at selected localities in Washington State, and at Astoria, OR, and Lewiston, ID

Location	Elevation (ft)	Winter (in.)	Spring (in.)	Summer (in.)	Autumn (in.)	Annual (in.)
1. Astoria, OR	6	28.4	14.9	5.0	19.3	67.4
2. Centralia	183	19.0	9.7	3.6	12.7	45.1
3. Longmire	2759	28.3	17.4	7.3	23.9	77.2
4. Mt. Rainier	5426	45.7	23.6	8.6	31.7	109.6
5. Yakima	1063	3.4	1.7	1.2	1.9	8.2
6. Richland	370	2.7	1.7	1.0	1.8	7.2
7. Walla Walla	948	5.5	4.2	1.9	4.4	16.0
8. Lewiston, ID	1433	3.3	3.5	2.7	3.1	12.6

2. At virtually all stations, the **[(*winter*)(*summer*)]** season receives the greater amount of precipitation on average.

3. As mentioned earlier in this investigation, greater precipitation at that season of the year is the consequence of **[(*more*)(*less*)]** frequent storms tracking inland from the Pacific Ocean.

Average annual, winter, and summer precipitation amounts, along with elevations, for each of the stations in Table 1 are plotted in **Figure 2** below. The relative locations of the stations in the general direction of west at the left and east to the right are given along the base. Elevations of the stations, in feet above mean sea level, are depicted with the vertical altitude scale shown to the lower right. Precipitation amounts for each station are plotted in the upper portion of the figure (vertical scale of precipitation in inches shown at the left). The magenta solid line connects triangles showing the annual mean precipitation by station, the aqua short-dash line connects diamonds indicating winter mean precipitation, and the red long-dash line connects squares signifying summer mean precipitation.

4. Traveling eastward from Astoria (1) on the Pacific coast to Centralia (2), average annual, winter, and summer precipitation **[(*increases*)(*decreases*)]** with little change in elevation but with increasing distance from the Pacific Ocean source region of moisture.

5. From Centralia eastward to Mt. Rainier (4, at the Paradise Ranger Station) the elevation of the Earth's surface rises about **[(*52*)(*520*)(*5200*)]** feet.

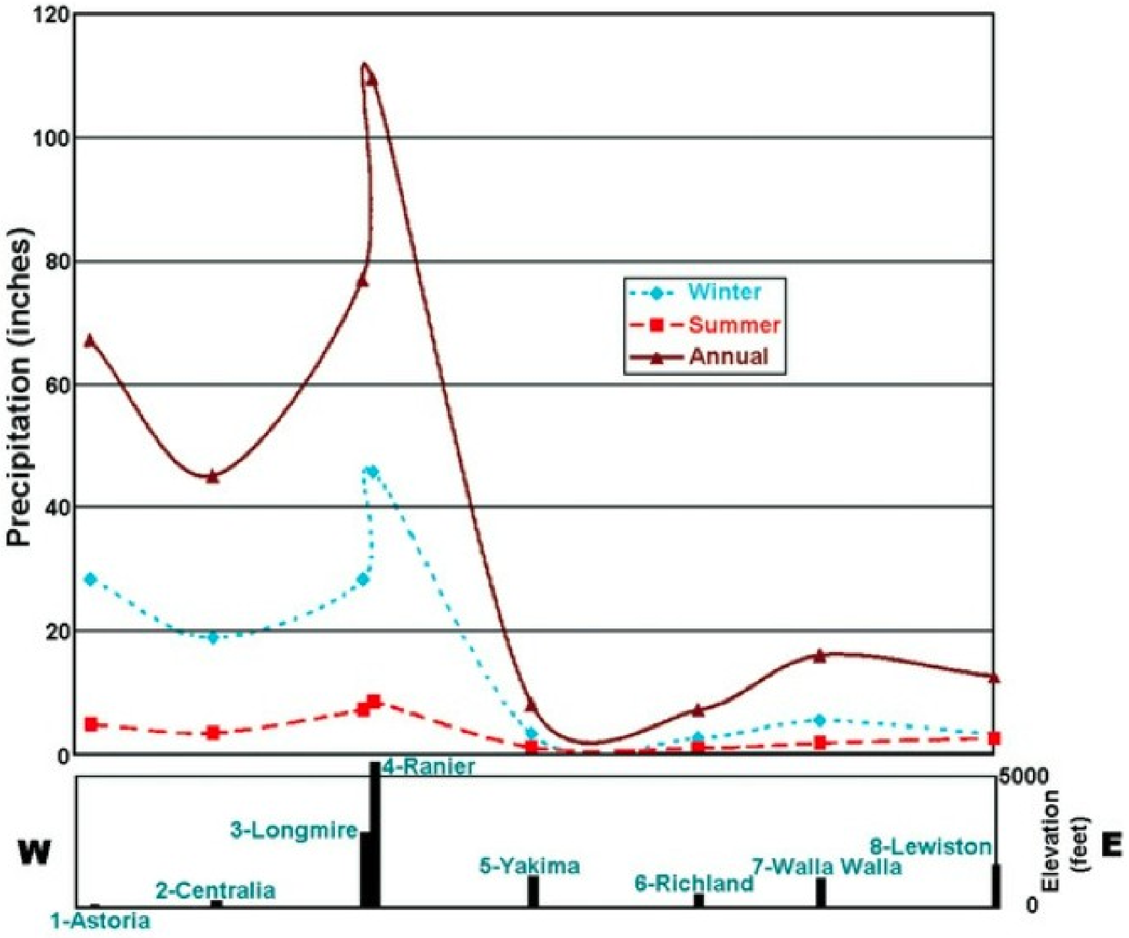


Figure 2.
Average annual, winter, and summer precipitation amounts, along with station elevations from west (W) to east (E) of locations shown on Figure 1 relief map.

6. From Centralia to the Mt. Rainier Ranger Station, average annual precipitation **[(*increases*) (*decreases*)]** with increasing elevation.

7. This is occurring on the mountain range's **[(*windward*)(*leeward*)]** slope.

8. From the two seasonal curves shown, greater precipitation occurs during **[(*summer*)(*winter*)]**.

9. From the Mt. Rainier Paradise Ranger Station eastward to Yakima (5), the elevation drops about 4400 feet and the average annual precipitation **[(*declines*)(*increases*)]** dramatically.

10. On an average annual basis, Yakima receives about **[(*7.5*)(*75*)(*750*)]** percent of the precipitation at the Mt. Rainier Paradise Ranger Station. Yakima is located on the leeward side of Washington State's Cascade Mountain range, of which Mt. Rainier is the peak.

11. Compare the two segments of the average annual precipitation curve west and east of Rainier's location. The segment **[(*west*)(*east*)]** of Mt. Rainier indicates noticeably less precipitation as

compared to the other segment as is characteristic of rain shadows caused by topographical barriers.

12. Further comparison of the two average annual precipitation curve segments indicates this rain shadow extends to about **[(*Richland*)(*Walla Walla*)(*Lewiston and beyond*)]**.
13. Based on the two average annual precipitation curve segments and knowing clouds are required for precipitation, residents to the **[(*west*)(*east*)]** of Mt. Rainier are likely to experience the greater number of cloudy days through the course of a year.

14. The summer and winter precipitation curves indicate these same residents are more likely to have cloudy skies in **[(*summer*)(*winter*)]**.

15. The indigenous vegetation surrounding Yakima and Richland (6) is likely to be **[(*rainforest*) (*desert*)]**.

16. On the basis of average annual precipitation, irrigation will probably be most needed for agriculture at **[(*Astoria*)(*Longmire*)(*Richland*)]**.

17. Average air temperature usually declines with increasing elevation. In traveling from Centralia eastward to Rainier, you would expect **[(*falling*)(*rising*)]** average temperatures.

18. Another reason for greater average precipitation at higher elevations (besides orographic lifting) is the fact that highlands are closer to the base of precipitation-producing clouds than lowlands. In general, the closer the ground is to cloud base, the **[(*less*)(*more*)]** the amount of precipitation that can vaporize in the unsaturated air beneath the clouds to reduce actual precipitation amounts.

Summary: Vertical motions in the atmosphere forced by topographical relief can be a major boundary condition in determining climates on local and regional scales. Orographic lifting can bring air to saturation, the formation of clouds and possibly precipitation, resulting in moist climates. Continued flow of the same air descending on leeward sides of mountains can produce relatively cloud-free and low humidity conditions with little precipitation. The resulting “rain shadows” can extend far downwind where semi-arid conditions prevail and limit agricultural productivity unless augmented by irrigation.