The Sun–Climate Connection

Geological evidence shows that for billions of years, the world has gone through cycles of global warming and global cooling. Any cold period when permanent ice sheets exists in both polar regions is defined as an "Ice Age." According to this definition and because ice sheets exist in both Greenland and Antarctica, the Earth is currently in an ice age but in a relatively mild period called an "interglacial period," which is not as extreme as the "glacial periods" that we typically think of when we think of "Ice Ages".

Geological records indicate that five major ice ages existed during the last 2.5 billion years starting with the Huroian ice age (from 2.4 until 2.1 billion years ago) and ending with the present one called the Quaternary (from 2.6 million years ago until the present). Warm periods, when there were no large areas of permanent ice present on the Earth, are sometimes called "greenhouse (or hothouse) periods." From geological evidence, the Earth has been in a "greenhouse period" about 85% of the time.

Since ice ages were discovered nearly 200 years ago, various theories have been put forward to explain these cycles in the Earth's surface temperature. Most of these theories consist of various combinations of two main hypotheses – changes in the amount of sunlight reaching the top of the Earth's atmosphere or changes in the Earth's atmosphere, which alters the balance between the amount of sunlight that reaches the Earth's surface and the amount of heat energy that radiates out to space.

Hypothesis 1: Changes Sunlight Reaching the Top of the Earth's Atmosphere

Most of the energy that heats the Earth's surface comes directly or indirectly from the sunlight that arrives at the top of the atmosphere. Only a relatively small amount of the energy that heats the Earth's surface come from inside the Earth. The total amount of energy arriving at the top of the atmosphere from the Sun is called the ***Total Solar Irradiance* (TSI)**. As you would expect, changes in TSI will affect the temperature at the Earth's surface. Two main mechanisms have been posited as to how changes in TSI might occur – changes to the Earth's orbit around the Sun or changes to the luminosity or the amount of light emitted by the Sun itself.

History of the Orbital Change Mechanism

In 1824, Jens Ensmark examined geological evidence for the ebb and flow of glaciers and proposed a series of worldwide ice ages to explain his observations. He suggested these ice ages were due to changes in climate caused by changes in the Earth's orbit. Similarly, in 1842, Joseph Adhemar suggested that the ice ages were due to the already established changes in the elliptical nature of the Earth's orbit.

Every year, the Earth completes one orbit around the Sun. However, this orbit is elliptical and not circular. Currently, the Earth is closest to the Sun about 2 weeks after the December solstice (during the Northern Hemisphere winter) and farthest away about 2 weeks after the June solstice (during the Northern Hemisphere summer). This 2-week difference is not constant. It drifts about a day every 58 years and can vary by up to 2 days from one year to another. Today, TSI is 6.7% greater in January when the Earth is closest to the Sun than in July when it is farthest away. Because the seasons are reversed between the Northern and Southern Hemispheres, this means that the Northern Hemisphere winters and summers are a bit milder than their Southern Hemisphere equivalents.

However, the shape of the Earth's elliptical orbit is not constant. Due to the gravitational effects of the moon and planets, it can vary approximately every 100,000 years from being nearly circular to being more elliptical. Other long millennial period changes also occur in the axial tilt and precession of the Earth itself (the change in the orientation of the Earth's axis) which could also give rise to changes in the amount of TSI reaching the Earth throughout the year. Thus, it may not be entirely coincidental that the word "climate" can be traced to the Greek word *Klima* which means inclination, slope, or latitude.

In 1920, Milutin Milankovitch explained how the full set of cyclic variations in the Earth's elliptical eccentricity, axial tilt, and precession caused distinct variations in the incoming solar radiation at different latitudes and change on multi-thousand-year timescales. His mathematical solutions are known as *Milankovitch Cycles*.

The Changes in the Solar Luminosity Mechanism

Besides the effects on TSI due to orbital changes, we also must consider that the Sun is not a constant star (*i.e.*, the amount of sunlight the Sun produces every year is not constant). Every so often, dark areas, called sunspots, occur on the Sun's surface. Sunspots have been recognised by Chinese astrologers/astronomers as early as the 4th century BCE and a sunspot observation dating from 165 BCE has been recognised as the earliest precisely dated sunspot. With the invention of telescopes at the time of Galileo in the 16th century CE, astronomers (including Galileo) began to systematically record these sunspots.

We now know that the occurrence of sunspots is quasi-periodic (or quasi-cyclical) with periods of about 11 years between the maximum and minimum number of sunspots on the surface. We say these “sunspot cycles” are quasi-periodic because although the average length of a cycle is about 11 years, the exact length of each cycle can vary from as short as 8 years to as much as 14 years. However, from around 1645 to 1715 CE (known as the *Maunder minimum*), virtually no sunspots occurred on the Sun’s surface.

Since the discovery of sunspots, much debate has occurred over what effect, if any, they have on the Earth’s climate. Some people maintained that since sunspots are dark, an increase in their number would reduce the amount of light given off by the Sun and this would reduce the amount of TSI arriving at the Earth, making the Earth colder. But as E. Walter Maunder and Annie Maunder noticed in the early 1900s, brighter areas called *faculae* and *plages* follow a roughly 11-year cycle, just as the darker sunspots went through a roughly 11-year cycle. The increase in the energy from faculae could equal or exceed the reduction caused by sunspots depending on the ratio of sunspots to faculae. Astronomers and astrophysicists who study other “sun-like” stars have shown that this ratio varies from star to star. Whether this is because the ratio is constant for each star and varies from star to star, or is not constant but varies over time, has not been fully established quantitatively.

Until the start of the satellite era, it was not possible to directly measure the TSI reaching the top of the atmosphere due to atmospheric interference. This is because ground-based measurements of the incoming TSI can vary based on how the atmosphere interacts with the incoming TSI. However, starting in the late 1970s, satellites orbiting the Earth have been able to make TSI measurements. Unfortunately, due to the short orbital life of these satellites, you must stitch together the records from each of the satellites to get a continuous record of TSI for the satellite era. This is not an easy endeavour. Satellite orbits change over their lifetime, their instruments degrade, and different satellites have different instruments. To stitch the TSI records from each of the satellites together, they must be calibrated relative to each other. Several plausible TSI composites exist, some of which imply quite different trends in TSI over the satellite era. Of the two main rival TSI composites, the ACRIM group finds a positive trend in TSI during the 1980s and 1990s while the PMOD group finds a negative trend over the entire satellite era from the 1970s to present day.

By comparing each of these composites to various proxies for TSI such as sunspot numbers, sunspot sizes, faculae numbers and sizes, 10.7 cm microwave emissions, and variations in the Earth’s magnetic field, it is possible to find different reconstructions of TSI going back over at least the last 150 years.

Many different plausible TSI reconstructions exist. For instance, eight different estimates are plotted in the accompanying figure. Of them, four imply little solar variability since the 17th century. If any of these are correct, then it is unlikely that changes in TSI have played a major role in the climate changes seen since the 19th century. On the other hand, four of the estimates imply a highly variable Sun, with periods of increasing or decreasing solar activity over multiple decades. If these high variability estimates are correct, then it is plausible that much (or even most) of the climate changes since the 19th century might have been solar-driven. A big part of deciding how big a role the Sun has played in recent climate change depends on which TSI reconstruction used.

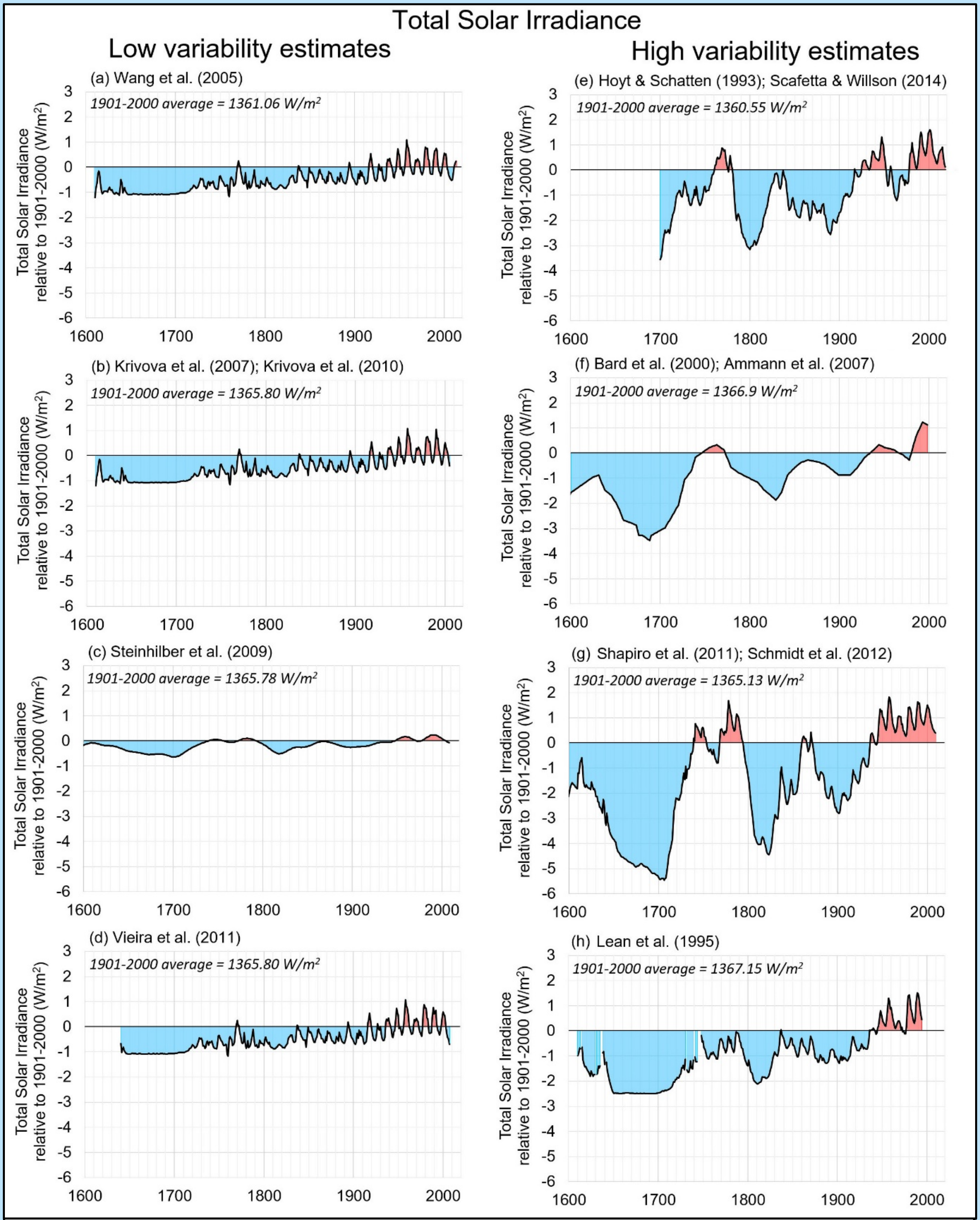
Hypothesis 2: Changes in the Earth's Atmosphere

By contrast to the solar-driven hypothesis which suggests that climate change is largely driven by factors outside of the Earth's atmosphere, many scientists have focused on mechanisms that could involve changes in the composition of the atmosphere itself over time. In the 19th century, these changes were assumed to have taken place naturally. However, during the 20th century, several scientists began to suggest that human activities might be significantly altering the atmospheric composition, and that we might therefore be contributing to "human-caused" climate change (the word "anthropogenic" is sometimes used instead of "human-caused").

Currently, the two main mechanisms usually considered within this hypothesis are:

1. Changes in the atmospheric concentration of the so-called "greenhouse gases" – chiefly water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), and nitrous oxides (N_2O). These changes could occur either naturally or from human activities. Increased greenhouse gas concentrations are believed to lead to a long-term warming trend.
2. Changes in the concentration of tiny particles called aerosols. These changes also could occur either naturally (*e.g.*, from volcanic eruptions, or from human activities, such as industrial emissions). Increased aerosols are believed to lead to a temporary cooling effect that can last for 1 to 2 years.

Because the second mechanism is mostly just a short-term effect, we will focus on just the historical development of the first mechanism.



Eight different estimates of how TSI has changed since the 17th century relative to the 20th century average (1901-2000). All estimates are calibrated to match with one of the satellite based TSI composites over the satellite era and then each uses different "solar proxies" to describe the trends before the satellite era. (Adapted from Soon, Connolly, and Connolly, 2015)

History of the Greenhouse Effect Mechanism

In 1767, Horace Benedict de Saussure used a cork-insulated box with a triple-glassed top to show that sunlight, coming in through the glass, heated to the same temperature the inside of two boxes – one located at the top of Mt. Crammont in the Swiss Alps and one in the plains below. This was notable because the air temperature at the lower altitude was 34°F (19°C) warmer than that at the higher altitude. In 1822, Joseph Fourier suggested the explanation for this result might be that the air absorbed the energy given off by the Sun heating the ground, much like the glass in Saussure's solar oven.

Then in 1862, John Tyndall, discovered in his laboratory that although oxygen and nitrogen were transparent to terrestrial rays (heat rays/infrared rays) and that some gases such as water vapor and carbon dioxide were not. He concluded *"As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the Earth's surface."*

Svante Arrhenius (who subsequently won a Nobel prize for chemistry) accepted Tyndall's conclusions and used arguments by Luigi De Marchi to reject changes in the Earth's orbit and the Sun's luminosity as contributing to the occurrence of the ice ages. Instead, Arrhenius proposed that changes in the levels of carbon dioxide in the air would change the amount of "sky radiation" incident on the Earth's surface, which would change the climate (by sky radiation, he meant the infrared radiation given off by warm air). In 1896, he calculated that halving the concentration of carbon dioxide in the atmosphere would be enough to cause an ice age. It is now recognised that the data available at the time was inadequate for the task, and even at the time, his fellow Swedish scientist Knut Angstrom, who published an infrared spectrum for carbon dioxide, rejected his conclusions claiming that the effects of water vapour would overwhelm any effect due to carbon dioxide.

Measuring Global Air Temperatures

Following the invention of a reliable thermometer by the Dutch scientist Daniel Gabriel Fahrenheit in 1714 and his later development of the temperature scale that bears his name, people and institutions started to keep records of local daily temperatures. However, it was not until roughly 1880 that enough observations became available to make reliable estimates of Earth's average temperature.

In 1938, Guy Stewart Callendar revived Arrhenius's theory that changes in atmospheric carbon dioxide could make a significant contribution to the world's temperature, but not enough to cause ice ages. Using temperature records from 200 locations around the world that were available from the Smithsonian Institution, Callendar calculated an annual global temperature series dating back to the mid-1800s (based on the temperature anomalies for each station).This temperature time series suggested that global air temperatures had increased by roughly 0.45°F (0.25°C) over the preceding 50 years. He also estimated the contribution that the burning of fossil fuels made to the concentration of carbon dioxide in the atmosphere over the same period. By comparing these two calculations, he estimated that, when the concentration of carbon dioxide reached 360 ppm, the world temperature would increase by 0.9°F (0.5°C – see table below). While praising the courage and work of Callendar, several scientists criticized his work on scientific grounds; their criticisms are still valid today.

Increase of Mean Temperature from the Artificial Production of Carbon Dioxide

Annual excess of carbon dioxide to the air is 4,300 million tons.
The partial pressure of carbon dioxide [$P(CO_2)$] is expressed in units of a ten-thousandth of an atmosphere.
ΔT is the increase from the mean temperature of the 19th century.
Sea water equilibrium time is 2,000 years.

Period	1910-1930	20th Century	21st Century	22nd Century
Mean $P(CO_2)$	2.82	2.92	3.30	3.60
Mean ΔT	+0.07°C	+0.16°C	+0.39°C	+0.57°C
Polar Displacement of Climate Zones	15 km	36 km	87 km	127 km

Adapted from Callendar (1938)

Most notably, carbon dioxide concentrations reached 360 ppm much quicker than Callendar predicted (*i.e.*, in 1990 and not 2200). Yet, the global temperature was roughly the same in 1990 as it was in 1938 and the current best estimate of the airborne fraction of carbon dioxide remaining in the atmosphere due to the burning of fossil fuels is closer to 50% than his estimate of 75%.

Nonetheless, Callendar's work still has had considerable influence. In 1955, Roger Revelle was inspired by Callendar's idea that increasing carbon dioxide in the atmosphere could cause an enhanced greenhouse effect. Revelle promoted what he referred to as the "Callendar Effect" and said publicly that considerable harmful effects could be realized by the end of the 20th century. Nevertheless, the 20th century has ended without these dire warnings coming true.

Revelle, along with Charles Keeling and Harry Wexler, established the Mauna Loa Observatory Measurements Program (in consultation with Callendar and others) in 1958 to monitor atmospheric changes in carbon dioxide. The results of this program, which continues to this day, are now referred to as the "Keeling Curve."

The Keeling Curve has shown that the concentration of carbon dioxide has increased from 0.031% of the atmosphere in 1958 to 0.041% in 2020. According to the current computer models, based on the work of Callendar and others, this should have led to a noticeable long-term human-caused global warming from the enhanced greenhouse effect mechanism. Therefore, scientists relying on these models believe that most of the climate changes since the 19th century have been human-induced.

Where Are We Today?

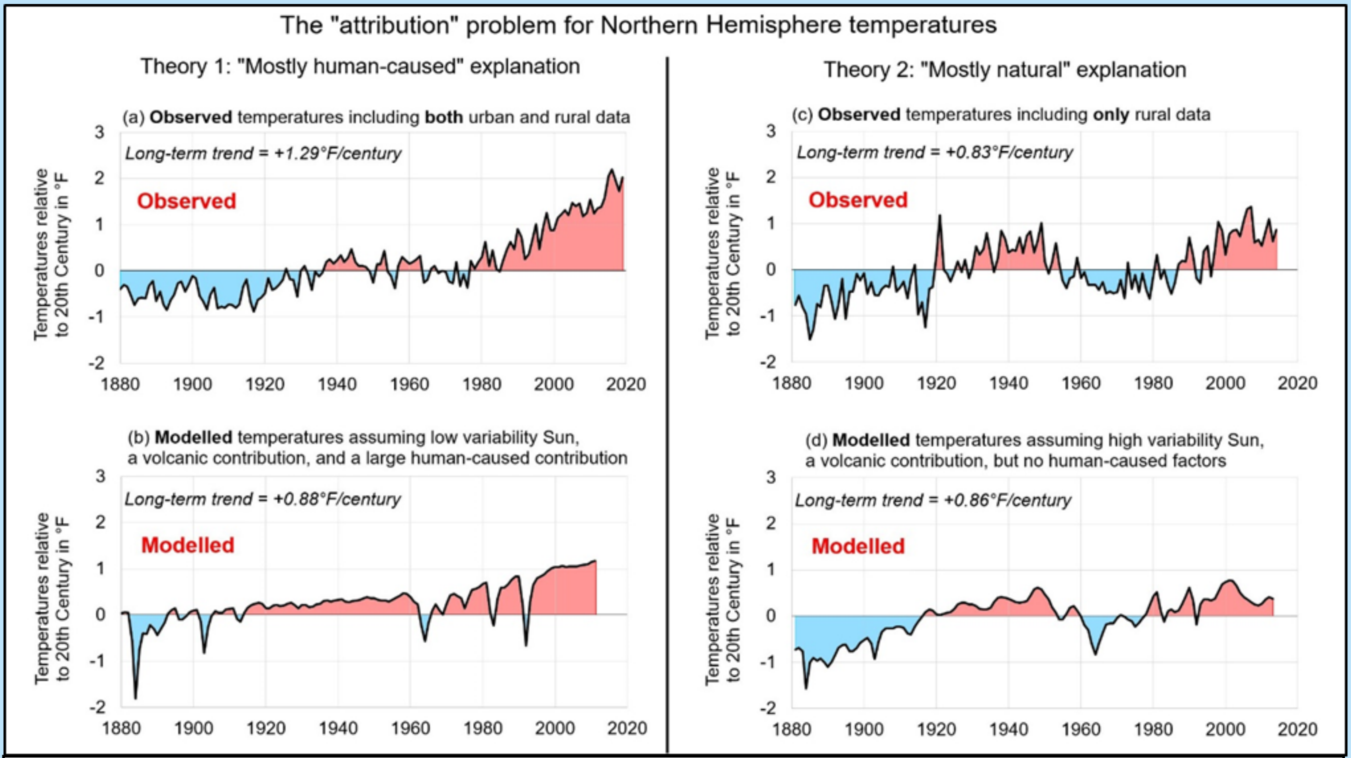
Most scientists agree that changes in carbon dioxide did not cause the ice ages but that the long-term change in carbon dioxide might, in fact, be due to the Milankovitch cycles. However, with respect to climate change over the last 150 years, the effect of Milankovitch cycles is generally assumed to be relatively slow and gradual and most scientists look elsewhere an explanation of changes over the past two centuries.

Since Callendar's time, thousands more station records have become available, more than half-a-century of carbon dioxide concentrations have been measured, and satellite estimates of TSI have been established. Despite these advances, many of the problems which were considered by Callendar and his peers remain unresolved in assembling a global temperature time series. Moreover, a suite of additional problems, unrealized by Callendar and his colleagues, have revealed more scientific difficulties.

Consider, for example, one such bias – the **Urban Heat Island Effect (UHI)**. Urban areas are known to be warmer than the surrounding countryside. As areas become more urbanized, the associated UHI becomes larger. Therefore, if a weather station is in an area with urban growth, there is a risk that the weather station's record might become biased by this localized urban warming. Callendar had suspected an urban bias might exist, but he calculated that it was quite modest.

To this day, an ongoing debate exists within the scientific community over whether urban biases are substantial or relatively minor. The **Intergovernmental Panel on Climate Change (IPCC)** has argued that the net effects of UHI biases are much smaller than the long-term global warming since the late 19th century. Other researchers disagree. For example, Soon, Connolly and Connolly (2015) calculated temperature trends for the Northern Hemisphere using only rural stations and they found different results than the standard estimates that included both urban and rural stations. These two contrasting estimates can be seen in the figure below. On the other hand, as can be seen from the right-side of the figure, if you use the rural-only estimates and consider one of the high solar variability TSI estimates, most of the trends since at least 1881 can be explained in terms of natural climate change.

Which of the two competing explanations is correct, or are they both wrong? Many non-scientists assume that the scientific process is linear, and science always moves forward. That is, scientists find an answer to one problem and then move on to the next. Science is much messier as, unlike common sense, science is not intuitive. Scientists analyzing the same data can often arrive at different conclusions. New data and insights are constantly revising our previous understanding. Thus, we encourage you to dig deeper and ask questions.



Comparison of two competing "attribution" explanations for Northern Hemisphere temperature trends since the late 19th century. The two graphs on the left-hand side present an explanation that suggests the trends are mostly human-caused with a very small role for the Sun, while the two graphs on the right-hand side suggest that the trends are mostly natural with a very large role for the Sun. The "long-term trend" values correspond to the linear temperature trend over the same common period, 1881-2011, for each time series. (Adapted from Connolly, Connolly, Carter, and Soon, 2020)

Dr. Michael Connolly, Center for Environmental Research and Earth Sciences, Salem MA
Dr. Ronan Connolly, Center for Environmental Research and Earth Sciences, Salem MA
Dr. Willie Soon, Astrophysicist, Harvard-Smithsonian Center for Astrophysics

For Further Information

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