Evidence #1: Since 1958, Earth's atmosphere and oceans have changed. The amount of carbon released to the atmosphere has risen. Dissolved carbon in the ocean has also risen. More carbon has increased ocean acidity and coral bleaching.

Figure 1.1 shows the amount of carbon dioxide in the air and ocean. In the figure, the symbol CO_2 stands for carbon dioxide. The red line shows that atmospheric CO_2 (CO_2 in the air) has been increasing. This increase is about 37% over 66 years. The green line shows that seawater CO_2 (ocean CO_2) has also been increasing. The blue line shows that seawater pH has been decreasing, which means the oceans are more acidic.

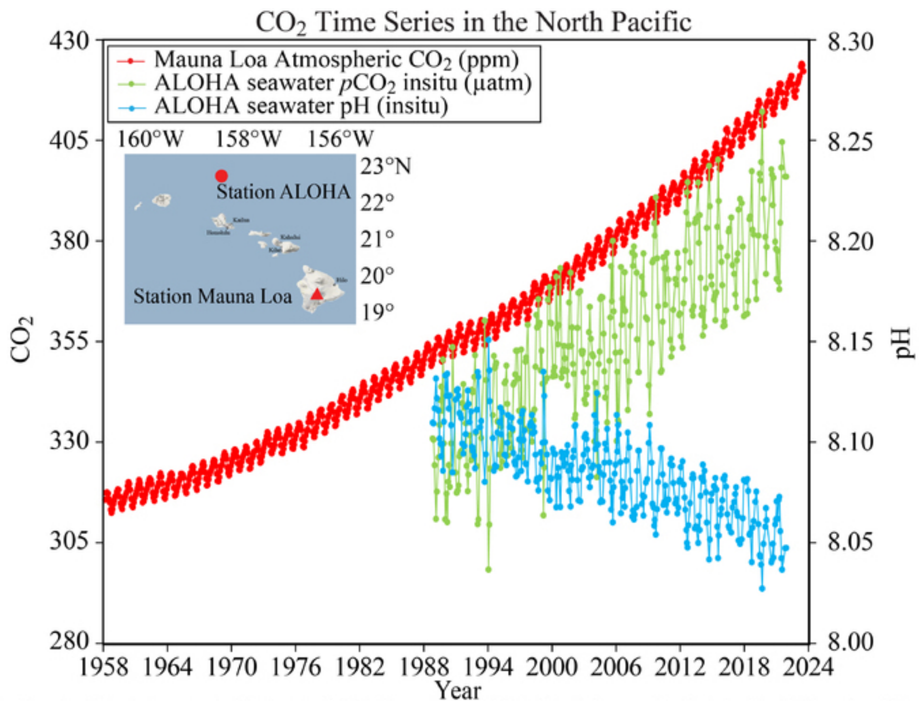

Figure 1.1. Carbon dioxide time series in the North Pacific Ocean.

Source: https://www.pmel.noaa.gov/co2/story/Quality+of+pH+Measurements+in+the+NODC+Data+Archives

Algae die in acidic waters. Algae are plant-like and often exist with coral. Coral is an ocean animal and needs algae to be strong. Coral turns white (bleaches) when it weakens.

Corals can form living reefs that exist just under the ocean surface. Some of the reefs can act as barriers. These barriers buffer shores from waves, storms, and floods. When coral reefs weaken, they are not strong barriers. Coral reefs also provide shelter for many marine organisms.

Evidence #2: From 1910 to 1995, record rainfall events increased across the United States. Over the same time period, there was a sharp increase in the amount of carbon released to the air. Much of this carbon comes from fossil fuel use.

Fossil fuels include coal, oil, and natural gas. When humans burn fossil fuels, carbon is emitted into the air. The blue line in Figure 2.1 shows the total amount of carbon released into the air from human activities over the past 80+ years.

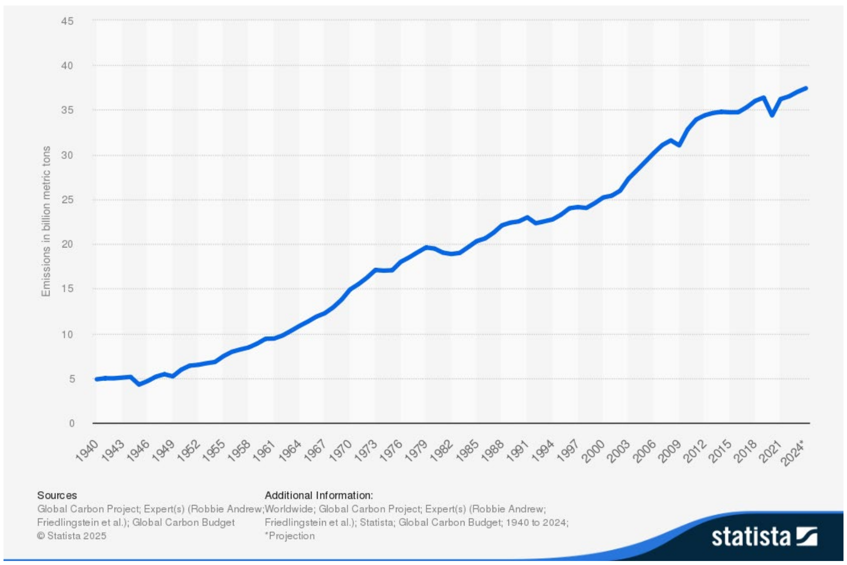

Figure 2.1. Annual carbon dioxide (CO_2) emissions worldwide from 1940 to 2024.

Source: https://www.statista.com/statistics/276629/global-co2-emissions/

Figure 2.2 shows that the amount of rain from extreme events (highest 1-day rain events in a year) has increased across the entire US. This increase has happened over about the same 100-year period as increasing carbon emissions.

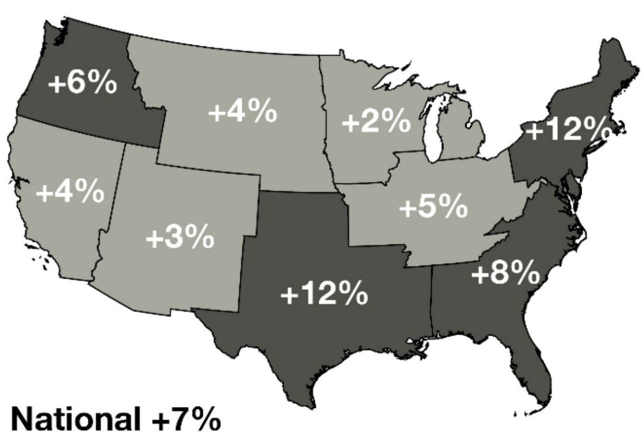

Figure 2.2. Trends in extreme 1-day precipitation events in the US. Wright Seneres based on Karl & Knight (1998).

Evidence #3: Ocean surface temperatures have increased since about 1970. In the North Atlantic, tropical storm power has also increased over this same time period. A storm's power depends on its strength and how long it lasts.

Tropical storms form over oceans. The dashed blue line in Figure 3.1 shows Tropical North Atlantic sea surface temperature trends in degrees Fahrenheit. It shows that ocean temperatures have increased since 1970.

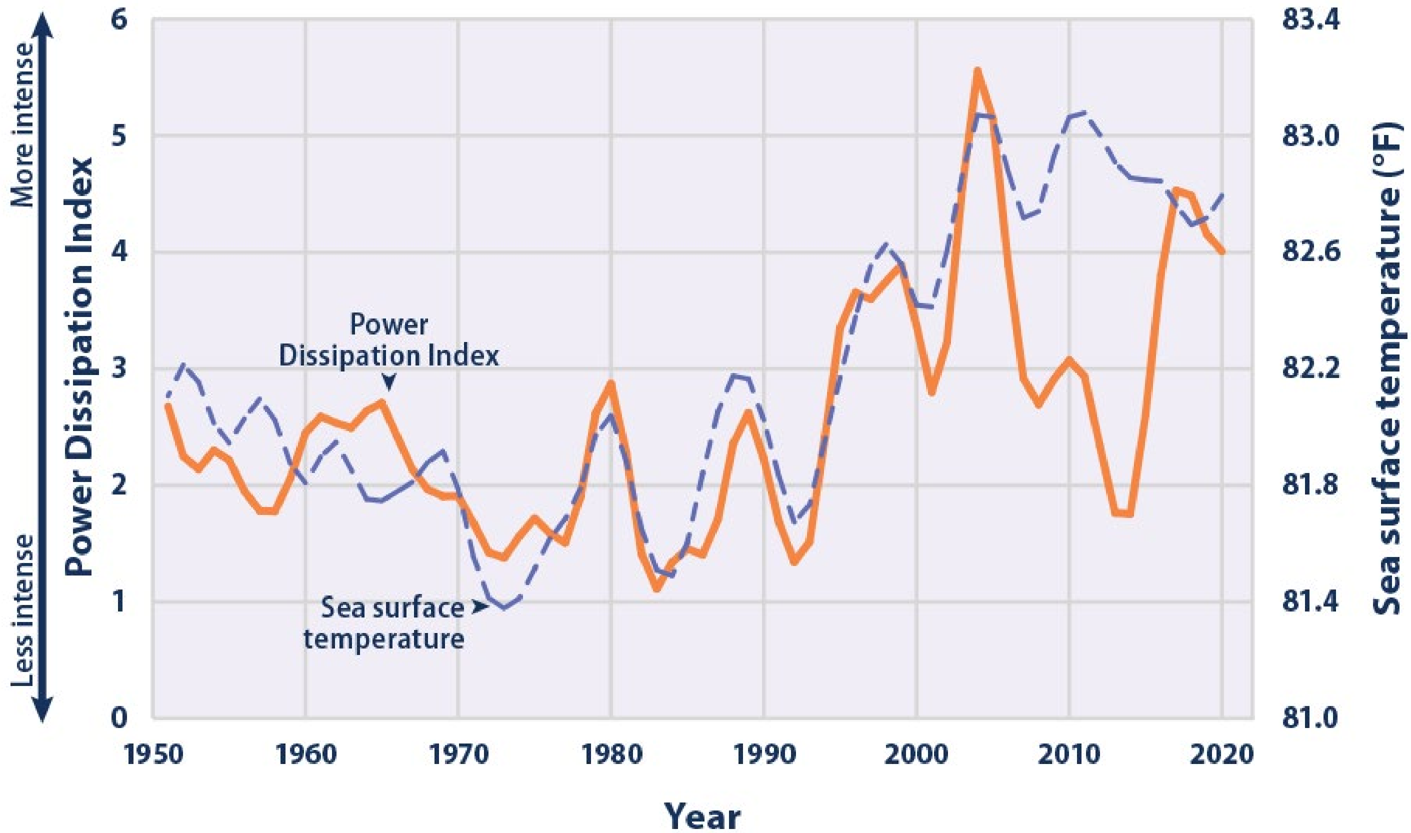

Figure 3.1. North Atlantic tropical cyclone activity according to the power dissipation index, 1949–2022.
Source: https://www.epa.gov/climate-indicators/climate-change-indicators-tropical-cyclone-activity

The solid orange line in Figure 3.1 shows the power dissipation index (PDI) for tropical cyclones in the Atlantic. The PDI measures the amount of energy storms release. The PDI of a storm depends on its strength, how long it lasts, and how often it occurs. It reflects the total destructive power of all tropical cyclones for a year. The PDI has also been increasing since about 1970. Note that sea surface temperature is measured in different units, but the values have been plotted alongside the PDI to show how they compare. The lines use a five-year weighted average, plotted at the middle year. The most recent average (2018–2022) is plotted at 2020.

Evidence #4: Since 2012, there have been more intense, extreme weather events around the world. Europe had the second-highest yearly temperature on record. The South Central United States had the costliest cold wave on record. The decade from 2013 to 2023 was the warmest ever since pre-industrial times.

Table 4.1 shows extreme weather events from 2012 to 2023.

Table 4.1. Record-breaking weather events worldwide between 2012 and 2023.
Source: https://www.weather.gov/mob/events

Year	Region	Record-breaking event	Impacts
2023	North America	Record highest temperatures in May	Devastating wildfires in Canada with 6 million acres burned
2022	Mexico	Hurricane Agatha strongest May hurricane to hit Mexican Coast	$50 million in damages
2022	Europe	Second-highest yearly temperature on record	Exacerbated drought and wildfires
2020	Atlantic Basin	Highest number of tropical cyclones ever recorded (30)	Hurricanes Eta and Iota caused $2 billion damage alone
2021	South Central United States	Costliest cold wave on record - Numerous cold temperature records broken	$196.4 billion in damage, widespread power outages in Texas
2019	Mississippi River Watershed	Ice melt and heavy rainfall caused record flooding	$20 billion in economic impact, 30,000 homes damaged
2018	Hawaii	49 inches of rain in 24 hour period (U.S. record)	Major flooding and mudslides
2017	Texas and Louisiana	Hurricane Harvey produced record rainfall in area	300,000 structures damaged or destroyed due to flooding
2016	Southern Africa	Second consecutive season of drought	Substantial agricultural losses
2016	United States	Highest average temperature recorded at the time	15 extreme weather related events causing over $1 billion in damage each
2015	Yemen	Chapala becomes first Category 1 Tropical Cyclone to reach Yemen	Displaced populations and spread mosquito borne diseases
2013	United States	34 different extreme weather events occurred, including floods, storms, and wildfires	1,221 fatalities and $208 billion in damage
2012	Philippines	Typhoon Bopha becomes southernmost Super Typhoon in Philippines	Over 1,000 fatalities and $1 billion in damage in area not known for having typhoons

Evidence #5: Since 1983, the number of fires each year in the U.S. has not changed. The number of acres burned by those fires has increased. Also, since 1983, the average annual temperature in the U.S. has increased.

The blue bars in Figure 5.1 show the number of large fires in the U.S. since 1983. The red bars show the number of acres burned by those fires. The red trend line shows how the acres burned have increased over time.

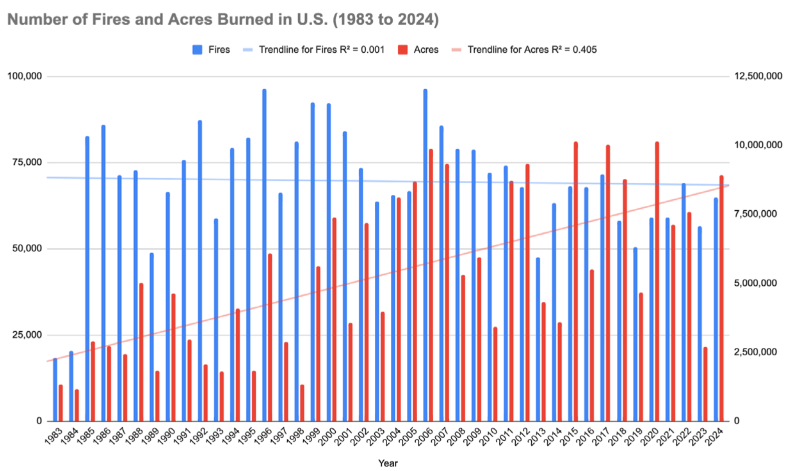

Figure 5.1. Number of large fires since 1983 (≥ 100 acres in timber or ≥ 300 acres in grass) together with acres burned.
Source: https://www.nifc.gov/fire-information/statistics/wildfires

The red bars in Figure 5.2 show the number of acres burned in the U.S. since 1983. The blue bars show the average annual temperature in degrees Fahrenheit in the U.S. during that time. The blue line shows an upward trend in these temperatures.

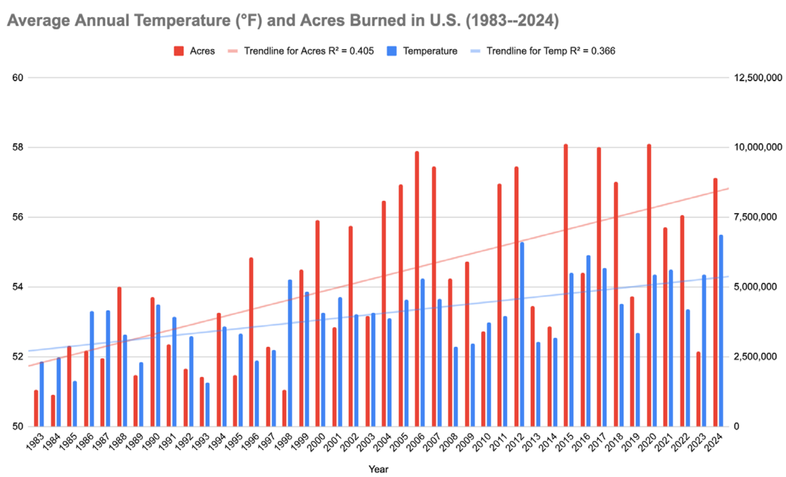

Figure 5.2. Average number of acres burned by large fires together with average annual temperature..
Source (fires): https://www.nifc.gov/fire-information/statistics/wildfires
Source (temperatures): https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/national/time-series

Evidence #6: In the last 100 years, global temperatures have increased. In that same time period, heavy precipitation events have also increased.

The black dotted line in Figure 6.1 shows annual, average, global temperature anomalies. Anomalies are things that differ from the “normal” or average conditions. The “0” on the left axis represents that average. It is the long-term, global, average, temperature between 1951 and 1980. The black dotted line shows that global temperatures have increased since 1910.

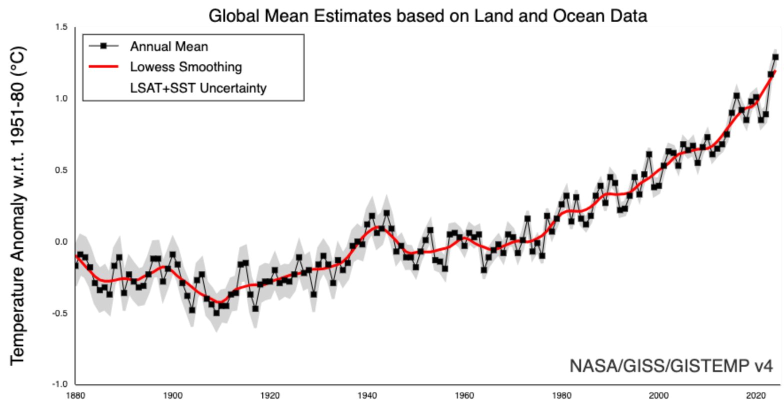

Figure 6.1. Trend of global annual surface temperature.
Source: https://data.giss.nasa.gov/gistemp/graphs_v4/

Figure 6.2 shows changes in precipitation patterns across the U.S from 1991 to 2012 compared to the 1901 to 1960 average. Changes are shown as a range of colors reflecting percent change. Green indicates increases in precipitation and red indicates decreases. Most parts of the U.S. received more precipitation.

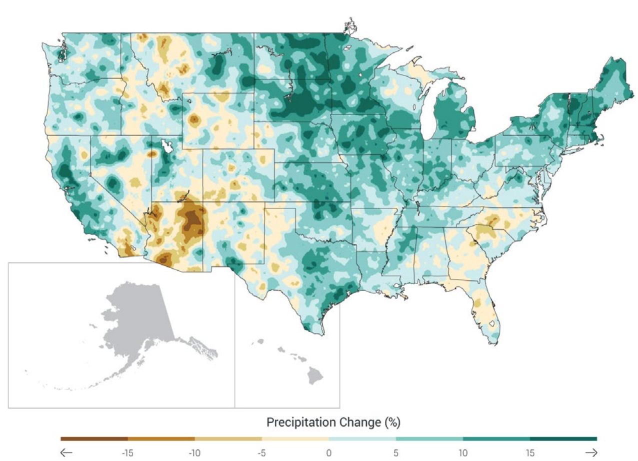

Figure 6.2. Trends per 100 years for precipitation change.
Source: https://nca2014.globalchange.gov/report/our-changing-climate/precipitation-change#intro-section-2

Evidence #7: The amount of ocean ice has declined, with the Arctic warming at a pace two to three times the planet's average. At the same time, record cold temperatures and snowfall have occurred in Europe and Asia.

Figure 7.1 shows relations between ocean ice loss and weather patterns in the Northern Hemisphere. In the late summer and early winter, moisture from melting sea ice shifts the tropospheric jet stream (blue band with arrows). Energy is transferred up higher in the atmosphere. This creates a stratospheric polar vortex (purple band with arrows). This polar vortex allows cold air to move from the Arctic into Europe and Asia (blue shaded region on right image). At the same time, the Arctic is warmer in the winter (brown shaded region on right image).

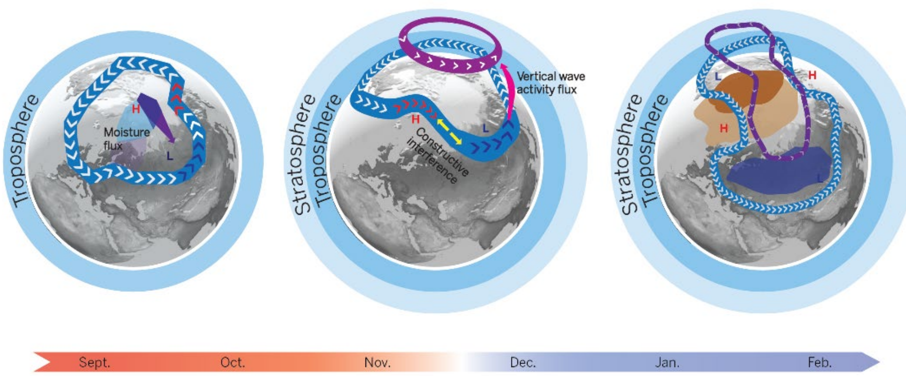

Figure 7.1. Relations between decreasing sea ice and increasing snow cover in Europe and Asia. Wright Seneres based on Cohen et al. (2014).

Figure 7.2 shows temperature anomalies in Europe during winter 2010. Anomalies are things that differ from the "normal" or average conditions.

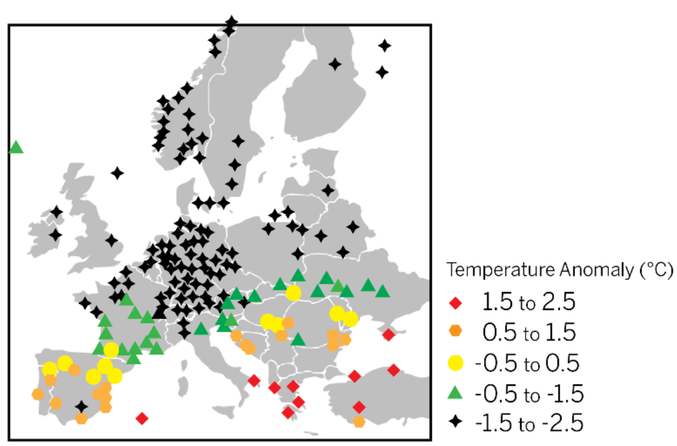

Figure 7.2. European temperature anomalies in winter 2010. Wright Seneres based on Cattiaux et al. (2010).

Evidence #8: Earth's orbit is elliptical. But, the shape of the ellipse is almost a perfect circle. In the Northern Hemisphere, Earth is slightly closer to the Sun in winter than in summer. Earth's surface receives more sunlight in summer than in winter.

Figure 8.1 shows the shape of Earth's orbit around the Sun. This view is looking directly down on the Sun and Earth from above the North Pole. Although the orbit is elliptical, the eccentricity is very small. This means that the orbit is almost a perfect circle, but not exactly. Because Earth's path is not perfectly circular, the amount of energy received from the Sun varies by about 3.5% during the year. The date when Earth is closest to the Sun shifts slightly over time. Currently, Earth is closest to the Sun in the middle of the Northern Hemisphere winter.

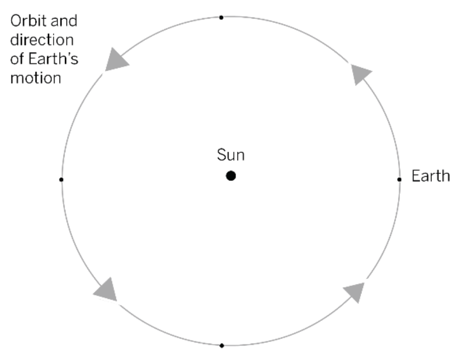

Figure 8.1. Earth's orbit around the Sun. Wright Seneres

Energy received from the Sun is called solar irradiance. Figure 8.2 shows changes in the solar irradiance that reaches Earth's surface. The orange line shows yearly solar irradiance. The irradiance depends some on Earth's orbital position. Since the 1600s, it has not changed much.

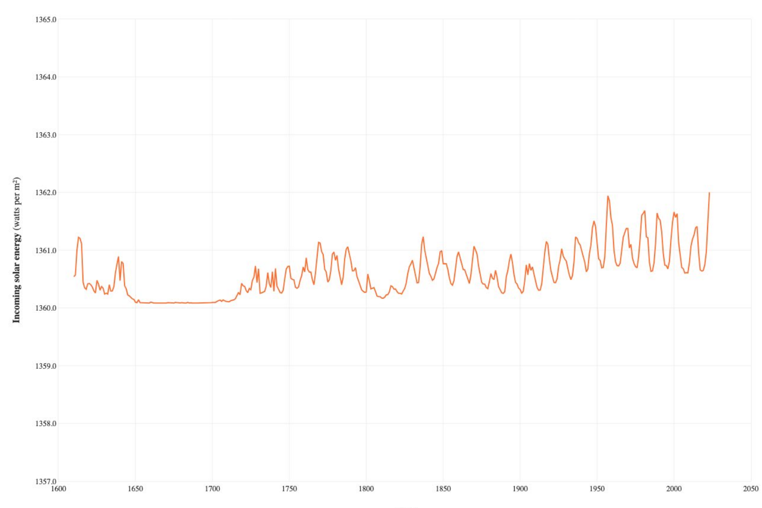

Figure 8.2. Reconstruction of total solar irradiance based on sunspot observations since the 1600s.

Source: https://www.climate.gov/news-features/understanding-climate/climate-change-incoming-sunlight