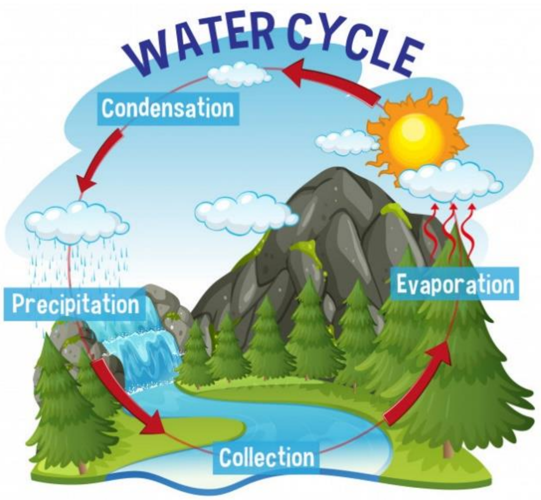
# The Water Cycle, Oxygen-18, and Ice Cores

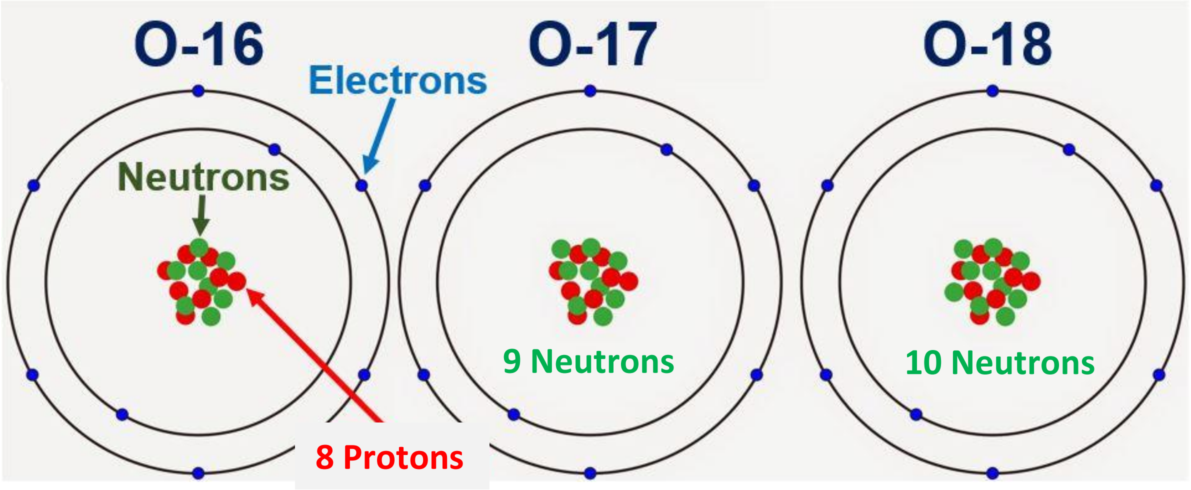
Name ___________________________

## The Water Cycle and Oxygen Isotopes



The water cycle is a key part of understanding Earth's climate. One process in the water cycle is evaporation. **Evaporation** is where molecules of H2O leave the liquid state becoming molecules of H2O vapor or gas in the air above. In the gaseous state, H2O can then move through the atmosphere.

Water, of course, contains both hydrogen and oxygen. *Oxygen is one of the most significant keys to deciphering past climates. Oxygen comes in heavy and light varieties, or isotopes, which are useful for paleoclimate research. Like all elements, oxygen is made up of a nucleus of protons and neutrons, surrounded by a cloud of electrons. All oxygen atoms have 8 protons, but the nucleus might contain 8, 9, or 10 neutrons. "Light" oxygen-16, with 8 protons and 8 neutrons, is the most common isotope found in nature, followed by much lesser amounts of "heavy" oxygen-18 with 8 protons and 10 neutrons.*[1] Water, therefore, will contain hydrogen as well as either oxygen-16 or oxygen-18 (shown as $H_2{}^{16}O$ and $H_2{}^{18}O$ respectively in the images on page 2).



So not all molecules of water are created equal – that's an important point. **Some molecules have more mass than others.** The following demonstration will illustrate this point. The demonstration simulates evaporation for H2O molecules with different masses.

**Demonstration** https://www.youtube.com/watch?v=fyW1E9lJMx4

**Watch the linked video.**

The teacher in the video has a box fan pointing upward with a clear plexiglass container sitting on top of the fan. Inside the plexiglass container are styrofoam balls which represent molecules of water that contain isotopes of oxygen. Then answer the questions below.

1. In what way are the styrofoam balls the same and different?

2. What do the styrofoam balls represent?

3. What do you think that the plexiglass container represents?

4. What do you think that the fan represents?

*In the video the teacher turns the fan on to simulate the evaporation of water. Watch the styrofoam balls closely and answer the following questions.*

5. Which styrofoam balls seem to be rising the highest?

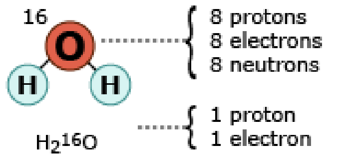
6. Which styrofoam balls tend to stay lower?

7. Come up with a hypothesis that will explain the observed motion of the styrofoam balls (use the words *mass* and *energy* within your hypothesis).

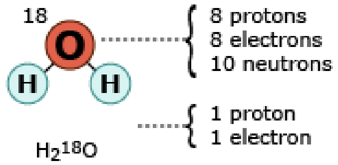
## Heavy Water

The demonstration above illustrates the difference in the evaporation of the two types of water molecules ($H_2{}^{16}O$ and $H_2{}^{18}O$ ) in the water cycle. Transport of these molecules out of the ocean (plexiglass) shows movement in the water cycle. But why were there two types of particles to represent $H_2O$ molecules ? You should have seen that they were raised above the fan at different heights ($H_2{}^{16}O$ higher and $H_2{}^{18}O$ lower). The diagram to the right shows $H_2O$ molecules A and B. Look at how they differ. The difference isn't big, but it's important in the water cycle.

**Water Molecule A**



**Water Molecule B**



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[1] source: http://earthobservatory.nasa.gov/Features/Paleoclimatology_OxygenBalance/

Molecule A has an oxygen with a mass = 16 coming from 8 protons and 8 neutrons. With two hydrogens, the total mass of $H2^{16}O$ is 18. Molecule B has an oxygen with a mass = 18 from 8 protons and 10 neutrons. Adding two hydrogens, the mass of $H2^{18}O$ is 20. These two molecules have different masses because $^{16}O$ and $^{18}O$ are two **isotopes** of oxygen. (Remember: an isotope is an element that has the same number of protons, but a different number of neutrons).
Because of their different masses, $H2^{16}O$ and $H2^{18}O$ behave differently in the water cycle.

As water condenses and precipitates out of the atmosphere it can be incorporated into existing ice sheets. Currently, the major ice sheets exist in the polar regions. At times in the past, ice sheets have also existed across the northern hemisphere. They covered much of the United States, all of Canada, and most of northern Europe. Existing ice sheets provide a continuous record of atmospheric conditions dating back as far as 1.5 million years. The water that comprises the frozen ice sheets contains a mixture of light and heavy isotopes. As water evaporates from the oceans, more of this water tends to be the low mass molecule of water ($H2^{16}O$). Over time, the precipitation that falls over the poles becomes part of the ice sheets. Thus, the ice sheets will have relatively more $H2^{16}O$ than $H2^{18}O$.

### Heavy Water

8. How is heavy water ($H_2^{18}O$) different from light water ($H_2^{16}O$)? Be specific.

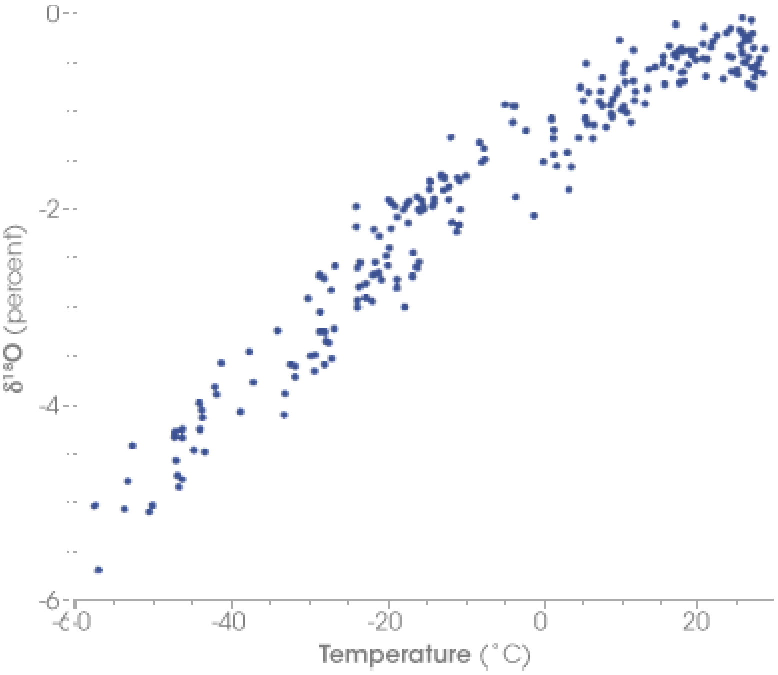
9. The different masses of $H_2^{16}O$ and $H_2^{18}O$ behave differently in the water cycle.
    a. Which one do you think preferentially evaporates?
    b. Which one do you think tends to remain in the ocean?

10. Why would a sample of water vapor taken from above the ocean contain a higher ratio of $H_2^{16}O$ compared to $H_2^{18}O$? Inlude the words *heat energy* within your explanation. (Hint: think about the styrofoam balls in the demonstration).

## Condensation and Precipitation

As air rises in the atmosphere and cools, the water vapor condenses and falls as precipitation. On a global scale, warm air rises at the equator and circulates towards the poles. Because it is heavier, $H2^{18}O$ will tend to condense first and the ratio of $H2^{18}O$ to $H2^{16}O$ will be greater in rain that falls at lower latitudes. As the moist air mass continues to circulate towards the poles, the precipitation that falls will become increasingly depleted of $H2^{18}O$ molecules. However, changes in global temperatures impact how far $H2^{18}O$ can travel from the equator before precipitating out as moisture.

Let’s focus for a moment on the precipitation of the different isotopes of water in the atmosphere. During periods of warmer global temperatures there is more heat energy in the atmosphere. This allows heavy water ($H2^{18}O$) to stay in the gaseous phase longer and travel farther from the equator before precipitating out. Thus, during times of higher global temperatures, the ratio of heavy water to light water ($H2^{16}O$) found in precipitation that falls at the poles changes with a higher percentage of heavy water being present. Scientists have an indicator for the relative amount of $H2^{18}O$ in water. It is $\delta^{18}O$, and is pronounced “delta-18-O”. The delta, δ, stands for “change,” and the $^{18}O$ represents the oxygen-18 in $H2^{18}O$. So, in ice core samples taken at the poles, a higher ratio of heavy water to light water indicates higher average global temperatures. The following figure illustrates this concept:



*The concentration of $^{18}O$ in precipitation decreases with temperature. This graph shows the difference in $^{18}O$ concentration in annual precipitation compared to the average annual temperature at each site. The coldest sites, in locations such as Antarctica and Greenland, have about 5 percent less $^{18}O$ than ocean water. (Graph adapted from Jouzel* et. al., *1994)*

Scientists have performed global atmospheric measurement that allow them to correlate temperature to the ratio of heavy water compared to light water. This laboratory data is then used as a standard to infer past temperatures based on the ratio of isotopes found in ice cores.

## Condensation and Precipitation

11. During a period of warmer temperatures, would you expect precipitation that falls over the poles to contain more or less heavy water ($H_2{}^{18}O$) compared to light water ($H_2{}^{16}O$) than during an ice age? Explain.

12. Refer to the $\delta^{18}O$ vs. temperature graph above. What is the relationship that exists between $\delta^{18}O$ and temperature?

# Using Proxy Data: Ice Cores and Past Temperatures

**Background Information:** In this investigation, you will be working with oxygen isotope data collected from twenty sites in Greenland by **paleoclimatologists** that has been statistically averaged through a process known as Principal Component (PC) analysis. You will be creating a graph of this data compared to average temperature data collected in that region. Both the ice core and temperature data represent conditions in the winter season (November--April) for the years 1829--1970.

## Procedures

1. Copy and paste the data set provided on the next page onto Excel. Create a **straight marked scatter chart** of temperature and time, where temperature is the dependent variable. Make sure to give the graph a title and properly label each axis. Copy and paste your graph in the space below:

2. Examine your completed graph of temperature vs. time to see if there are predictable or repeatable patterns.

3. Now insert a trendline. Does the trendline indicate a long--term pattern in the temperature vs. time data? Explain.

4. Create a second **straight marked scatter chart** using PC1 (Oxygen-18 isotope ratios) and time and add a trendline. Make sure that PC1 is your dependent variable. Copy and paste your graph in the space below:

5. Is there a long-term pattern in the PC1 vs. time data? Explain.

6. Now look at both graphs. What similarities and/or differences do you see in temperature and Oxygen-18 ratios in the ice core data over time? Does the data indicate that a relationship exists between temperature and Oxygen-18 ratios in the ice cores? Remember, the smaller the PC1 value, the lower the ratio of Oxygen-18 to Oxygen-16.

7. Finally, create a **marked scatter chart** using PC1 data as your dependent variable and temperature as your independent variable. Insert a trendline with the $R^2$ value. To see if a correlation exists, look at the $R^2$ value. The closer this value is to 1, the stronger the correlation between PC1 and temperature. If the R2 value is closer to 0, that means the 2 variables are not affecting each other. Copy and paste your graph in the space below:

## Analysis Questions

1. Look at the first two line charts that you created.

   a) What 3 years had the lowest recorded average temperatures?

   b) What 3 years had the lowest PC1 values?

   c) Based on your answers to 1a and 1b and the observed trendlines for both charts, does there seem to be a relationship between temperature and the ratio of Oxygen-18 to Oxygen-16 in the ice sample (again, remember that the lower the PC1 value, the lower the Oxygen-18 to Oxygen-16 ratio)?

2. Look at the scatter chart you created.

   a) As temperatures increase, what happens to the ratio of Oxygen-18 to Oxygen-16?

   b) Explain why temperature would have an impact on the ratio of Oxygen-18 to Oxygen-16 present in the ice core samples.

**Greenland Ice Core Data 1829-1970 with Temperarture & Oxygen Isotope Ratios (as PC1 of the δO18-O18/O16 ratio)**

| Year | Average Temperature (°C) | PC1(δO18-O18/O16 Ratio) |
|---|---|---|
| 1970 | -6.4 | 2.277 |
| 1969 | -5.0 | 2.928 |
| 1968 | -6.9 | -0.886 |
| 1967 | -7.7 | -0.271 |
| 1966 | -5.5 | 1.715 |
| 1965 | -5.1 | 3.630 |
| 1964 | -5.6 | 2.682 |
| 1963 | -4.3 | 3.092 |
| 1962 | -4.9 | 0.618 |
| 1961 | -7.2 | 2.096 |
| 1960 | -6.7 | 4.183 |
| 1959 | -6.2 | 1.336 |
| 1958 | -6.4 | -0.662 |
| 1957 | -8.1 | -2.041 |
| 1956 | -5.7 | 0.643 |
| 1955 | -7.1 | -0.506 |
| 1954 | -7.9 | 0.846 |
| 1953 | -5.2 | 3.421 |
| 1952 | -7.4 | -1.570 |
| 1951 | -7.2 | 0.568 |
| 1950 | -7.8 | -0.539 |
| 1949 | -10.0 | -1.425 |
| 1948 | -6.2 | 2.647 |
| 1947 | -2.8 | 5.455 |
| 1946 | -5.4 | 5.387 |
| 1945 | -8.2 | -1.803 |
| 1944 | -6.6 | -0.959 |
| 1943 | -5.9 | -0.361 |
| 1942 | -6.0 | 3.396 |
| 1941 | -3.6 | 0.766 |
| 1940 | -4.4 | 5.541 |
| 1939 | -7.9 | 0.967 |
| 1938 | -8.2 | 1.240 |
| 1937 | -7.7 | -1.732 |
| 1936 | -3.9 | 0.788 |

| | | |
|---|---|---|
| **1935** | **-5.8** | **2.675** |
| **1934** | **-6.7** | **3.906** |
| **1933** | **-7.7** | **0.482** |
| **1932** | **-5.4** | **2.819** |
| **1931** | **-7.3** | **-0.246** |
| **1930** | **-6.4** | **-0.388** |
| **1929** | **-2.8** | **3.827** |
| **1928** | **-5.6** | **-0.473** |
| **1927** | **-6.8** | **-2.741** |
| **1926** | **-4.9** | **1.875** |
| **1925** | **-9.4** | **-1.588** |
| **1924** | **-5.5** | **-2.249** |
| **1923** | **-6.6** | **1.420** |
| **1922** | **-9.2** | **-2.176** |
| **1921** | **-10.7** | **-2.401** |
| **1920** | **-8.7** | **-1.264** |
| **1919** | **-9.2** | **-3.102** |
| **1918** | **-10.2** | **-2.353** |
| **1917** | **-5.1** | **5.574** |
| **1916** | **-5.3** | **3.482** |
| **1915** | **-9.9** | **-3.439** |
| **1914** | **-10.9** | **-1.457** |
| **1913** | **-8.0** | **-1.973** |
| **1912** | **-7.1** | **1.850** |
| **1911** | **-9.3** | **-0.271** |
| **1910** | **-10.8** | **-2.106** |
| **1909** | **-7.5** | **2.325** |
| **1908** | **-8.6** | **-0.434** |
| **1907** | **-11.3** | **-5.378** |
| **1906** | **-10.6** | **-5.028** |
| **1905** | **-7.2** | **-2.887** |
| **1904** | **-9.2** | **-0.371** |
| **1903** | **-10.3** | **-1.585** |
| **1902** | **-7.4** | **-0.635** |
| **1901** | **-7.4** | **0.973** |
| **1900** | **-7.5** | **-4.145** |
| **1899** | **-10.1** | **-0.390** |
| **1898** | **-11.1** | **-2.485** |
| **1897** | **-10.4** | **-0.128** |
| **1896** | **-10.9** | **1.045** |
| **1895** | **-6.6** | **2.300** |
| **1894** | **-12.0** | **-1.262** |
| **1893** | **-7.3** | **1.184** |
| **1892** | **-8.1** | **0.381** |

| | | |
|---|---|---|
| 1891 | -10.4 | -1.183 |
| 1890 | -10.3 | -3.772 |
| 1889 | -9.0 | -0.478 |
| 1888 | -6.8 | 2.693 |
| 1887 | -11.3 | -0.261 |
| 1886 | -10.1 | -0.943 |
| 1885 | -8.7 | -1.642 |
| 1884 | -12.8 | -1.481 |
| 1883 | -9.6 | -2.253 |
| 1882 | -11.6 | -2.797 |
| 1881 | -5.9 | 1.666 |
| 1880 | -9.8 | -0.357 |
| 1879 | -4.6 | 3.038 |
| 1878 | -7.7 | -1.080 |
| 1877 | -7.2 | -0.371 |
| 1876 | -7.2 | 2.939 |
| 1875 | -6.6 | 1.464 |
| 1874 | -8.9 | -2.949 |
| 1873 | -7.9 | 0.304 |
| 1872 | -4.1 | 1.812 |
| 1871 | -6.7 | 2.183 |
| 1870 | -9.6 | -1.419 |
| 1869 | -9.6 | -2.365 |
| 1868 | -9.7 | 0.309 |
| 1867 | -9.2 | -0.436 |
| 1866 | -10.2 | -1.077 |
| 1865 | -7.6 | 0.784 |
| 1864 | -11.3 | -5.969 |
| 1863 | -14.1 | -4.336 |
| 1862 | -9.7 | -0.671 |
| 1861 | -9.5 | -0.276 |
| 1860 | -6.9 | -1.009 |
| 1859 | -9.8 | -0.052 |
| 1858 | -9.0 | -0.767 |
| 1857 | -7.6 | -1.937 |
| 1856 | -4.1 | 3.449 |
| 1855 | -8.2 | 0.382 |
| 1854 | -10.3 | -0.554 |
| 1853 | -6.7 | 3.191 |
| 1852 | -7.3 | 3.038 |
| 1851 | -7.2 | 1.697 |
| 1850 | -8.2 | 0.373 |
| 1849 | -10.0 | -0.661 |
| 1848 | -9.9 | -1.731 |

| | | |
|---|---|---|
| 1847 | -2.7 | 3.710 |
| 1846 | -7.8 | -1.284 |
| 1845 | -8.4 | -0.707 |
| 1844 | -12.5 | -2.076 |
| 1843 | -7.5 | 1.904 |
| 1842 | -10.3 | -1.201 |
| 1841 | -8.9 | 1.669 |
| 1840 | -8.0 | -0.667 |
| 1839 | -10.3 | -1.963 |
| 1838 | -11.9 | 1.857 |
| 1837 | -11.8 | -4.312 |
| 1836 | -8.4 | -1.907 |
| 1835 | -11.7 | -5.998 |
| 1834 | -11.3 | -2.981 |
| 1833 | -11.1 | -3.312 |
| 1832 | -10.6 | 1.682 |
| 1831 | -6.9 | 2.133 |
| 1830 | -7.1 | 1.735 |
| 1829 | -5.7 | 1.853 |