





EFFECTS OF THE SUN ON WEATHER AND CLIMATE

A Brief History

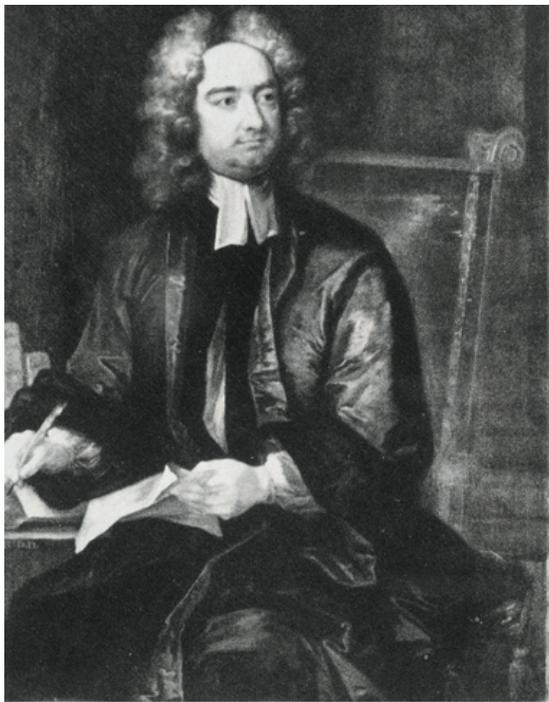
It has long been known that the Sun provides almost all of the energy that powers the weather machine, including the mighty forces that drive winds and storms, push ocean currents, and cycle the water between the surface and the air. What is not as well established—even today—is the extent to which variations in the weather and climate arise from fluctuations, short or long, in the energy the Sun delivers at our door.

This practical question, so often asked, has been around in one form or another for a long, long time. For at least 200 years natural philosophers and astronomers, then solar physicists and meteorologists, and now climatologists and paleoclimatologists and oceanographers have tried to find the answers, in the hope of achieving practical weather and climate prediction.

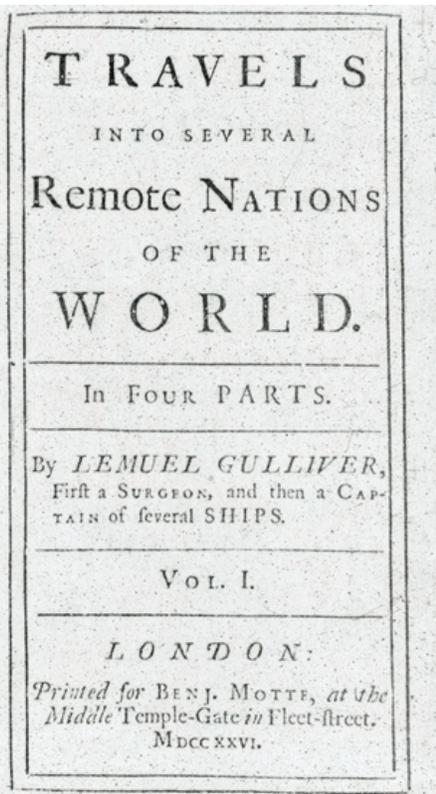
Concerns about the Sun's constancy are common in early religions, and probably as old as human thought. Almost as old, we may presume, are the intuitive feelings that since the Sun is the obvious source of heat and light and day and night, might it not also control the seemingly random vacillations of weather and longer-lasting changes in climate?

Soon after Galileo and his co-discoverers first saw dark spots on the face of the Sun, in 1609, it was apparent that the number of [sunspots](#) (and their sizes and positions) changed from day to day. That these variations on the surface of the Sun might possibly affect weather in Europe or elsewhere on the Earth must have been to them an obvious deduction. And one that has never gone away. The conjecture that sunspots might somehow affect the weather was common enough that about a hundred years later, Jonathan Swift in 1726 wove this common presumption into his tales of *Gulliver's Travels*.

There he tells of the floating island of Laputa: a mythical land populated by philosophers and astronomers who—equipped with telescopes better than ours—were not only obsessed with the sky, but always troubled by what they saw. Among their many apprehensions was a fear that the face of the Sun might become so covered with dark spots that it would no longer provide sufficient heat and light to the world. When the Laputians met an acquaintance early in the day, he tells us, their first question was not the customary “How are you?” but “How did the *Sun* look this morning?”



Jonathan Swift



Jonathan Swift (1667-1745) and the title page of his book published under the pen name Lemuel Gulliver in 1726. Throughout Swift's life, astronomers and other learned people were well aware of an unusual paucity of spots on the face of the Sun persisting for fully 70 years, from about 1645 until 1715: a paradox which probably influenced Swift to include a fanciful but related episode in Gulliver's Travels.

Real astronomers in the eighteenth and nineteenth centuries who looked at the real Sun in the real world were also intrigued by the possibility of a Sun-weather connection. Quite apparent to any of them was the enormous practical benefit to society—in an age when the prediction of weather was based almost entirely on accumulated lore and seasonal expectations—were a clear connection to be found linking the presence or absence of easily observed features on the [disk of the Sun](#) to local or regional weather conditions.



Many claimed to have found it, including Sir William Herschel, the celebrated astronomer and builder of large telescopes, whose paper published in 1801 in the *Philosophical Transactions of the Royal Society* reported his own discovery of a persistent relationship between the prevalence of sunspots and the price of a bushel of wheat on the London market. Based on his own and earlier observations of the Sun since about 1650, he found that during protracted periods when sunspots were scarce the price of wheat was always higher. Herschel reasoned that fewer spots on the Sun denoted abnormality and an



Sir William Herschel (1738–1822), widely considered the leading astronomer of his day, was among those who suspected a strong link between protracted periods of unusually low or high solar activity, measured in the numbers of sunspots seen, and the Earth's weather. His conclusions, published in 1801, preceded by almost half a century the realization that sunspots followed a short-term cycle of about 11 years.

accompanying deficiency in the amount of heat the Sun released, leading to poorer growing conditions, diminished agricultural production, and through the inexorable law of supply and demand, higher commodity prices.

When Herschel published his paper, the cyclic 11-year rise and fall in the number of sunspots was not yet known, and wouldn't be for nearly half a century. The belated discovery of this strongly periodic feature in the annually-averaged numbers of spots on the visible surface of the Sun was announced, as we have noted earlier, by Heinrich Schwabe in Germany in 1843.

In time Schwabe's discovery proved to be a seminal revelation into the physical nature of [solar activity](#) and variability. In the mid-nineteenth century, however, the principal effect on scientists and many other people was a rush to find statistical evidence of meaningful connections with other phenomena—and particularly the weather, in the hope of finding keys to practical weather prediction. Schwabe's announcement triggered an avalanche of claims that continued unabated for years, each purporting to have found meaningful correlations between the [sunspot cycle](#) and a host of things meteorological, hydrologic, oceanographic, physiological, behavioral, and economic.

Sir Norman Lockyer, the Victorian solar physicist who founded and for fifty years edited the journal *Nature* was an early champion of these searches, counseling in 1873 that "...in Meteorology, as in Astronomy, the thing to hunt down is a cycle." He had found one, himself, the previous year, in records of the intensity of monsoon rains in Ceylon that were clearly linked, he said, to the ups and downs of the 11-year sunspot cycle; adding, with characteristic

modesty, that based on his discovery, "...the riddle of the probable times of occurrence of Indian Famines has now been read."

Indeed, until relatively late in the 20th century almost the only tool available for the investigation of possible influences of solar variability on weather and climate was the statistical comparison of indices of solar activity with contemporary meteorological records. And while some of these searches proved valuable as probes and tests of a complex system, most of what was found seemed soon to go away, and few of the correlations that were claimed stood up to rigorous statistical tests. Without the buttress of a solid physical explanation, none proved to be of any significant value in practical weather or climate prediction. The required leap of faith between what was seen on the Sun and what was felt at the bottom of an ocean of air on a small planet 93 million miles away was simply too great, in the absence of a fuller knowledge of what happens in between.

Beginning in the 1870s, heroic efforts were made by the American astronomer Samuel Pierpont Langley and others to put the question on a more solid basis by attempting direct measurements of the Sun's [radiation](#) from the top of Mt. Whitney and Pike's Peak and other high-altitude stations. Through the persistence of Langley's assistant and successor, Charles Greeley Abbot, attempts to identify possible changes in [solar irradiance](#) from the surface of the Earth were continued at different stations around the world through the first half of the ensuing century: but to little avail, due to difficulties in absolute calibration and larger uncertainties in allowing for the variable absorption and [scattering](#) of solar radiation in the intervening atmosphere.

In spite of more than a century of dedicated effort, the very practical question of whether and how solar variability affects the Earth's weather and climate would remain largely unanswered until relatively recently when needed facts were at last obtained.

The Missing Pieces

Missing and badly needed in early attempts to find answers to the Sun-Climate question were (1) a fuller understanding of the effects of sunspots and other apparent changes on the energy released from the Sun; (2) a more complete understanding of other forces that perturb the climate; (3) the availability of analytical tools to test and evaluate proposed responses to solar fluctuations in a system that was both complex and interactive; (4) a reliable record of global climatic changes, both past and present; and perhaps most important; (5) quantitative measurements of any changes in the amount of solar energy the Earth receives.

While some facts were known about the surface of the Sun two hundred years ago when Sir William Herschel proposed a causal connection between sunspots and the price of wheat, next to nothing was known about what we now call *climate*, as opposed to short-term *weather*. The same was true almost a century later when Sir Norman Lockyer laid his shaky claim to having unlocked the secrets of the Indian monsoon.

The fundamental questions were these: Through what limits *does* the energy received from the Sun vary, from day to day or year to year? *How much* does the climate vary at any place, or over the Earth as a whole? How does the climate system work, and *how important* a player is the Sun?

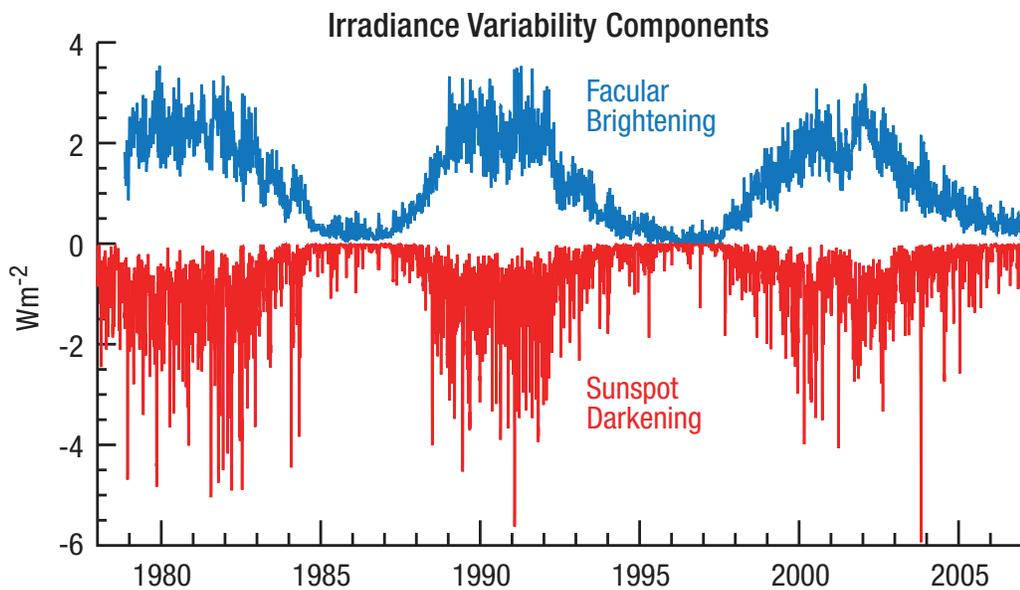
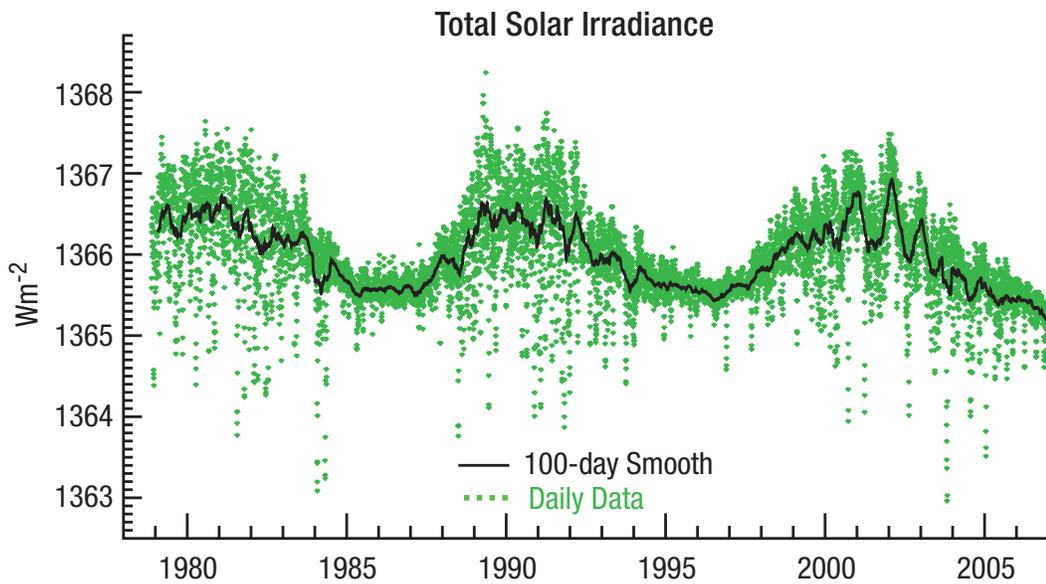
Today we have most of the answers, due largely to our ability to observe the Sun and global phenomena from the vantage point of space, and the modern capability of creating and testing realistic models of the entire climate system that incorporate variable inputs from the Sun. Major advances have also been made in the last few decades about the interactive climate system and the history of climate change, driven in large part by world concerns regarding global warming and its likely economic, societal and environmental effects.

Metering the Energy the Earth Receives

Many of the advances of the past few decades in understanding the effects of the Sun on climate come from direct measurements from space of the fluctuations in solar energy received at the top of the Earth's atmosphere: truly, where the rubber meets the road. These seminal measurements of [total solar irradiance](#)—initiated in 1978 and continuing today—give needed substance to modern investigations of the Sun and Climate, while providing answers to the oldest of all solar questions: How constant is the Sun?

We now know that the total solar irradiance varies from minute-to-minute, reflecting activity-driven changes on the face of the Sun; from day-to-day in step with solar [rotation](#) and the evolution of solar [active regions](#), with day-to-day amplitudes of up to about 0.3%; and more important in terms of climate, from year-to-year with a peak-to-peak amplitude of about 0.1%, in phase with Schwabe's 11-year sunspot cycle. In years when the Sun is more active, and more spots are seen, more radiative energy is delivered to the Earth—just as Herschel had surmised, 200 years ago.

The impact of variations of this amplitude on surface temperature depends on the persistence of an increase or decrease, and the sensitivity of the climate system to solar forcing. In theory, and were nothing else at work, a sustained



Upper: Changes in the total radiation received from the Sun at the top of the Earth's atmosphere through three 11-year solar cycles, starting in 1978 when continuous radiometric measurements of this fundamental parameter were begun. Maxima and minima are in phase with coincident changes in solar activity, with maximum radiation received in years of maximum solar activity.

Lower: Day-to-day changes in total radiation expected from daily measurements of the areas of bright faculae (which increase the radiation received) and sunspots (which act in the opposite direction) observed on the surface of the Sun. Although sunspots are more easily seen, faculae and bright regions exert a greater effect on the annual average of solar radiation received at the Earth, as is apparent in the upper figure.

increase of 0.1% in total solar irradiance can be expected to warm the surface temperature of the Earth by about 0.1°F.

And indeed, changes of this amount have since been found in averaged regional and global weather records, extending back for fifty years or more, in both the temperature of the air and in surface and subsurface temperatures of the oceans. These could easily be attributed to changes in total solar irradiance, since the amplitudes and phase of the temperature anomalies are consistent with the observed 11-year variation in the radiative output of the Sun.

But the remarkably close agreement with the ocean data, in particular, is in some ways enigmatic, for the **thermal inertia** of the oceans should more heavily damp the climate system's response to "rapid" fluctuations in solar energy.

It takes about three years for the upper, mixed layer of the ocean to fully respond to heat added at the surface. This means that unlike the air, its temperature at any time tells not so much about *today* as about the *past*, and more precisely of what it remembers of conditions during the last several *years*. Yet the Sun's 11-year cyclic forcing persists for only a few years in one direction before reversing itself: three years to rise from minimum to maximum, two or three years there, then a slower fall of five or six to the next minimum.

The effect of the oceans' three-year memory in responding to short-duration changes of about the same length should significantly reduce its theoretical sensitivity to imposed solar forcing. Yet the 11-year variation found in ocean temperature data is not less but *more* than what is expected.

What seems likely is that other climatic processes are indeed at work, including possible feedbacks that tend to amplify the response of the Earth's climate system to subtle solar forcing. In addition, 11-year variations larger in magnitude than in the total solar irradiance are found in the Sun's *spectral* irradiance and in its output of high-energy particles. Either or both of these could well prove responsible for amplifying the apparent response of the atmosphere to 11-year solar forcing.



Other important questions still remain. Is the Sun so massive and imperturbable that the more superficial 11-year modulation of total and spectral irradiance and solar particles are the *only* significant variation in the energy it releases? Might there be other, longer-term changes? Our only continuous record of solar energy received at the Earth—from 1978 to the present day—covers but the blink of an eye in the life of the Sun. Nor has it

yet allowed us to detect the effects of known fluctuations in solar activity that persist for decades and longer.

Best known among these longer-term changes are the recurrent 50 to 100-year episodes of severely suppressed activity, like the [Maunder Minimum](#) of 1645-1715, that are prominent features in both historic records of sunspots and in the far longer [proxy records](#) of solar activity obtained from dated ice cores and tree-rings. Nor did the space-borne measurements begin early enough to catch the systematic rise in the overall level of solar activity which was the Sun's dominant characteristic through the first half of the 20th century.

RECENT PROLONGED EPISODES OF LOW AND HIGH SOLAR ACTIVITY

EPISODE	DURATION
Spörer Minimum	1540 - 1450
Maunder Minimum	1645 - 1715
Dalton Minimum	1790 - 1830
Modern Minimum	1875 - 1915
Modern Maximum	1940 - Present

There could be other, deeper-lying causes of change in solar irradiance—periodic or aperiodic, related or unrelated to solar activity—that operate more slowly and on longer scales of time. And because of the thermal inertia of both the land and the oceans, we should expect the climate system to be more responsive to slower and more persistent forcing than to daily, annual, or 11-year fluctuations.

One reason for *suspecting* longer-term changes of larger-amplitude in solar radiation include an apparent correlation between the Spörer and Maunder minima of solar activity in the 15th through the early 18th centuries and particularly cold epochs of the contemporaneous Little Ice Age, and the close correspondence between features in the paleoclimate record of the [Holocene epoch](#) with what is known of the behavior of solar activity from proxy data during the same periods of time. But these apparent associations are with indices of solar *activity* and not necessarily solar *irradiance*. While irradiance changes are arguably the most likely solar cause, they are but one of several activity-related variations in the output of the star.



An auxiliary method for studying possible long term changes in the radiative output of the Sun is by adding statistical evidence from dedicated, ongoing observations of the spectra and brightness of Sun-like stars. Some early studies

seemed to indicate likely similarities. But these have not been substantiated and as yet the radiometric findings from other stars are far from conclusive on this matter.

Recovering the Past History of the Sun

We know now that sunspots *inhibit* the upward convective transport of energy to the [photosphere](#) and *diminish* the emergent radiation in proportion to their total projected area as seen from the Earth. Bright areas that surround sunspots and the bright boundaries of the tops of convective solar [granules](#) act in the opposite direction to *increase* the Sun's total energy output. As a result of this ongoing tug-of-war the amount of radiation the Sun emits and we receive is continually driven up and down: at times increasing the energy we receive and at others reducing it.

In the long run, when averaged over a year or so, the brighter elements prevail, as is apparent in the observed rise (of about 0.1%) in measured total irradiance in years of greater solar activity, and the ensuing fall as solar activity declines.

These clear associations linking easily-observed solar *features* to solar *irradiance*—a parameter which is far more difficult to measure and monitor—provide a kind of Rosetta Stone, or template, for translating earlier historical observations and records of the numbers of spots seen on the Sun into histories of associated changes in total or spectral irradiance.



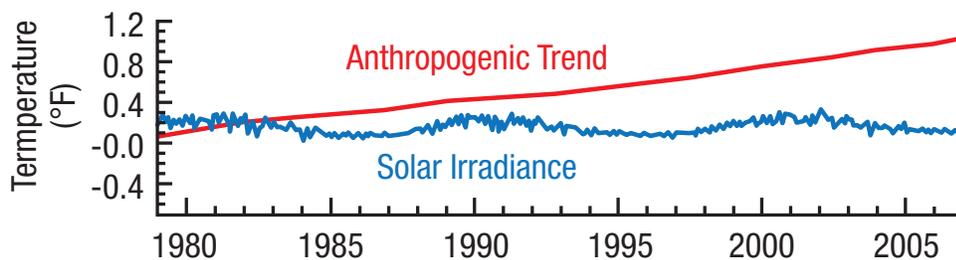
Drawings and other accounts of the number of spots that were seen on the Sun on any day are available through most of the long 400-year history of telescopic solar observations. But the period in which these can most reliably be employed to recover associated changes in solar irradiation does not begin until the second half of the 19th century: on the heels of Heinrich Schwabe's discovery in Dessau.

It was then, in response to fast-growing interest in the possible terrestrial effects of the sunspot cycle, that a daily photographic patrol of the [white-light](#) solar disk was first begun: initially in 1858, at London's Kew Observatory; not long after, on the banks of the Thames at the Royal Greenwich Observatory; and in due course at other stations in other countries around the world. A corresponding set of continuous photographic images of the solar [chromosphere](#) is available from at least 1905 onward. For the period of time between about 1880 until 1978, when direct measurements began, the changes in total solar irradiance

that are related to the 11-year [solar cycle](#) can be reconstructed with some confidence. What they cannot tell, however, is whether there were other, slower and possibly larger changes as well.

Nevertheless, estimates of solar radiation derived in this way from historical sunspot records resemble quite closely the long-term trends and excursions in the mean global surface temperature of the Earth for the same period. Moreover, when postulated changes of greater amplitude than those measured in the past quarter century of record are included—keyed to known, long-term changes in the overall level of solar activity—the fit with the surface temperature record of the last 100 years is remarkably good.

Based on the presumption that these long-term changes in the overall level of solar activity tell of changes of larger amplitude in solar irradiance, about half of the documented rise in the surface temperature of the Earth in the period from about 1900 to 1940 might possibly be attributed to the Sun. In the remaining years of the century just ended, the fraction of the total change in mean surface temperature that can be attributed with certainty to solar variability drops to less than 5% of the concurrent steeper rise in temperature, with the remainder widely attributed to the direct effect of ever-increasing levels of greenhouse gases. But it must be emphasized that the larger-amplitude, slower changes in solar irradiance on which these conclusions are drawn are largely speculation. The more conservative assessment which dismisses the possibility of as-yet undetected irradiance changes of longer term, is that the effect of solar changes are no more than a ripple on the back of a gigantic swell driven by increasing greenhouse gases.



A comparison of the effects of two forcing factors on the mean surface temperature of the Earth through the period from 1978 and 2007: in blue, from recorded measurements of the total radiation received from the Sun; and in red, the calculated long-term trend due to the recorded increase in atmospheric greenhouse gases. The human-induced (anthropogenic) trend far exceeds the amplitude of the expected effect of the Sun on the Earth's surface temperature, washing out the periodic lower-amplitude effect of recorded changes in solar forcing.



How much farther back in time can we hope to improve our knowledge of past activity-related changes in solar irradiance?

Drawings of the disk of the Sun, and written records of sunspots and bright [faculae](#) are indeed available for the last several hundred years. And in almost all of these the Sun's 11-year cycle, including changes in its amplitude, are readily found. But the reliability of the pre-1850 records begins to fray when there are fewer than 365 sampled dates in any year, since the face of the Sun can vary a great deal from one day to the next, in both active and quiet years.

By this criterion the quality of the historical record of annually-averaged sunspot activity (and by association, of reconstructed changes in solar irradiance) degrades from *excellent* in the period since 1850, to *fair* from that date to about 1818, and successively *poorer* before that time.

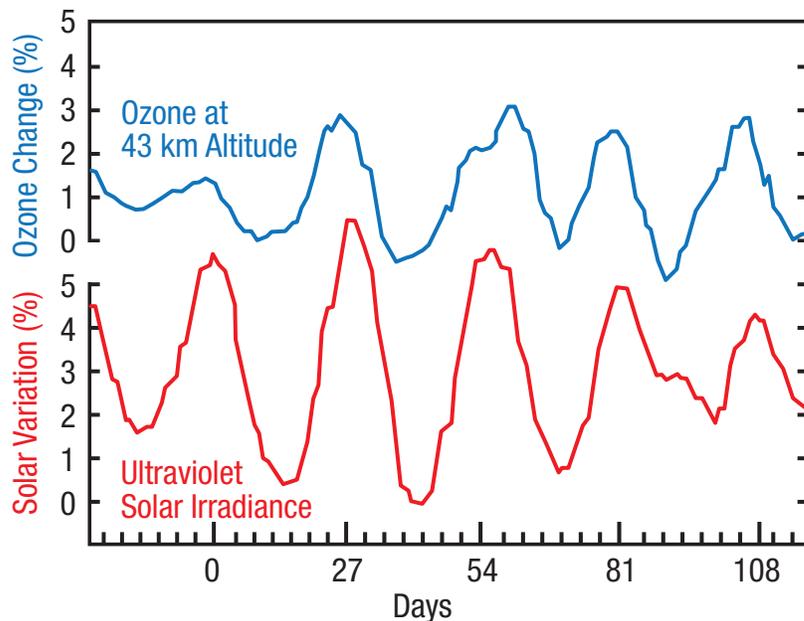
Nonetheless, the patched-together accounts of the number of sunspots seen on the Sun—beginning in the early 17th century and continuing to this day—comprise what is probably one of the longest continuous diaries of anything in science. And this long record can now be read, both as proof of an ongoing 11-year solar cycle and as evidence of slower variations of longer term in the behavior of the Sun.

The less direct but far longer proxy records of past solar behavior obtained from the carbon and beryllium [isotopes](#) ^{14}C and ^{10}Be , described later in this section, also speak eloquently and emphatically of recurrent long-term changes in solar activity. In the most recent five hundred years of these proxy data the same long-term variations appear that are found in early historical records of sunspots and [aurorae](#).

Effects of Solar Spectral Radiation

As we have seen, the bulk of the radiation from the Sun, in the visible and [near-infrared](#) regions of the [spectrum](#), comes from the 10,000° F surface of the photosphere, while solar radiation in both shorter or longer [wavelengths](#) originates in higher and much hotter levels in the [solar atmosphere](#): in the chromosphere, [transition zone](#) and [corona](#).

In these magnetically-dominated levels in the Sun's atmosphere, solar activity plays a greater role, and for this reason the radiation they emit varies through a much wider range than does the Sun's light and heat in the visible and near-infrared.



Measured changes in solar ultraviolet radiation received at the top of the atmosphere (in red) over a period of about five months, showing modulation due to the effect of the Sun's 27-day rotation. In blue are contemporaneous measurements of percentage change in the amount of ozone in the high stratosphere where ozone is created by the action of this form of solar radiation on molecular ozone.

Of particular interest are the regions of the more variable parts of the [ultraviolet spectrum](#) that control the chemical composition and photochemistry of the middle atmosphere, including the [stratospheric ozone layer](#).

The connection between 11-year cyclic variations in solar [ultraviolet radiation](#) and the amount of ozone in the [stratosphere](#) is well established, although a quantitative relationship, based upon measurements taken during the last two solar cycles, was made more difficult by the chance occurrence of two major volcanic eruptions—which can affect the transparency of the air and the production of ozone—during the same period of time: *El Chichón* in Mexico in 1982 and *Mt. Pinatubo* in the Philippines in 1991.

Stratospheric ozone can also affect the dynamics of the atmosphere, including the circulation in the [troposphere](#). The chain of physical and chemical processes that link solar ultraviolet radiation to stratospheric ozone and then to radiative or dynamical coupling between the stratosphere and troposphere is one of the two most likely mechanisms—on the basis of available energy—to explain apparent connections between solar activity and climate. The other is direct solar heating through changes in the total solar irradiance. The effects of either one could be either damped or amplified by possible feedback mechanisms within the internal climate system.

Past changes in the Sun's ultraviolet spectral irradiance can also be reconstructed from photographic images of the solar disk made in the [visible spectrum](#), taken in the restricted light of the center of strong [absorption lines](#) in the solar spectrum that originate at the same higher level in the solar atmosphere as does much of the ultraviolet radiation.

Measurements of the radiation the Earth receives in different parts of the solar spectrum—from the far ultraviolet through the near infrared—have been recorded continuously since 2003 when NASA's *SORCE* (*Solar Radiation and Climate Experiment*) spacecraft was launched. Measurements from *SORCE*, which also carries a total radiation monitor, make it possible for the first time to examine the relative contributions of different spectral components to the total radiation received: a powerful aid in determining their possible roles as agents of weather and climate change.

Sensitivity of Climate to Solar Fluctuations

Through how many degrees should we expect the mean surface temperature of the Earth to rise (or fall) were the Sun's total output of energy to increase (or decrease) by a given amount, say 1%? A quantitative answer to this simple but important question defines what is called the [climate sensitivity](#), which is among the fundamental parameters required in sophisticated numerical models of the climate system.

It is possible to calculate, based on fundamental physical principles, what the temperature response should be. The answer is that in the absence of any internal amplification or feedbacks, each increase of 1% in the total solar radiation received at the Earth should raise the mean surface temperature of the planet by about 1° F—or as noted earlier, 0.1° F for each 0.1% increase.

But it is more to the point to determine the sensitivity of climate to solar forcing *empirically*: that is, based on real measurements under real conditions in the real atmosphere. And this also has been done.

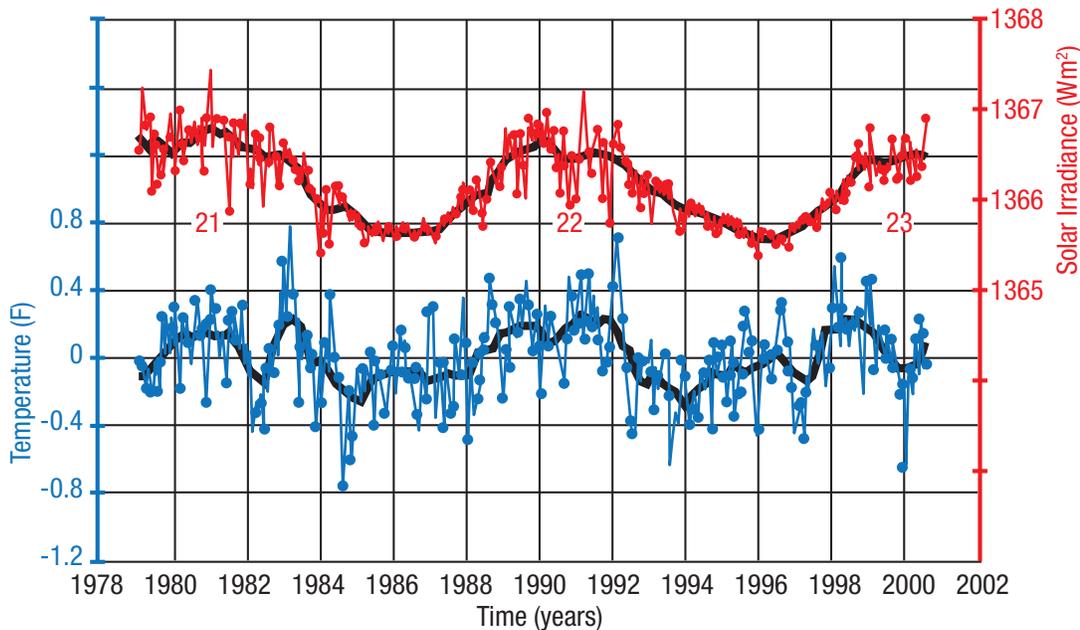


One of the most recent and extensive determinations of climate sensitivity was based on the analysis of globally-complete meteorological data sets for the twenty-five year period for which direct measurements of total solar irradiance were then available. When the known effects of the other dominant forcing mechanisms are subtracted—including [El Niño/La Niña](#), volcanic eruptions, and the documented increases in greenhouse gases and atmospheric [aerosols](#)—a clear 11-year modulation remains. Moreover, it is in phase—as we should

expect—with the solar activity cycle, in the sense that years when the planet is hotter correspond to years when the Sun is more active.

If we assume that variations in solar *irradiance* are the cause, the amplitude of the apparently solar-driven modulation in surface temperature is about two times greater, as noted earlier, than simple theory would predict: or about 0.2° F for the observed 0.1% change in total solar irradiance.

The difference of a factor of two is in agreement with a similar study of *ocean* temperature data sets, and also with what is implied in another even more extensive study of a remarkably robust correspondence between reconstructed temperatures for the last 11,000 years and proxy records of changes in solar activity during the same period. A likely explanation of what seems to be a consistent difference is a feedback in the climate-system that amplifies the direct impacts of rather small changes in solar irradiance.



A comparison of (1) measurements of the total solar radiation received at the Earth during solar cycles 21, 22, and 23 (in red); an (2), in blue, spacecraft measurements of the northern hemisphere temperature of the lower troposphere in the same period. The effects of volcanoes, El Niño/La Niña events, and a fitted linear trend have been removed from the temperature record.

A similar investigation, based on global surface temperatures covering the entire 20th century came to a similar conclusion. In common with other modeled studies of the same kind, it was found that combining solar *and anthropogenic* (human-driven) forcing in approximately equal amounts provided a good fit to the global documented global warming of the Earth in the first half of the century. However, to fit the continued and steeper rise in mean surface temperature in the period following 1940 required additional

non-solar heating, which was attributed to the rapid increase in greenhouse gases and atmospheric aerosols at this time. In this more recent period the ratio of anthropogenic to solar forcing needed to explain the observed temperature rise was about 4:1. Which infers that increased solar warming, acting alone, might explain only about 20% of the rise.

An apparent amplification of the effects of changes in solar irradiance was also found in climate models when more CO₂ and other greenhouse gases were introduced into the atmosphere.

These and other results suggest that the effect of solar irradiance variability on climate depends to some degree on pre-existing conditions and what else is at work at the time, and where, in the coupled (land-ocean-atmosphere) climate system. If so, it may help explain the will o' the wisp nature of so many of the here-today, gone-tomorrow correlations that have been claimed through the years linking weather and climate parameters with the sunspot cycle—including, among others, Norman Lockyer's purported discovery of an 11-year monsoon cycle in British India in 1872 .

11-Year Solar Forcing

Beginning in the high stratosphere, some thirty miles above the surface of the Earth, any changes in the atmosphere are directly driven by the Sun, which exacts pronounced responses to any variations in solar spectral irradiance and incoming atomic particles. Examples can be found in the dramatic solar-driven changes in the number of electrons and [ions](#) in the [ionosphere](#), and in the instantaneous temperature responses of the [thermosphere](#). Variations that are clearly related to the 11-year solar cycle are also apparent in the lower stratosphere, in the long series of readings taken there by sounding balloons.

All of these more rarefied regions of the Earth's atmosphere are more directly exposed and in many ways more vulnerable to solar disturbances and fluctuations. But the dense troposphere—the realm of all weather and climate—is only weakly linked to the more vacuous middle and upper atmosphere, due to these great differences in [density](#).

Apparent 11-year effects have been noted through the years in local and regional weather records, but it is only recently that the marks of the Sun have been unequivocally found in hemispheric or globally-averaged tropospheric data sets.

One of these, covering forty years of Northern Hemisphere temperature measurements from balloon sondes at heights of about two to eight miles above

the surface, reveals a clear 11-year signal, in phase with the solar activity cycle, with higher temperatures, as expected, in years of maximum solar activity. Another, covering the entire globe, found a similar 11-year temperature response that varied, in both sign and amplitude, as a function of both latitude and height above the surface. The nature of the differences suggests that the solar signal observed is imposed from the stratosphere, as a result of dynamical motions in the atmosphere.

Another—cited earlier—based on global measurements of the troposphere in low and mid latitudes from 1958 through 2001 found that not only the temperature, but all major meteorological observables in low and mid-latitudes were strongly correlated with the phase of the 11-year solar cycle, when signals due to other known sources of climate forcing were removed from the data. The latter included known [El Niño Southern Oscillation](#) (or [ENSO](#)) effects, volcanic eruptions, changes in atmospheric aerosols, and a linear trend attributed to global greenhouse gases.

Solar Forcing of the Oceans

The oceans are a major element of the global climate machine, affecting year-to-year and longer changes in climate through ocean-atmosphere interactions and internal modes of climate variability such as the Pacific Ocean ENSO and the [North Atlantic Oscillation](#), or [NAO](#): a similar phenomenon involving a quasi-regular see-saw in sea-level air pressure between large-scale regions, in this case in the North Atlantic Ocean.

The oceans also influence climate by storing heat in ocean basins, and by temperature-driven changes in the [thermohaline circulation](#) of the deep oceans that are driven by systematic differences in the salinity of ocean water.

Variations in solar irradiance are a likely forcing factor in each of these, as has been shown in recent studies of different ocean characteristics. In one of them, 11-year cyclic variations were found in surface and subsurface ocean temperatures, which were consistent—in both phase and amplitude—with measured 11-year variations in solar irradiance. Another, which we describe later, found a striking correlation throughout the last 11,000 years between ocean temperatures and recurrent eras of prolonged suppression of solar activity, like the Maunder Minimum.

Clear marks of 11-year solar forcing were also found in ocean temperature measurements covering forty-two years of surface and sub-surface temperature sampling in the Atlantic, Indian, Pacific, and global-averaged Oceans, spanning conditions from latitude 20° to 60° N. These reveal systematic cyclic changes

in ocean temperatures, like those found in the atmosphere, that are in phase with the 11-year solar activity cycle, and consistent with the variations found in total solar irradiance. The 11-year temperature response was evident from the ocean surface to a depth of about 500 feet, which is about the maximum distance to which sunlight penetrates. (The transparency of the [photic zone](#) of the upper ocean—which in the clearest ocean water extends to a depth of about 650 feet—is greatest in the blue part of the visible spectrum, and in more turbid seashore waters in the green and green-yellow. To most of the ultraviolet and infrared, the seas are almost opaque.)

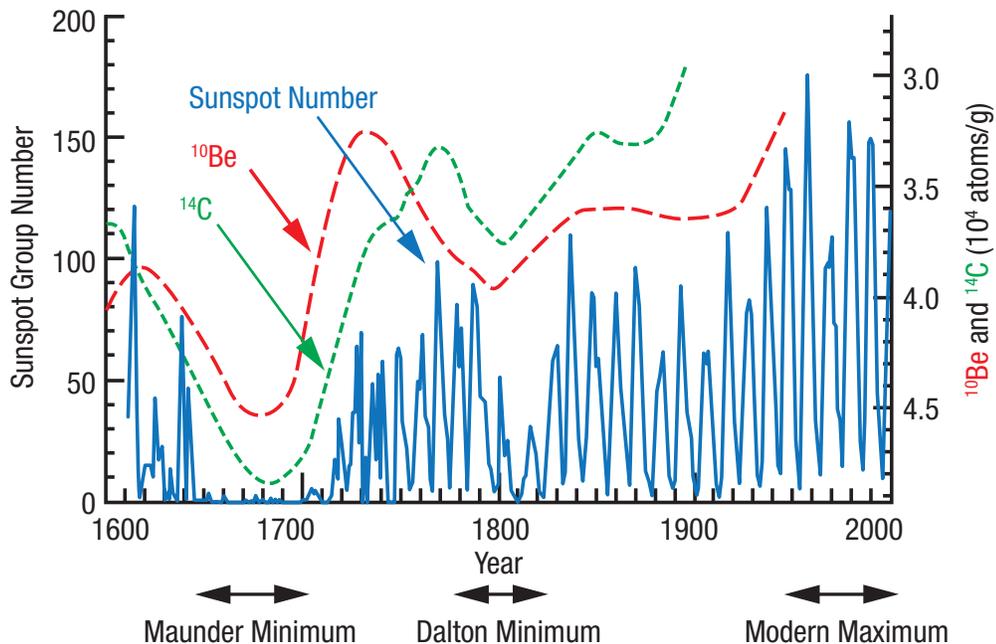
Although many questions remain, these documented changes in long-term records suggest that natural modes of the global climate system are locked in phase to the 11-year solar activity cycle.

That subtle changes in solar irradiation might serve as a phase-locking device for year-to-year changes in climate is in agreement with our present understanding of the glacial-interglacial cycles, tens of thousands of years long, that characterize the climate of the [Pleistocene epoch](#) of the last million years or so. In the latter case, relatively small changes in the distribution of [insolation](#) (radiant solar energy) over the globe, arising from gradual changes in the orbit of the Earth and the inclination of its axis of rotation—today a tilt of $23\frac{1}{2}^\circ$ —are thought to have served as the pace-maker for the coming and going of the major Ice Ages.

Hidden Diaries of the Ancient Sun

Radiocarbon (^{14}C) is an unstable isotope of carbon that has long been employed in archaeology for establishing the date of production of samples of cellulose or bone or other carbon-bearing matter. It and the beryllium isotope of [atomic weight ten](#) (^{10}Be) are the best known and most abundant of the so-called [cosmogenic nuclides](#) which when naturally sequestered in wood or compacted snow can also serve as indirect, or proxy indicators of past changes in solar activity. The recovery and analysis of both of these— ^{14}C from the wood in annual growth-rings of the oldest-living trees, and ^{10}Be in layered ice drawn from deep polar cores—have confirmed the existence of prolonged episodes of major depression in the overall level of solar activity, such as the Maunder Minimum of 1645-1715. In so doing they have greatly extended the span of retrievable solar history.

Cosmogenic nuclides are created in the rarefied air of the middle atmosphere when energetic [cosmic rays](#) impinge on neutral [atoms](#) of air. Each carbon-14 atom is the product of a direct hit by an incoming [neutron](#)—itself the newly-born product of a preceding cosmic ray collision higher in the atmosphere—on an atom of neutral nitrogen (^{14}N): the most abundant component of air.



Average number of sunspot groups seen each year (in blue) compared with the rates of production of radiocarbon (^{14}C , dashed green) and beryllium-10 (^{10}Be , dashed red) in the Earth's atmosphere for the period since the introduction of the telescope on 1610. These cosmogenic isotopes are produced by incoming cosmic rays whose numbers are modulated by solar activity, and hence serve as indirect proxies of solar activity. Their past concentrations are obtained for carbon through laboratory analyses of dated tree-rings and for beryllium from cores of layered Arctic and Antarctic ice. The data used for carbon-14 measurements come to an end at about 1900, by which time the carbon introduced into the atmosphere by the ever-increasing burning of fossil fuels erases, in effect, the more subtle solar signature in the tree-ring record.

In the process a **proton** is jarred loose from the impacted atom's **nucleus**, leaving behind an unstable isotope of carbon of atomic weight 14: the most abundant cosmogenic nuclide. ^{10}Be , the second most abundant, is produced by a similar process when incoming cosmic ray protons bombard and break apart neutral atoms of either oxygen or nitrogen.

The number of cosmic ray particles that reach our planet to do this work is modulated by changes in both the strength of the Earth's **magnetic field**, and by changes in solar activity, both of which act to deflect cosmic rays that pass through the **heliosphere**.

The strongest of these are changes on times scales of thousands of years in the strength of the Earth's magnetic field. The higher **frequency** (10 to 100 yr) effects of solar changes are imposed on top of these like noise on a sinusoidal wave form. Among these higher frequency effects are the slower but greater amplitude changes like the Maunder Minimum in the overall level of solar activity, persisting for decades to a hundred years or so. Present as well are the even higher frequency effects of the Sun's eleven-year cycle of activity.

More cosmic particles reach us when the Earth's magnetic field is weaker, as it was seven thousand years ago, and fewer as it grows stronger, as it did until about two thousand years ago when it began again to gradually weaken.

More cosmic particles also reach the Earth when the Sun is less active; and fewer when it is more active. Thus the rates of production of ^{14}C and other cosmic nuclides in our atmosphere are strongly *anti*-correlated with solar activity, as confirmed by more than half a century of direct observation of the flux of cosmic rays using [neutron monitors](#) at mountain-top stations.

The Fate of Carbon-14

Soon after they are created, atoms of ^{14}C combine with neighboring atoms of oxygen to form gaseous carbon dioxide, most of which, in time, diffuses downward into the lower atmosphere. When it reaches ground level, some is ingested through pores in the leaves of trees.

There, through [photosynthesis](#), CO_2 separates into its component atoms of carbon and oxygen. The freed carbon, still of weight 14, is then metabolized in the plant, this time combining with hydrogen and oxygen to form cellulose: the carbohydrate that is a fundamental constituent of all plant fiber, including the wood of trees.

And so it is that a carbon atom of weight 14, born of mixed parents high in the sky, is—after years of traveling around the world—at last sequestered in the thin sheath of living cells that form a ring of springtime growth in the stem of a growing tree.



Carbon 14 is inherently unstable in that it radio-actively decays with time into ordinary carbon of weight 12.

After 5730 years—the expected [half-life](#) of the isotope—about 50% of the ^{14}C remains, and after 30,000 years, only 10%. When a third of a million years has gone by, 99% of the original ^{14}C has been converted to ordinary ^{12}C . In coal and oil and natural gas—which were created during the late carboniferous period, about 300 million years ago—all of the radiocarbon then present in the small aquatic plants and animals that gave us these now troublesome fuels is gone.

Thus, like sand in an hourglass, the amount of radiocarbon present in any form of carbon-based life—living or dead—tells us of its age: or more specifically, the

time that has gone by since the instant each atom of radiocarbon was created, high in the sky. To a close approximation this tells as well of the time that has elapsed since the plant-eating animal whose bones we find was last alive and grazing; or when the tree from which the sample of wood was cut, however long ago, was yet in leaf.



The ratio of ^{14}C to ^{12}C in a dated tree-ring also reflects the average *rate of production* of ^{14}C in the atmosphere, which is in turn a measure of the flux of high-energy cosmic rays at the Earth, and from this, the level of solar activity at that time.

Through this chain, precision analyses of $^{14}\text{C}/^{12}\text{C}$ ratios in annual rings of the long-lived bristlecone pine have provided a continuous, proxy record of long-term changes in the level of solar activity through the last 11,000 years—since the end of the last Ice Age—extending the length of the historical, written record of sunspots by a factor of about thirty. An 11-year modulation, though severely attenuated by the amount of time it takes for the newly-created carbon-14 atom to make it into the leaves of trees, can be detected, albeit with difficulty, throughout. A much more obvious feature in the long radiocarbon record are repeated Maunder Minimum-like depressions in the overall level of solar activity, each persisting for thirty to about 100 years.

Beryllium-10 in Ice Cores

An independent verification of these reconstructions of solar history is available through the analysis of another cosmogenic nuclide, beryllium-10 (^{10}Be), sequestered in polar ice and deep-ocean cores. Since the rates of deposition of ^{10}Be and of ^{14}C result from very different processes, we can at first assume that major features common to both of them are due to their rate of creation, and hence traceable to the Sun.

Cosmogenic ^{10}Be is like ^{14}C in that it accumulates in the lower stratosphere for a while before entering the troposphere. But unlike radiocarbon, beryllium-10 finds its way down to the Earth's surface more directly and expeditiously, through either precipitation or dry deposition, and is not biogeochemically recycled en route as carbon-14 often is. Although we never see or feel it, ^{10}Be is deposited on our roofs and yards and the tops of our cars, wherever we are, each time it rains or snows.



Thus, had he but known, Robert Louis Stevenson in *A Child's Garden of Verses* could instead have written

*The rain is raining all around,
It falls on field and tree.
Big drops of H₂SO₄
And chunks of ¹⁰Be.*

The beryllium that reaches the surface in polar regions is entrapped in annual layers of fallen snow that are in time compressed and preserved as annual layers of hardened ice, initially separated by lines of superficial thawing and refreezing. Since ¹⁰Be is rapidly washed out of the air by precipitation, its abundance in the atmosphere varies considerably in both space and time. Because of this, the amount sequestered in any ice core layer reflects not only the solar-driven production rate of the cosmogenic nuclide but also atmospheric circulation patterns and precipitation rates that brought it to that individual spot on the ground in the snows of yesteryear.

Because of this and unlike ¹⁴C—which in the form of CO₂ is uniformly mixed throughout the global atmosphere—the amount of ¹⁰Be that accumulates on the surface of the Earth varies considerably from place to place: very much a function of the amount of rain or snow that has fallen there, and hence of local and regional weather. Variations found in layers of snow and ice at any site can be corrected for local precipitation effects, but corrections for non-local meteorological variations in the delivery of ¹⁰Be to the ice caps is far more difficult.

Nevertheless, sequestered in a much older repository, and with a half-life of 1.5 million years (compared to 5730 years for ¹⁴C) ¹⁰Be in ice offers the potential of extending the reach of recorded solar history in the deepest, Greenland ice cores more than 200,000 years into the past, and potentially, in the deepest Antarctic cores, to as much as 400,000 years, through a number of glacial-interglacial cycles: in all, a span of time that today is the best documented and most studied period of the past climate of the Earth.

Since the ¹⁰Be record is capable of finer temporal [resolution](#) than ¹⁴C, what may be more valuable is the prospect of high resolution year-by-year information on changes in solar activity through the last several thousand years, derived from analyses of ice nearer the surface, where annual layering is more clearly preserved.

As one drills deeper and deeper into the ice, what were once clearly-defined annual layers of compressed snow and [firn](#)—separated by annual lines of partial

thawing and refreezing—gradually lose these valued earmarks: their identities squeezed out of them by the accumulating load of glacial snow and ice that lay above, in some places more than a mile deep.

Still, what these ice-core or tree-ring proxies tell us of the ancient Sun is not a direct account of past changes in solar *irradiation*—which climatologists would most like to know—but of changes in solar *magnetic activity*, which is one step removed.

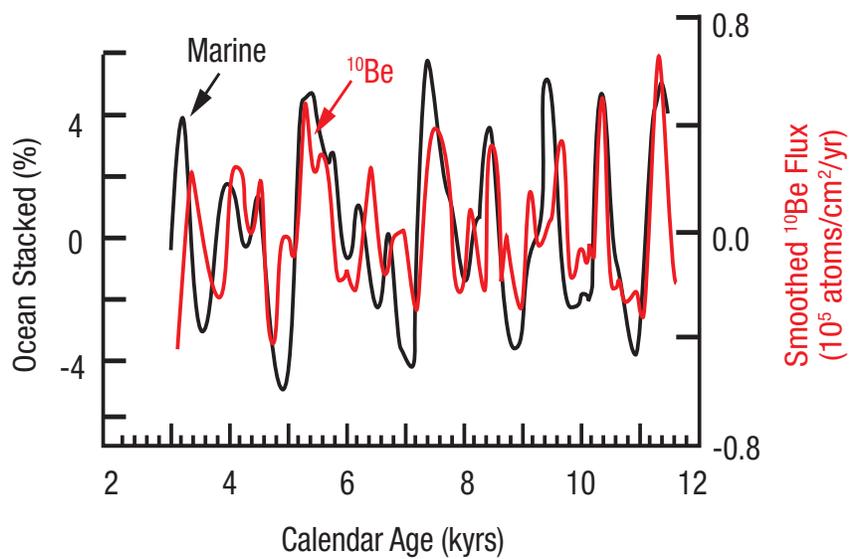
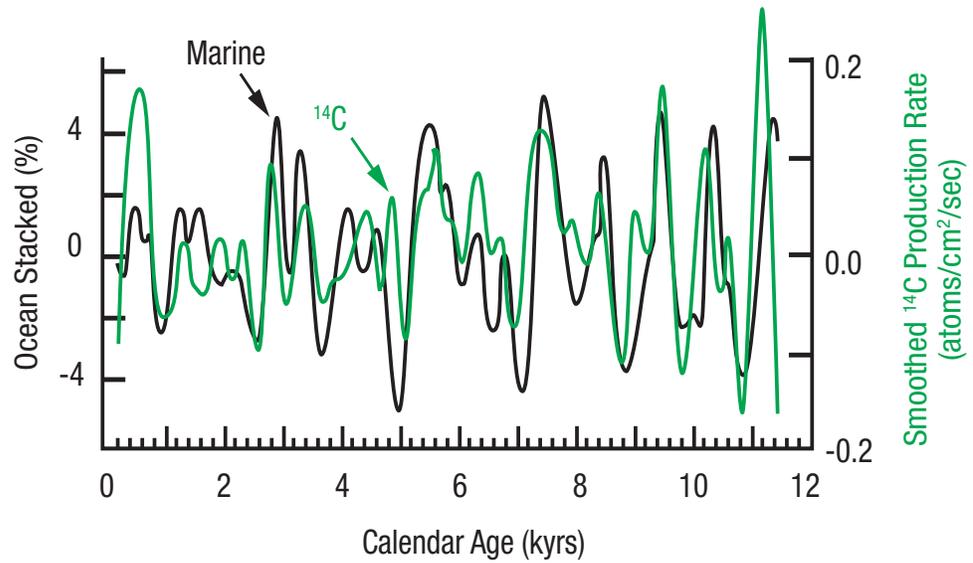
Marks of the Sun on North Atlantic Climate During the Last 11,000 Years

An extensive paleo-oceanographic study—based on the recovery of data that tell of climatic changes during the present post-glacial or **Holocene epoch**—has yielded what may be the most compelling evidence for a connection between longer-term changes in climate and the changing moods of the Sun. Found was not one but an unbroken series of responses of regional climate to episodes of suppressed solar activity like the Maunder Minimum, each lasting from 50 to 150 years.

The paleoclimatic data, which cover the full 11,000 year span of the present interglacial epoch, were derived from records of the concentration of identifiable mineral tracers in layered sediments on the sea floor of the northern North Atlantic Ocean. The timing and duration of periods of suppressed solar activity came from a different source: from analyses of the ratio of ^{14}C to ^{12}C in dated growth rings of the long-lived bristlecone pine that cover the same period of time, and from concurrent measurements of ^{10}Be in polar ice cores.

The minerals used as ocean tracers come from the soil in high latitude regions, which, through erosion, is carried out to sea in drift ice. When southerly-drifting ice reaches waters warm enough to melt it, the tracers are released and sink to the bottom of the ocean. There they are gradually covered over with other sedimentary material, that in time build up a layered history of what fell to the bottom of the ocean at that place, and when.

Sea-cores drilled from ships at sea into the mud of the ocean bottom can sample this imbedded information. Each core is in effect a time capsule that holds a continuous record of the material that has sunk to the sea-floor at that location. Analyzing many cores in this way—taken from different locations in the North Atlantic Ocean—allows the investigator to draw a meaningful map of the southern limit of drifting sea ice at any time in the past.



Comparison of proxy records of solar activity from tree-rings (upper figure, in green, for carbon-14) and ice cores (lower, in red, for beryllium-10) with temperature in the North Atlantic ocean (black curve, upper and lower, from deep-sea cores) for about the last 11,000 yrs (the Holocene epoch). Evident is a remarkable agreement between long-term excursions in climate, lasting hundreds of years, and contemporaneous conditions on the Sun. Periods of suppressed solar activity (peaks in the red and green curves) like the Maunder Minimum correspond to times of cooler ocean temperatures, with higher temperatures during long periods of greater solar activity which is of the same nature as the suggested connection in more modern times between the Maunder Minimum in solar activity (1645-1715) and the coldest temperatures of the concurrent but longer-lasting Little Ice Age.

In years when the climate is systematically colder in the region, waters sufficiently warm to melt floating ice are not encountered until the floe has drifted far to the south. In warmer periods, the opposite is true, and the southern limit of drift ice shifts back toward polar waters.

The study revealed that the sub-polar North Atlantic Ocean has experienced nine distinctive expansions of cooler water in the past 11,000 years, occurring aperiodically but roughly every 1000 to 2000 years, with a mean spacing of about 1350 years.

Each of these regional cooling events coincides in time with strong, distinctive minima in solar activity, derived from records of the production of ^{14}C from tree-ring records and of ^{10}Be from deep-sea cores covering the same period of time.

This remarkable North Atlantic finding—the patient and painstaking work of a diverse group led by the late Gerard Bond—suggests that solar variability has been a major climate driver throughout the present Holocene epoch.

But to produce so strong and consistent a response, the solar driving force—whatever its origin—would need some assistance, if what we know of the bounds of solar variations still applies to these longer time scales. One of these might be an amplification of the impacts of slowly-varying changes in solar irradiation through their impact on the oceans' [thermohaline circulation](#).

