Real World Globes - Where There's Smoke, There's Fire

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Purpose:

- To understand the principle cause of climate change.
- To understand the impact of climate change on global and regional atmospheric conditions as a result of wildfires.
- To understand what the air quality index (AQI) is and how it is calculated.
- To investigate how global air currents distribute smoke pollution around the world.
- To know what can be done to minimize health risks associated with poor air quality.

Target Audience:

- High school students

Materials:

- 18" Mother Earth Globe™ or Regular 12" Globe
- Clear 18" hemispheres or 12" hemispheres
- Dry-erase markers, eraser, calculator, computer with internet connection

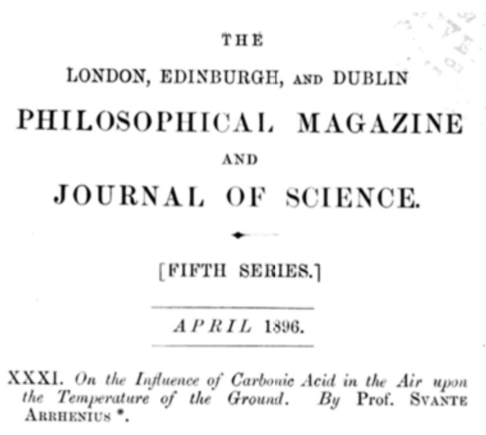
Introduction:

History and Background:

Climate change is a topic that has received a lot of attention in the news over recent years. **Climate change** is defined as the long-term alteration in Earth's climate and weather patterns. While there is evidence that Earth's climate has naturally fluctuated over thousands and millions of years as a result of changes in the Earth's orbital eccentricity and rotation (see **Milankovitch cycles**), the changes we humans are currently experiencing are unprecedented in nature. The primary difference between past climate changes and current climate change is the ***rate*** at which the climate is changing. At no point in Earth's history has the global climate fluctuated as quickly as it is now. So what could be the reason for such rapid changes in global climate? Very simply - humans!

Human activity has accelerated over the past 150 years with the advent of the industrial revolution during the latter part of the 18th century and into the mid-19th century. During this time the burning of carbon sources (e.g. coal and fossil fuels) to produce energy has resulted in the emission of enormous amounts of carbon dioxide (CO_2) into the Earth's atmosphere. Since the industrial revolution about 375 billion tonnes (or about 82.7 trillion pounds) of CO_2 has been emitted into the atmosphere solely by human activities.

Scientists in the late 19th century began to wonder what the future effects of such proliferative release of CO_2 into the atmosphere could be. Swedish chemist Svante Arrhenius (1859 - 1927) published a paper in 1896 titled *"On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground."*



THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

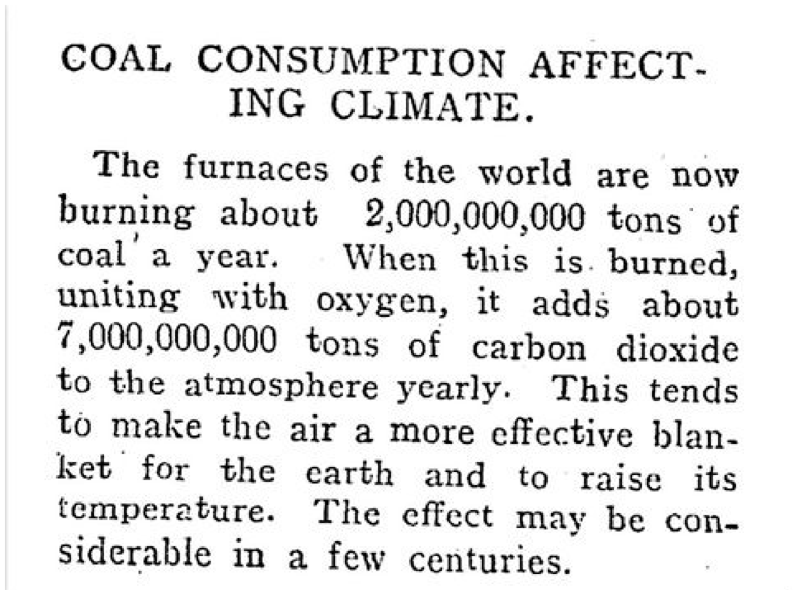
[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

Figure 1: Swedish chemist Svante Arrhenius and his landmark publication in 1896, first describing the effects of increased CO_2 emissions on ground temperatures.

In his paper, Arrhenius provided extensive experimental evidence that CO_2 has a "blanketing effect" on the Earth, producing an increase in surface temperatures when irradiated with light. This led him to coin the term **"global warming"**, which today most people are familiar with. The idea began to spread quickly, even making its way into local and national newspapers, such as the New York Times.



COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

Figure 2: An excerpt from the New York Times (August 1912) summarizing Arrhenius' findings over a decade later.

Because our understanding of the physics of Earth's atmosphere and oceans was relatively primitive in the early 20th century, nobody could say with certainty how quickly, or with what degree this warming effect would have on global climate. As our models of the Earth's climate began to advance and gain accuracy, it became possible to produce mathematical models to simulate how Earth's climate might be affected by the increased release of CO_2 into the atmosphere. The first computerized models of weather patterns were developed in the early 1950s, and by the mid-1960s and into the 1970s, with the establishment of the National Oceanic and Atmospheric Administration (NOAA) and the National Center for Atmospheric Research (NCAR), accurate climate models began to be developed.

Figure 3: The National Center for Atmospheric Research (NCAR) in Boulder, Colorado.

Advances in climate science began to show a definitive correlation between atmosphere CO_2 levels and average global temperature changes.

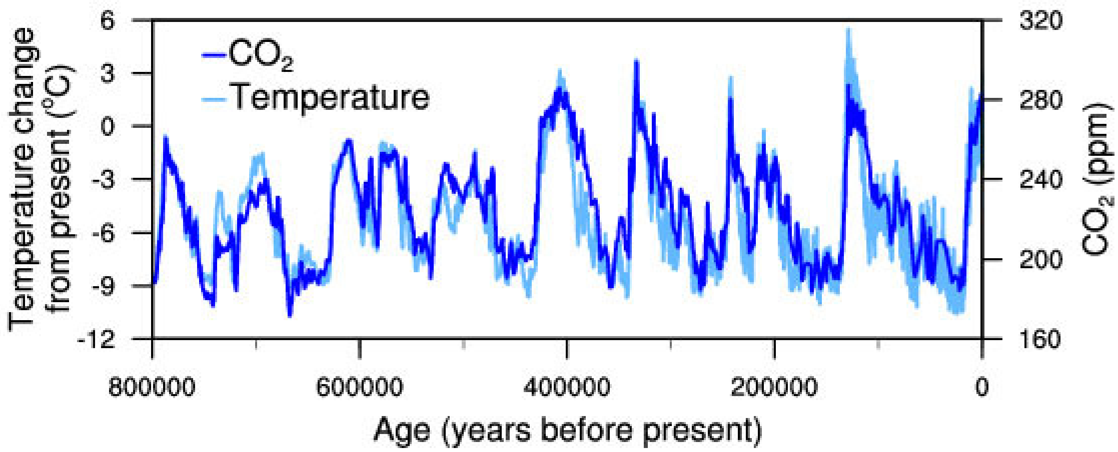


Figure 4: Graph showing the correlation between atmospheric CO_2 levels (dark blue line) and global average temperature change (light blue line) as a function of time. The graph indicates that over hundreds of thousands of years, global temperatures have correlated directly with atmospheric CO_2 concentrations. (Taken from The National Climatic Data Center).

A now famous graph of time versus atmospheric CO_2 concentration is shown below, and indicates the startling increase in CO_2 levels between the years 1925 and 1950 (see **Figure 5**).

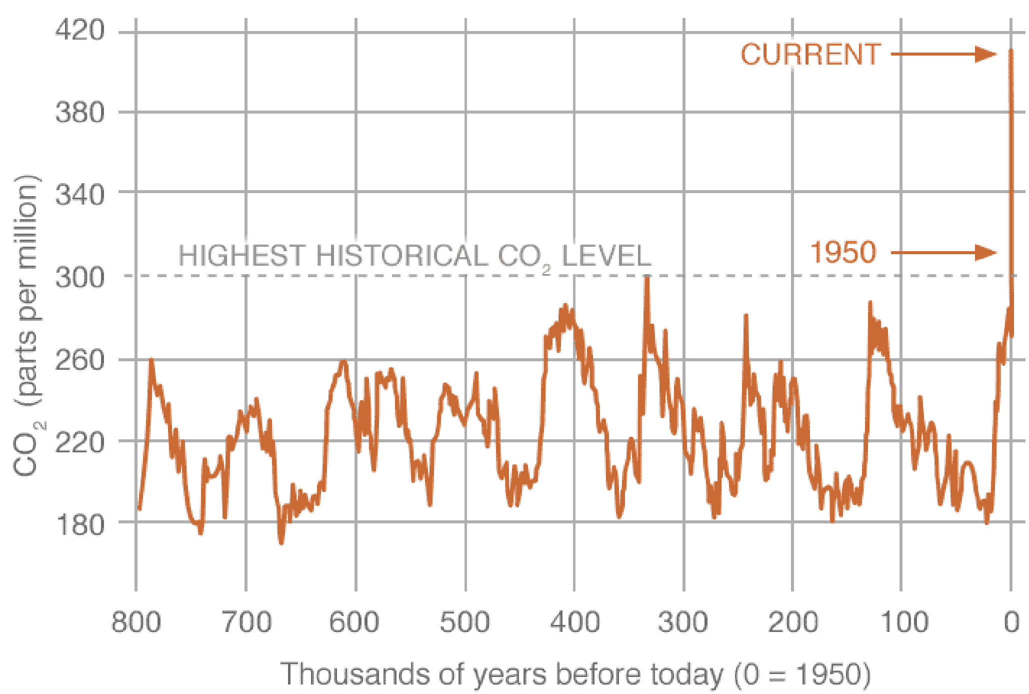


Figure 5: Time versus atmospheric CO_2 concentration. (Taken from NASA Climate Change).

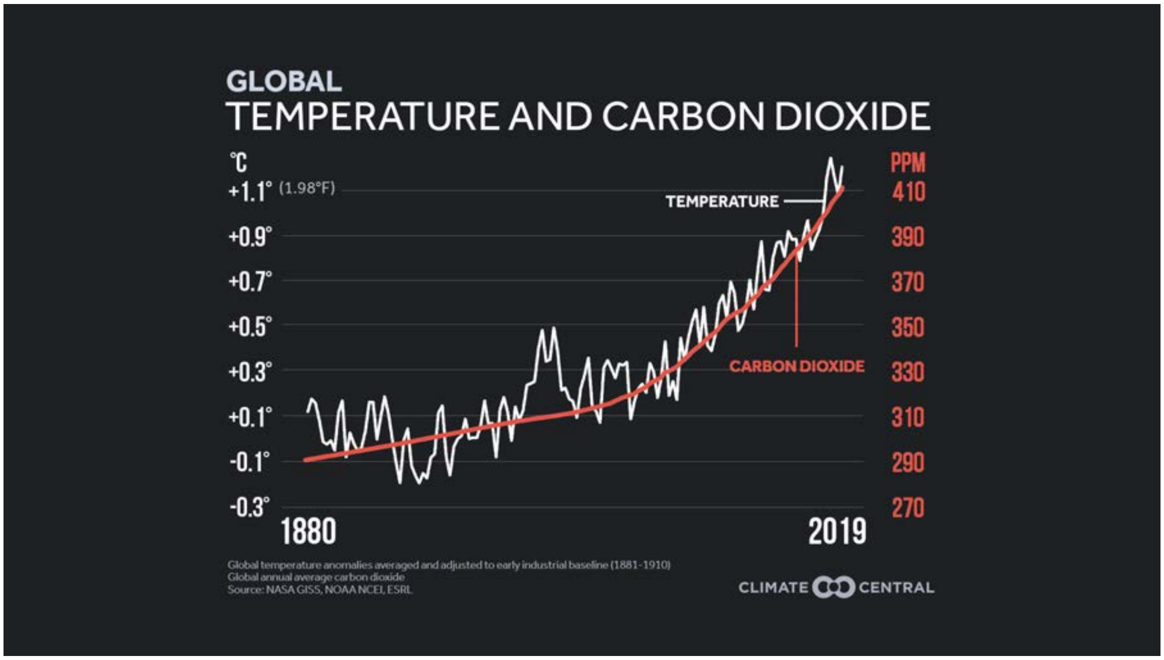


Figure 6: Plot of average global atmospheric CO_2 concentration (red line) and global average temperature change (white line) between the years 1880 and 2019. (Taken from NASA GISS, NOAA NCEI, ESRL).

Finally, when co-plotting average global atmospheric CO_2 concentration and average global temperature change together versus time (see Figure 6), the correlation between CO_2 levels and increasing global temperatures becomes obvious. This is known as the **"hockey stick graph"**, as the sudden upturn resembles the end of a hockey stick.

Everything's Connected:

A central theme of climate science is the idea of **interconnectedness -** when one thing changes, there is a cascading effect that produces many additional changes on a global scale. As we have just seen, increasing atmospheric CO_2 levels directly leads to increasing average global temperatures. Increasing temperatures leads to the melting of polar ice caps (both on land and at sea), which causes sea levels to rise, ocean salinity (and density) to decrease, and this in turn affects ocean currents which are driven by differences in ocean water density. Changes in ocean currents result in changes in ocean temperatures, which influence the temperature of the atmosphere above the oceans. This leads to atmospheric changes, and changes in global weather patterns. Droughts, floods, and tropical storms all become intensified which in turn have a socioeconomic impact on humans around the world. This is the essence of climate change, and it is why it has an effect for everyone on the planet, regardless of where they live.

Heat, drought, wildfires, and air quality:

In many parts of the world, climate change has led to increased average temperatures and modified weather patterns that result in decreased rainfall. As a result, persistent droughts have become more common in these areas. In the United States and Canada, the geographic location of such droughts has been in western states and provinces (e.g. California and British Columbia). The increasingly hot and dry conditions in these areas has led to the formation of wildfires which, in many cases, burn out of control. The devastating impact of these wildfires is multifaceted. Property loss and/or damage, habitat loss, ecological destabilization, human fatalities, and economic strain are the immediately-felt effects from wildfires. However, from a long-term climate perspective, wildfires have two major self-reinforcing implications: 1) the release of enormous amounts of CO_2 (and other pollutants) into the atmosphere and 2) the destruction of plant life - which acts as a natural carbon sink to sequester and "lock away" excess carbon in the atmosphere. Thus, the burning of plant life not only adds more carbon to the atmosphere, but also destroys the ecosystem's natural ability to remove that carbon from the atmosphere (via photosynthesis in plants). This leads to increased warming, and increased risk of future wildfires, in what is known as **forest fire feedback** - a type of **positive feedback loop** that self-amplifies with time.

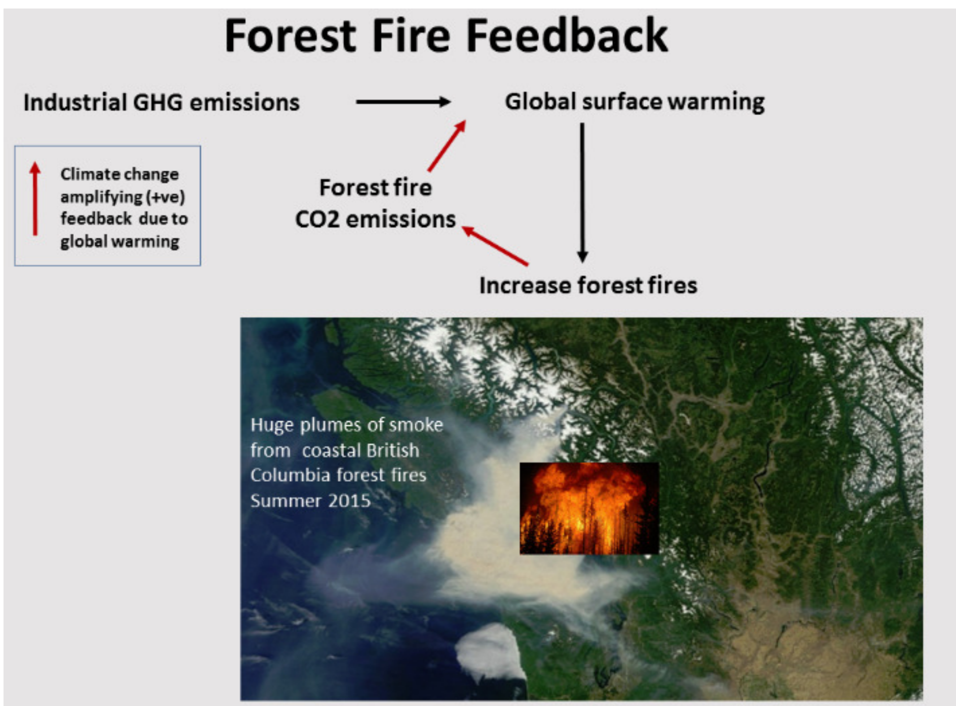


Figure 7: Forest fire feedback - a type of positive feedback loop. (Taken from Climate Emergency Institute).

Air Quality Index (AQI):

The Air Quality Index (AQI) is calculated for any one of six common air pollutants using the table below (**Figure 8**) and **Equation 1**.

O_3 (ppm)	PM_{10} (ug/m^3)	$PM_{2.5}$ (ug/m^3)	CO (ppm)	SO_2 (ppm)	NO_2 (ppm)	AQI Values	Level of Health Concern
0.000 – 0.059	0 – 54	0.0 – 15.4	0.0 – 4.4	0.000 – 0.034	–	0 – 50	Good
0.060 – 0.075	55 – 154	15.5 – 40.4	4.5 – 9.4	0.035 – 0.144	–	51 – 100	Moderate
0.076 – 0.095	155 – 254	40.5 – 65.4	9.5 – 12.4	0.145 – 0.224	–	101 – 150	Unhealthy for Sensitive Groups
0.096 – 0.115	255 – 354	65.5 – 150.4	12.5 – 15.4	0.225 – 0.304	–	151 – 200	Unhealthy
0.116 – 0.374	355 – 424	150.5 – 250.4	15.5 – 30.4	0.305 – 0.604	0.65 – 1.24	201 – 300	Very Unhealthy
–	425 – 504	250.5 – 350.4	30.5 – 40.4	0.605 – 0.804	1.25 – 1.64	301 – 400	Hazardous
–	505 – 604	350.5 – 500.4	40.5 – 50.4	0.805 – 1.004	1.65 – 2.04	401 – 500	Hazardous

Figure 8: The six most commonly measured air pollutants measured when calculating AQI. (Taken from Saad *et al.*, 2017).

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{HI} - BP_{Lo}}(C_p - BP_{Lo}) + I_{Lo}.$$

Where I_p = the index for pollutant p

C_p = the truncated concentration of pollutant p

BP_{Hi} = the concentration breakpoint that is greater than or equal to C_p

BP_{Lo} = the concentration breakpoint that is less than or equal to C_p

I_{Hi} = the AQI value corresponding to BP_{Hi}

I_{Lo} = the AQI value corresponding to BP_{Lo}

Equation 1: The formula used to calculate the air quality index (**I_p**) for any of the six commonly measured air pollutants. (Taken from Met One Instruments, Inc.).

Let's try an example for calculating the air quality index (**I_p**) for ozone (O_3). First, we need a measurement value for ozone from a sample of air. Let's say that the ozone concentration is measured to be 0.090 ppm (parts per million). This becomes the **C_p** value, so **C_p = 0.090**.

Next, we use the table in **Figure 8** to find the range in which this concentration lies. Consulting the table, we can see that 0.090 lies in the range of **0.076 - 0.095**, which are known as the low breakpoint (**BP_{Lo}**) and high breakpoint (**BP_{Hi}**). It is in this row that we will take all of our numbers. Within this row, the AQI values are **101 - 150**, which are known as the low index (**I_{Lo}**) and high index (**I_{Hi}**). Now, we have everything we need to substitute into our equation to calculate the **I_p** for this concentration of ozone.

I_{Lo} **I_{Hi}**

BP_{Lo} **BP_{Hi}**

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$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{HI} - BP_{Lo}}(C_p - BP_{Lo}) + I_{Lo}.$$

$$I_p = \frac{150 - 101}{0.095 - 0.076}(0.090 - 0.076) + 101$$

$$I_p = (2578.947)(0.014) + 101$$

$$I_p = 137.105$$ ← **Unhealthy for Sensitive Groups**

It is this value (**I_p** = 137.105) that would be reported as the air quality index for ozone for that particular sample of air. This same calculation process can be done for any of the other five air pollutants (PM_{10}, $PM_{2.5}$, CO, SO_2, NO_2).

Note: It is the $PM_{2.5}$ air quality index value that is most commonly included in weather reports. $PM_{2.5}$ is the concentration of very fine particulate matter that has a diameter of 2.5 micrometers (2.5 x 10^{-6} meters) or less. PM_{10} is a measure of larger particulate matter, such as that produced by construction sites, landfills and agriculture, wildfires and brush/waste burning, industrial sources, wind-blown dust from open lands, pollen and fragments of bacteria (California Air Resources Board).

Global air circulation:

Winds are produced by the uneven heating of the Earth's surface by the Sun. Regions of the Earth near the equator receive the greatest amount of solar radiation on average. This is why regions near the Earth's equator tend to be warm year-round and change very little from season to season. Conversely, regions of the Earth near the poles receive the least amount of solar radiation on average. This is why regions near the Earth's poles tend to be cool or cold year-round.

As the Sun heats the Earth's surface, it warms up, gaining thermal (heat) energy. This thermal energy is then transferred to the air immediately above the Earth's surface, causing it to heat up as well. As the air heats up it becomes less dense, and so it begins to rise vertically. As it continues to rise it expands and cools, eventually spreading out horizontally once it reaches the same density as the atmosphere around it. As it cools further, the air becomes more dense than the surrounding atmosphere and so it begins to sink vertically. When the air reaches the surface, it spreads out horizontally along the surface, and eventually returns back to the location where it started. This cycle of convection forms what is known as a **convective cell** (see **Figure 9**).

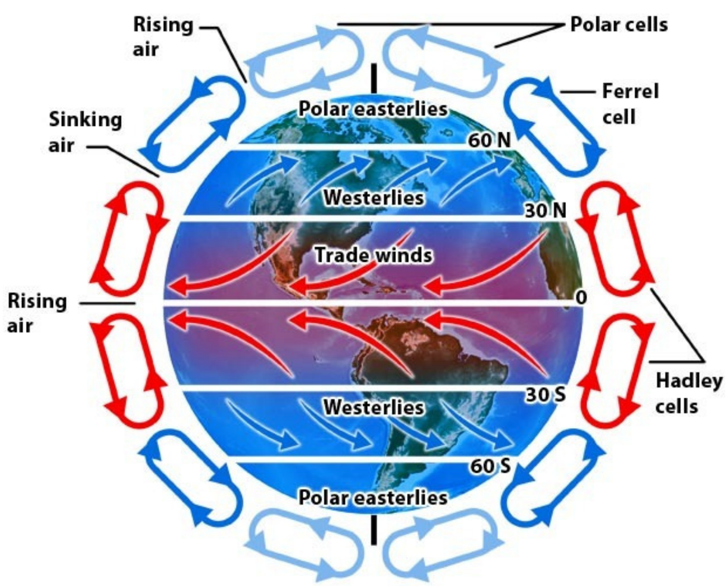

Figure 9: Earth's atmospheric convective cells (represented by loops of air currents). Each hemisphere contains three convective cells that encircle it (called the Hadley, Ferrel, and Polar cell). The driving force for this circulation of air is the uneven heating of the Earth's surface by the Sun. (Courtesy of Quizlet).

Due to the Coriolis effect from the Earth's rotation, surface winds are deflected toward their right in the northern hemisphere. The opposite occurs in the southern hemisphere (surface winds are deflected toward their left). This results in the global wind circulation patterns shown in **Figure 9**.

As a result, for those of us living in North America, the prevailing surface winds north of about 30°N latitude blow from west to east (called **"westerlies"**). South of 30°N latitude, the prevailing surface winds blow from east to west (called **"trade winds"**). As most of the continental United States is north of 30°N, we generally experience weather moving toward the east as it makes its way across the country as a result of these westerly winds. And it is these same winds that carry smoke and particulate matter from wildfires in the western portion of the United States across the midwest to the east coast, and beyond.

Activity - Tracking smoke from wildfires

In this activity, you will be choosing one or more wildfire locations in the continental United States and locating them on a globe. Making sure the clear plastic hemispheres are placed on the globe, use a black dry-erase marker to mark several different locations of current wildfires. An excellent resource to locate current wildfires in the United States and Canada is FIRMS (Fire Information for Resource Management System), which is produced by a partnership between NASA and the U.S. Forest Service. A link to an interactive map is given below:

https://firms.modaps.eosdis.nasa.gov/usfs/map/#d:24hrs;@-100.0,40.0,4z

The red dots on the map indicate “hot spots” as detected by the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the NOAA-20 satellite, which indicate fires large enough to be detected from space by this instrument.

Once you have marked several “hot spots” on your globe, go to the following website:

https://earth.nullschool.net/

This will take you to an interactive global wind map that allows you to visualize the wind speed and direction at many different altitudes.

Zoom in on the continental United States and click on the black box in the bottom left corner of the screen that says “earth.” This will open a menu where you can select different data sets or change the visual layout of the data. For this activity, you will only be changing the **Height** measurement in the menu. Note that there are different heights above the ground that you can select to see the wind direction and speed at a given altitude (Sfc = surface; 1000, 850, 700, 500, 250, 70, and 10 hPa (hectopascals)). For reference, the altitudes that correspond to these barometric pressure levels are given below:

Sfc = 0 ft.
1000 hPa = 360 ft.
850 hPa = 4,800 ft.
700 hPa = 9,900 ft.
500 hPa = 18,300 ft.
250 hPa = 34,000 ft.
70 hPa = 58,000 ft.
10 hPa = 85,000 ft.

For our purposes, we can assume that wildfire smoke particulate matter is heavy enough to stay below 18,300 ft. (>500 hPa), and that only the smallest particles will even make it to this altitude.

By toggling between the various heights (Sfc to 500 hPa), on your globe use different colored dry-erase markers to trace out the path of the smoke particles at different altitudes as they ride the winds at their particular altitude. What do you notice about the wind speeds as you increase in altitude? What about their direction? Which types of particulate matter do you think will travel the furthest? Explain your reasoning.

Zoom out so that the entire Earth comes into view, but still looking over North America. Under the **Height** option on the menu select 500 hPa. You should see an image similar to the one shown below (**Figure 10**). The yellow line has been added to show the global wind patterns in the northern polar region of the Earth. The highest velocity winds (in red/pink) are part of the north polar jet stream, and it is primarily these winds that carry and distribute smaller particulate matter produced by wildfires throughout the northern hemisphere.

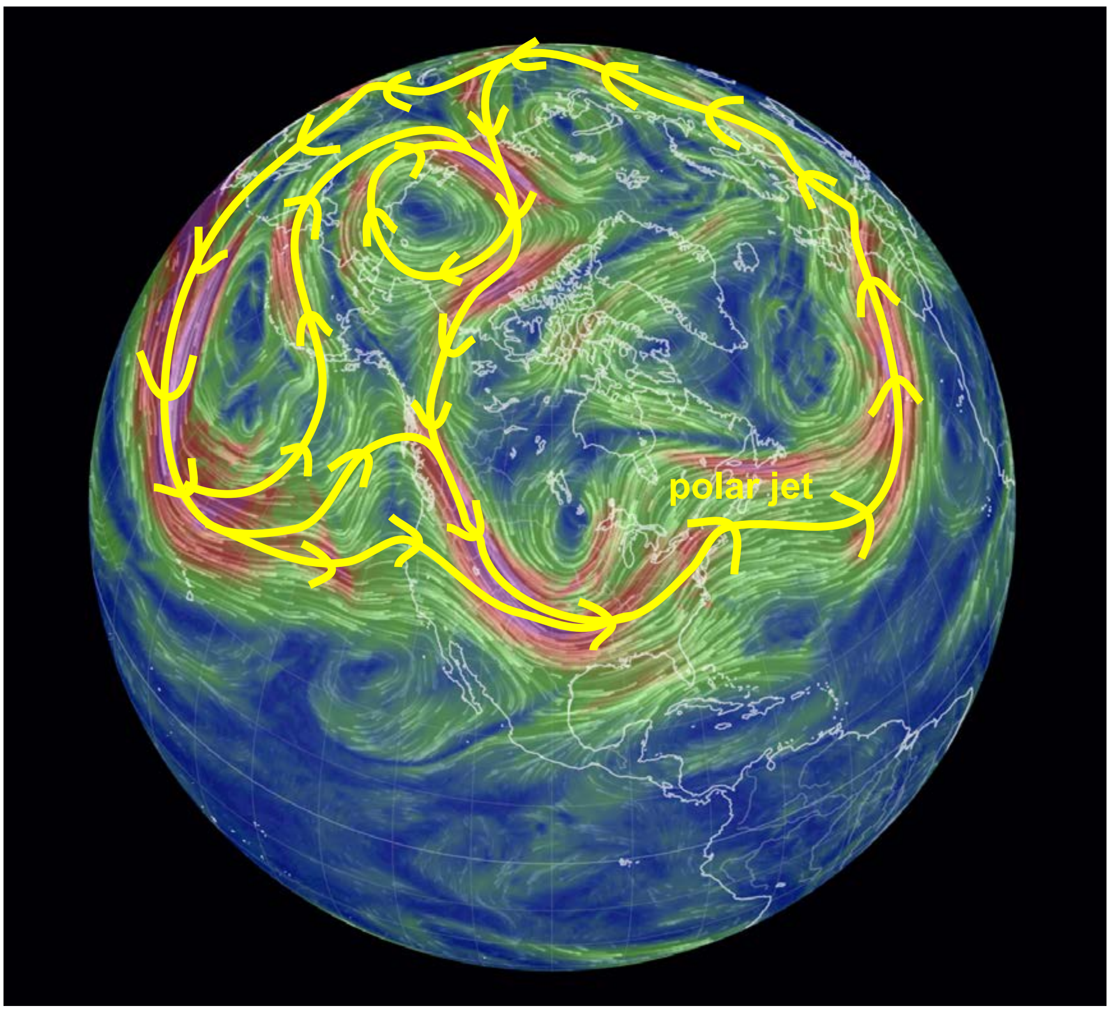

Figure 10: 500 hPa global winds with the north polar jet (and associated polar eddies) outlined in yellow. Smaller particulate matter produced by wildfires can travel around the northern hemisphere via these wind pathways.

Therefore, wildfires in places even thousands of miles away from one location can have a significant impact on sky clarity and/or air quality over a broad geographic area downwind from these fires. This was the case during the 2021 California wildfires, where over 8,600 fires burned more than 2.5 million acres of land.

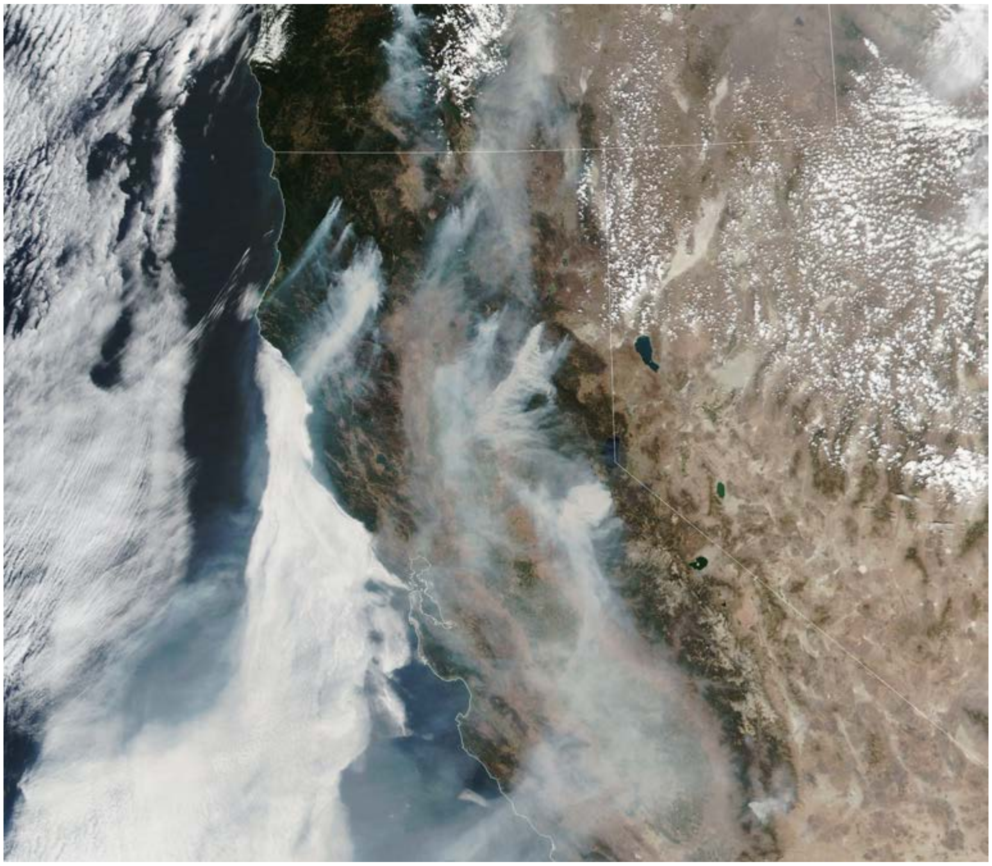

Figure 11: Image taken on August 19, 2021 by the VIIRS natural-color sensor aboard the NOAA Suomi NPP satellite. Gray-colored smoke from California wildfires can clearly be seen near the center of the image. (Taken from NASA Earth Observatory).

Figure 12: Image of the New York City skyline in July 2021. Sky clarity and air quality were significantly impacted by the smoke from western wildfires in areas all along the east coast of the United States. (Taken from The Washington Post).

What can be done?

With our currently forecasted projections of CO_2 emissions increasing in the near future, and the looming reality of climate change, droughts and, as a result, wildfires, are only going to continue well into the future. With this in mind it is important to know some guidelines for individuals dealing with poor air quality. Ten tips from the American Lung Association include:

1. Checking daily air pollution forecasts in your area.
2. Avoid exercising outdoors when pollution levels are high.
3. Always avoid exercising near high-traffic areas.
4. Use less energy in your home.
5. Encourage your child's school to reduce exposure to school bus emissions.
6. Walk, bike, or carpool.
7. Don't burn wood or trash.
8. Use hand-powered or electric lawn care equipment rather than gasoline-powered.
9. Don't allow anyone to smoke indoors and support measures to make all public places tobacco-free.
10. Get involved in the Healthy Air Campaign.

In addition to the tips provided above some companies, such as IQAir, a Swiss-based company specializing in air purification equipment, produce devices for individual residences and commercial settings. Investing in such equipment may be of particular benefit to those suffering from chronic lung diseases, such as asthma, emphysema, chronic obstructive pulmonary disease (COPD), and cystic fibrosis.

Critical Thinking Questions:

1. Using the table in **Figure 8** and **Equation 1**, calculate the air quality index (**I_p**) for a sample of air where the $PM_{2.5}$ is 14.1 ug/m^3. Referencing the table, what is the level of health concern for this air? Show all work in the space below.

   I_p = ________________

   Level of health concern = _________________

2. Describe the general speed and direction of the prevailing winds over one of the wildfire locations at the different altitudes that you observed using the https://earth.nullschool.net/ website. Simply click on the wildfire location of your choice and this information will be displayed in the lower left corner of the screen. Fill in the table below.

	Surface	**1000 hPa**	**850 hPa**	**700 hPa**	**500 hPa**	**250 hPa**	**70 hPa**	**10 hPa**
Direction (degrees)								
Speed (km/h)								

3. Looking at the global wind pathways you drew on your globe, what do you notice about the path of the particulate matter? Does it encircle the entire globe? Just the northern hemisphere? How far north/south does the particulate matter move from its original latitude?

4. Do you think it's possible for particulate matter produced by a wildfire in the northern hemisphere to migrate to the southern hemisphere? Why or why not? (Provide evidence by citing global wind patterns).

5. How does climate change impact drought conditions in the western United States? List some consequences that you think will arise because of our changing climate.

6. Should someone who lives on the east coast of the United States be concerned about air quality effects from wildfires in the western United States? What would be the ideal upper air wind patterns that would facilitate the migration of smoke and particulate matter across the United States?

7. List three actions you can take personally to reduce exposure to, and generation of, emissions of air pollutants.

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