Changing Sun, Changing Climate?

Since it is the Sun's energy that drives the weather system, scientists naturally wondered whether they might connect climate changes with solar variations. Yet the Sun seemed to be stable over the timescale of human civilization. Attempts to discover cyclic variations in weather and connect them with the 11-year sunspot cycle, or other possible solar cycles ranging up to a few centuries long, gave results that were ambiguous at best. These attempts got a well-deserved bad reputation. Jack Eddy overcame this with a 1976 study that demonstrated that irregular variations in solar surface activity, a few centuries long, were connected with major climate shifts. The mechanism was uncertain, but plausible candidates emerged. The next crucial question was whether a rise in the Sun's activity could explain the global warming seen in the 20th century? By the 1990s, there was a tentative answer: minor solar variations could indeed have been partly responsible for some past fluctuations... but since the 1960s, warming from the rise in greenhouse gases far outweighed any solar effects.[1]

The Sun so greatly dominates the skies that the first scientific speculations about different climates asked only how sunlight falls on the Earth in different places. The very word climate (from Greek *klimat*, inclination or latitude) originally stood for a simple band of latitude. When scientists began to ponder the possibility of climate change, their thoughts naturally turned to the Sun. Early modern scientists found it plausible that the Sun could not burn forever, and speculated about a slow deterioration of the Earth's climate as the fuel ran out. In 1801 the great astronomer William Herschel introduced the idea of more transient climate connections. It was a well-known fact that some stars varied in brightness. Since our Sun is itself a star, it was natural to ask whether the Sun's brightness might vary, bringing cooler or warmer periods on Earth? As evidence of a connection between Sun and weather Herschel pointed to periods in the 17th century, ranging from two decades to a few years, when hardly any sunspots had been observed. During those periods, he remarked, the price of wheat had been high, presumably reflecting spells of drought.[2]

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[1] This essay is partly based, by permission, on an essay by Theodore S. Feldman, "Solar Variability and Climate Change," rewritten and expanded by Spencer Weart. For additional material, see Feldman's site at http://www.agu.org/history/SV.shtml.

[2] Feldman (1993); Fleming (1990); Herschel (1801), pp. 313-16; on Sun-weather relations see Hufbauer (1991) and Hoyt and Schatten (1997).

Chasing Sunspot Cycles

Speculation increased in the mid-19th century following the discovery that the number of spots seen on the Sun rose and fell in a regular 11-year cycle. It appeared that the sunspots reflected some kind of storminess on the Sun's surface—violent activity that strongly affected the Earth's magnetic field. Astronomers also found that some stars, which otherwise seemed quite similar to the Sun, went through very large variations. By the end of the century a small community of scientists was pursuing the question of how solar variability might relate to short-term weather cycles, as well as long-term climate changes.[1] Attempts to correlate weather patterns with the sunspot cycle were stymied, however, by inaccurate and unstandardized weather data, and by a lack of good statistical techniques for analyzing the data. Besides, it was hard to say just which of many aspects of weather were worth looking into.

At the end of the 19th century, most meteorologists held firmly that climate was stable overall, about the same from one century to the next. That still left room for modest cycles within the overall stability. A number of scientists looked through various data hoping to find correlations, and announced success. Enthusiasts for statistics kept coming up with one or another plausible cycle of dry summers or cold winters or whatever, in one or another region, repeating periodically over intervals ranging from 11 years to several centuries. Many of these people declined to speculate about the causes of the cycles they reported, but others pointed to the Sun. An example was a late 19th-century British school of "cosmical meteorology," whose leader Balfour Stewart grandly exclaimed of the Sun and planets, "They feel, they throb together."[2]

Confusion persisted in the early decades of the 20th century as researchers continued to gather evidence for solar variation and climate cycles. For example, Ellsworth Huntington, drawing on work by a number of others, concluded that high sunspot numbers meant storminess and rain in some parts of the world, resulting in a cooler planet. The "present variations of climate are connected with solar changes much more closely than has hitherto been supposed," he maintained. He went on to speculate that if solar disturbances had been magnified in the past, that might explain the ice ages.[3]

Meanwhile an Arizona astronomer, Andrew Ellicott Douglass, announced a variety of remarkable correlations between the sunspot cycle and rings in trees. Douglass tracked this into past centuries by studying beams from old buildings as well as Sequoias and other long-lived trees. Noting that tree rings were thinner in dry years, he reported climate effects from solar

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[1] Notably, for variations related to the evolution of the Sun and stars, Dubois (1895); for sunspot cycles Czerney (1881).

[2] See for example, Brückner (1890b), chapter 1; translated in Stehr and von Storch (2000), pp. 116-121; Stewart: Gooday (1994).

[3] Huntington (1914), quote p. 480; Huntington (1923); summarized in Huntington and Visher (1922).

variations, particularly in connection with the 17th-century dearth of sunspots that Herschel and others had noticed. Other scientists, however, found good reason to doubt that tree rings could reveal anything beyond random regional variations. The value of tree rings for climate study was not solidly established until the 1960s.[1]

Through the 1930s the most persistent advocate of a solar-climate connection was Charles Greeley Abbot of the Smithsonian Astrophysical Observatory. His predecessor, Samuel Pierpont Langley, had established a program of measuring the intensity of the Sun's radiation received at the Earth, called the "solar constant." Abbot pursued the program for decades. By the early 1920s, he had concluded that the solar "constant" was misnamed: his observations showed large variations over periods of days, which he connected with sunspots passing across the face of the Sun. According to his calculations, over a period of years when the Sun was more active it was brighter by nearly one percent. Surely this influenced climate! As early as 1913, Abbot announced that he could see a plain correlation between the sunspot cycle and cycles of temperature on Earth. (This only worked, however, if he took into account temporary cooling spells caused by the dust from volcanic eruptions.) Self-confident and combative, Abbot defended his findings against all objections, meanwhile telling the public that solar studies would bring wonderful improvements in weather prediction.[2] He and a few others at the Smithsonian pursued the topic single-mindedly into the 1960s, convinced that sunspot variations were a main cause of climate change.[3]

Other scientists were quietly skeptical. Abbot's solar constant variations were at the edge of detectability if not beyond. About all he seemed to have shown for certain was that the solar constant did not vary by more than one percent, and it remained an open question whether it varied anywhere near that level. Perhaps Abbot was detecting variations not in the solar constant, but in the transmission of radiation through the atmosphere.[4] Still, if that varied with the sunspot cycle, it might by itself somehow change the weather.

Despite widespread skepticism, the study of cycles was popular in the 1920s and 1930s. By now there were a lot of weather data to play with, and inevitably people found correlations between sunspot cycles and selected weather patterns. Respected scientists and over-enthusiastic amateurs announced correlations that they insisted were reliable enough to make predictions.

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[1] Douglass (1936) ; Webb (2002), chapter 3; Webb (1986). Fritts (1962) pioneered accurate use of tree rings; Fritts (1976) notes the skepticism (page v) and shows how it was overcome. Climate periods of 11-12 years as well as longer cycles also appeared in annual layers of clay laid down in lake beds (varves), Bradley (1929); for references and summary, see Brooks (1950a).

[2] Abbot and Fowle (1913); similarly A. Ångström, using Abbot's data, said the solar constant varied with sunspot number, although decades later he retracted. Ångström (1922); Ångström (1970); historical studies are Hufbauer (1991), p. 86; DeVorkin (1990).

[3] Abbot (1967); Aldrich and Hoover (1954).

[4] Fröhlich (1977).

Sooner or later, every prediction failed. An example was a highly credible forecast that there would be a dry spell in Africa during the sunspot minimum of the early 1930s. When that came out wrong, a meteorologist later recalled, "the subject of sunspots and weather relationships fell into disrepute, especially among British meteorologists who witnessed the discomfiture of some of their most respected superiors." Even in the 1960s, he said, "For a young [climate] researcher to entertain any statement of sun-weather relationships was to brand oneself a crank."[1] Specialists in solar physics felt much the same. As one of them recalled, "purported connections with... weather and climate were uniformly wacky and to be distrusted... there is a hypnotism about cycles that... draws all kinds of creatures out of the woodwork."[2] (This was a robust tradition: into the 21st century, enthusiasts with weird or incomprehensible theories of solar influences, backed up by selected weather data and intricate graphs, continued to show up at scientific meetings of meteorological societies.) By the 1940s, most meteorologists and astronomers had abandoned the quest for solar cycles in the weather. Yet some respected experts continued to suspect that a connection did exist, lurking somewhere in the data.[3]

Less prone to crank enthusiasm and scientific scorn, if equally speculative, was the possibility that the Sun could affect climate on much longer time-scales. During the 1920s, a few people developed simple models that suggested that even a modest change in solar radiation might set off an ice age, by initiating self-sustaining changes in the polar ice. A leading British meteorologist, Sir George Simpson, believed the sequence of ice ages showed that the Sun is a variable star, changing its brightness over a cycle some 100,000 years long.[4] "There has always been a reluctance among scientists to call upon changes in solar radiation... to account for climatic changes," Simpson told the Royal Meteorological Society in a Presidential address of 1939. "The Sun is so mighty and the radiation emitted so immense that relatively short period changes... have been almost unthinkable." But none of the terrestrial causes proposed for ice ages was at all convincing, he said, and that "forced a reconsideration of extra-terrestrial causes."[5]

Such thinking was still in circulation in the 1950s. The eminent astrophysicist Ernst Öpik wrote that none of the many explanations proposed for ice ages was convincing, so "we always come back to the simplest and most plausible hypothesis: that our solar furnace varies in its output of heat." Öpik worked up a theory for cyclical changes of the nuclear reactions deep inside the Sun. The internal fluctuations he hypothesized had a hundred-million-year timescale that seemed to

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[1] Lamb (1997), pp. 192-93.

[2] J. Eddy, interview by Weart, April 1999, AIP, online at https://www.aip.org/history-programs/niels-bohr-library/oral-histories/22910, p. 6.

[3] Nebeker (1995), p. 95.

[4] Simpson (1934); Simpson (1939-40). Simpson cited A. Penck, who argued that the entire world had cooled and only solar changes could explain this.

[5] Simpson (1939-40), p. 210. Solar models were also put into doubt by the "faint early Sun paradox" (or "faint early Sun...") Astrophysicists calculated that in its youth Earth should not have received enough sunlight to prevent it from freezing over. See the essay on "Venus and Mars." Zirin et al. (1976), p. 379, also p. 381 (neutrinos).

match the major glacial epochs. Meanwhile, within a given glacial epoch "a kind of 'flickering' of solar radiation" in the Sun's outer shell would drive the expansion and retreat of ice sheets.[1] When reviews and textbooks listed various possible explanations of ice ages and other long-term climate changes, ranging from volcanic dust to shifts of ocean currents, they often invoked long-term solar variation as a particularly likely cause. As a U.S. Weather Bureau expert put it, "the problem of predicting the future climate of Planet Earth would seem to depend on predicting the future energy output of the sun..."[2]

Searching for a Mechanism (1950s - Early 1970s)

Some people continued to pursue the exasperating hints that minor variations in the sunspot cycle influenced present-day weather. Interest in the topic was revived in 1949 by H.C. Willett, who dug out apparent relationships between changes in the numbers of sunspots and long-term variations of wind patterns. Sunspot variations, he declared, were "the only possible single factor of climatic control which might be made to account for all of these variations." Others thought they detected sunspot cycle correlations in the advance and retreat of mountain glaciers. Willett admitted that "the physical basis of any such relationship must be utterly complex, and is as yet not at all understood." But he pointed out an interesting possibility. Perhaps climate changes could be due to "solar variation in the ultraviolet of the sort which appears to accompany sunspot activity." As another scientist had pointed out a few years before, ultraviolet radiation from the explosive flares that accompany sunspots would heat the ozone layer high in the Earth's atmosphere, and that might somehow influence the circulation of the lower atmosphere.[3]

In the 1950s and 1960s, instruments on rockets that climbed above the atmosphere managed to measure the Sun's ultraviolet radiation for the first time. They found that the radiation did intensify during high sunspot years. However, ultraviolet light does not penetrate below the stratosphere. Meteorologists found it most unlikely that changes in the thin stratosphere could affect the layers below, which contain far more mass and energy. Still, the hypothesis of atmospheric influence remained alive, if far from healthy.

A few scientists speculated more broadly. Maybe weather patterns were affected by the electrically charged particles that the Sun sprayed out as "solar wind." More sunspots throw out more particles, and they might do something to the atmosphere. More indirectly, at times of high sunspot activity the solar wind pushes out a magnetic field that tends to shield the Earth from the cosmic rays that rain down from the universe beyond. When these rays penetrate the upper reaches of the atmosphere, they expend their energy producing sprays of charged particles.

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[1] Öpik (1958); "flickering" (due to uncertain convective changes): Öpik (1965), p. 289.

[2] E.g., Brooks (1949), ch. 1; Shapley (1953); Wexler (1956), quote p. 494, adding that turbidity (from volcanoes) was equally important.

[3] Willett (1949), pp. 34, 41, 50; see Lamb (1997), p. 193; the earlier hypothesis (not cited by Willett) came from Haurwitz (1946) (admitting it was "vague"), whose work inspired Wexler (1956), p. 485 (citing glacier papers); subsequently Wexler (1960) dismissed the idea.

Therefore, more sunspots would mean fewer of these particles. Either way there might be an influence on the weather. Meteorologists gave these ideas some credence.[1] But the solar wind and ultraviolet carried only a tiny fraction of the Sun's total energy output. If they did influence weather, it had to be through a subtle triggering mechanism that remained altogether mysterious. Anyway variations connected with sunspots seemed likely to bear only on temporary weather anomalies lasting a week or so (the timescale of variations in sunspot groups themselves), not on long-term climate change.[2]

People continued to report weather features that varied with the sunspot cycle of 11 years, or with the full solar magnetic cycle of 22 years (the magnetic polarity of sunspots reverses from one 11-year cycle to the next). There were also matches to possible longer solar variation cycles.[3] It was especially scientists in the Soviet Union who pursued such correlations. In the lead was a team under the Leningrad meteorologist Kirill Ya. Kondratyev, who sent balloons into the stratosphere to measure the solar constant. In 1970 his group claimed that the Sun's output varied along with the number of sunspots by as much as 2%. This drew cautious notice from other scientists. But the authors admitted that the conclusion would remain in doubt unless it could be verified by spacecraft entirely above the atmosphere.[4]

Another tentatively credible study came from a team led by the Danish glaciologist Willi Dansgaard. Inspecting layers of ancient ice in cores drilled from deep in the Greenland ice cap, they found cyclical variations. They supposed the Sun was responsible. For the cycle that they detected, about 80 years long, had already been reported by scientists who had analyzed small variations in the sunspot cycle.[5] Another cycle with a length of about 180 years was also, the group suspected, caused by "changing conditions on the Sun." The oscillations were so regular that in 1970 Dansgaard's group boldly extrapolated the curves into the future. They began by matching their results with a global cooling trend that, as others reported, had been underway since around 1940. The group predicted the cooling would continue through the next one or two decades, followed by a warming trend for the following three decades or so.[6]

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[1] A possible connection between cosmic rays and clouds was already established at the end of the 19th century by the inventor of the cloud chamber, Wilson (1899); it was admittedly "speculation" that ionization in the upper troposphere affected storminess. Ney (1959); the ideas found some favor with, e.g., Roberts (1967), pp. 33-34.

[2] Sellers (1965), pp. 220-23.

[3] Lamb (1977), pp. 700-704.

[4] Kondratyev and Nikolsky (1970); Fröhlich (1977).

[5] Johnsen et al. (1970); similarly, Dansgaard et al. (1971), same quote p. 44; the period they reported was precisely 78 years, and Schove (1955) had reported a 78-year variation between long and short sunspot cycles as well as a possible 200-year period; in addition, not noted by the glaciologists, a roughly 80-year modulation in the amplitude of the sunspot cycle was reported by Gleissberg (1966); weather correlations with the 80-year cycle were reported in 1962 by B.L. Dzerdzeevski as cited by Lamb (1977), p. 702.

[6] Johnsen et al. (1970); see also Dansgaard et al. (1971); Dansgaard et al. (1973).

The geochemist Wallace Broecker was impressed. He "made a large leap of faith" (as he later put it) and assumed that the cycles were not just found in Greenland, but had a global reach.[1] He calculated that the global cooling trend since around 1940 could be explained by the way the two cycles both happened to be trending down. His combined curve would bottom out in the 1970s, then quickly head up. Greenhouse effect warming caused by human emissions of carbon dioxide gas (CO_2) would come on top of this rise, making for a dangerously abrupt warming.

(Later studies failed to find Dansgaard's cycles globally. If they existed at all, the cause did not seem to be the Sun, but quasi-cyclical shifts in the North Atlantic Ocean's surface warmth and winds. This was just another case of supposed global weather cycles that faded away as more data came in. It was also one of several cases where Broecker's scientific instincts were sounder than his evidence. Whatever caused the downturn in temperature since the 1940s, probably a combination of factors including a surge of industrial pollution, it would eventually be overcome by the steadily increasing greenhouse gases. Indeed warming did resume in the 1970s.)[2]

By now it was clear that if you applied powerful statistical techniques to enough tree ring samples, you would sometimes turn up the 11-year solar cycle. Solar activity definitely had some kind of effect on climate in some places—but nothing obviously strong or consistent. For example, the 1970s saw controversial claims that weather data and tree rings from various parts of the American West revealed a 22-year cycle of droughts, presumably driven by the solar magnetic cycle. Coming at a time of severe droughts in the West and elsewhere, these claims caught some public attention.[3] Scientists were beginning to understand, however, that the planet's climate system could go through purely self-sustaining oscillations, driven by feedbacks between ocean temperatures and wind patterns. The patterns cycled quasi-regularly by themselves on time scales ranging from a few years (like the important El Niño – Southern Oscillation in the Pacific Ocean) to several decades. That might help to explain at least some of the quasi-regular cycles that had been tentatively associated with sunspots.

All this helped to guarantee that scientists would continue to scrutinize any way that solar activity might influence climate, but always with a skeptical eye. If meteorologists had misgivings, most astronomers dismissed outright any thought of important solar variations on a timescale of hundreds or thousands of years. Surface features like sunspots might cycle over decades, but that was a weak, superficial, and short-term effect. As for the main energy flow, improved theories of the nuclear furnace deep within the Sun showed stability over many

[1] Broecker (1999).

[2] Broecker (1975). Broecker discussed his prediction ("the product of dumb luck") in Broecker (2017).

[3] Roberts and Olson (1975) (admitting that "A mere coincidence in timing... will not, of course, constitute proof of a physical relationship"); Mock and W.D. Hibler (1976) (a "pervasive" but only "quasi-periodic" 20-year cycle); Mitchell et al. (1979) (tree-ring data analysis "strongly supports earlier evidence of a 22 yr drought rhythm... in the U.S.... in some manner controlled by long-term solar variability...").

millions of years. Alongside this sound scientific reasoning there may have been a less rational component. “We had adopted a kind of solar uniformitarianism,” solar physicist John (Jack) Eddy suggested in retrospect. “As people and as scientists we have always wanted the Sun to be better than other stars and better than it really is.”[1]

Carbon-14 and Jack Eddy

Evidence was accumulating that the Sun truly does change at least superficially from one century to another. Already in 1961 Minze Stuiver had moved in the right direction. Stuiver was concerned about peculiar variations in the amount of radioactive carbon-14 found in ancient tree rings. Carbon-14 is generated when cosmic rays from the far reaches of the universe strike the atmosphere. Stuiver noted how changes in the magnetic field of the Sun would change the flux of cosmic rays reaching the Earth.[2] He had followed this up in collaboration with the carbon-14 expert Hans Suess, confirming that the concentration of the isotope had varied over past millennia. They were not suggesting that changes in carbon-14 (or cosmic rays) altered climate; rather, they were showing that the isotope could be used to measure solar activity in the distant past. *For the development of this important technique, a good example of laboratory work and its attendant controversies, see the supplementary essay on Uses of Radiocarbon Dating.*

In 1965 Suess tried correlating the new data with weather records, in the hope that carbon-14 variations “may supply conclusive evidence regarding the causes for the great ice ages.” He focused on the bitter cold spell that historians had discovered in European writings about weather from the 15th through the 18th century (the “Little Ice Age”). That had been a time of relatively high carbon-14, which pointed to low solar activity. Casting a sharp eye on historical sunspot data, Suess noticed that the same centuries indeed showed a low count of sunspots. In short, fewer sunspots apparently made for colder winters. A few others found the connection plausible, but to most scientists the speculation sounded like just one more of the countless correlations that people had announced over the past century on thin evidence.[3]

Meanwhile carbon-14 experts refined their understanding of how the concentration of the isotope had varied over past millennia. They could not decide on a cause for the shorter-term irregularities. Solar fluctuations were only one of half a dozen plausible possibilities.[4] The early 1970s also brought claims that far slower variations in the Earth’s magnetic field correlated with

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[1] Eddy (1977a), p. 92.

[2] Stuiver (1961).

[3] Suess (1968), p. 146; in the best review of sunspot history available to Suess at this time, D.J. Schove took no notice of any anomaly such as the early-modern minimum, although it is visible in his data. Schove (1955); a tentative longer-term correlation of climate (glacier advances) with C-14 was shown by Denton and Karlén (1973), who suggest that “climatic fluctuations, because of their close correlation with short-term C14 variations, were caused by varying solar activity,” p. 202; for the Little Ice Age, see Fagan (2000); Lamb (1995), ch. 12.

[4] Ralph and Michael (1974).

climate. In cores of clay drawn from the seabed reaching back a million years, colder temperatures had prevailed during eras of high magnetism. The magnetic variations were presumably caused by processes in the Earth's interior rather than on the Sun, but the correlation suggested that cosmic rays really did influence climate. As usual the evidence was sketchy, however, and it failed to convince most scientists.[1]

In 1975 the respected meteorologist Robert Dickinson, of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, took on the task of reviewing the American Meteorological Society's official statement about solar influences on weather. He concluded that such influences were unlikely, for there was no reasonable mechanism in sight—except, maybe, one. Perhaps the electric charges that cosmic rays generated in the atmosphere somehow affected how dust and other aerosol particles coalesced. Perhaps that somehow affected cloudiness, since cloud droplets condensed on the nuclei formed by aerosol particles. This was just piling speculation on speculation, Dickinson hastened to point out. Scientists knew little about such processes, and would need to do much more research "to be able to verify or (as seems more likely) to disprove these ideas." For all his frank skepticism, Dickinson had left the door open a crack. One way or another, it was now at least physically conceivable that changes in sunspots could have something to do with changes in climate. Most experts, however, continued to believe the idea was not only unproven but preposterous. Interest might be piqued when someone reported a new correlation between solar changes and weather, but nobody was surprised when further data and analysis knocked it down.[2]

In 1976, Eddy tied all the threads together in a paper that soon became famous. He was one of several solar experts in Boulder, where a vigorous community of astrophysicists, meteorologists, and other Earth scientists had grown up around the University of Colorado and NCAR. Yet Eddy was ignorant of the carbon-14 research—an example of the poor communication between fields that always impeded climate studies. He had won scant success in the usual sort of solar physics research, and in 1973 he lost his job as a researcher, finding only temporary work writing a history of NASA's Skylab. In his spare time he pored over old books. Eddy had decided to review historical naked-eye sunspot records, with the aim of definitively confirming the long-standing belief that the sunspot cycle was stable over the centuries.

Instead, Eddy found evidence that the Sun was by no means as constant as astrophysicists supposed. Especially intriguing was evidence suggesting that during the "Little Ice Age" of the 16th-17th centuries, sky-watchers had observed almost no sunspot activity. People clear back to

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[1] Wollin et al. (1971); Gribbin (1982), ch. 7.

[2] Dickinson (1975); a similar speculation, connecting cosmic rays with storminess, was offered by Tinsley et al. (1989). Tinsley's work was stimulated by a correlation reported by Wilcox et al. (1973), which attracted some attention but grew weaker as the next decade of data accumulated. Another weather-Sun correlation was laid out in Herman and Goldberg (1978), which met strong resistance including attempts to suppress publication, according to Herman (2003), ch. 18.

Herschel had noticed this prolonged dearth of sunspots. A 19th-century German astronomer, G.W. Spörer, had been the first to document it, and a little later, in 1890, the British astronomer E. Walter Maunder drew attention to the discovery and its significance for climate. Other scientists, however, thought this was just another case of dubious numbers at the edge of detectability. Maunder's publications sank into obscurity. It was only by chance that while Eddy was working to prove the Sun was entirely stable, another solar specialist told him about Maunder's work.[1]

"As a solar astronomer I felt certain that it could never have happened," Eddy later recalled. But hard historical work gradually persuaded him that the early modern solar observers were reliable —the absence of sunspot evidence really was evidence of an absence. Digging deeper, he found the inconstancy confirmed by historical sightings of auroras and of the solar corona at eclipses (both of which reflected activity on the Sun's surface). Once his attention was drawn to the carbon-14 record, he saw that it too matched the pattern. All the evidence pointed to long-sustained minimums and at least one maximum of solar activity in the past two thousand years. It was "one more defeat in our long and losing battle to keep the Sun perfect, or, if not perfect, constant, and if inconstant, regular. Why we think the Sun should be any of these when other stars are not," he continued, "is more a question for social than for physical science."[2]

As it happened, the ground had already been prepared by developments in astrophysics in the early 1970s. Physicists had built a colossal particle detector expressly to observe the elusive neutrinos emitted by the nuclear reactions that fueled the Sun. The experiment failed to find anywhere near the flux of neutrinos that theorists insisted should be reaching the Earth. Was it possible that deep within the Sun, production of energy was going through a lull? Perhaps the output of stars like the Sun really could wander up and down, maybe even enough to cause ice ages? The anomaly was eventually traced to neutrino physics, not solar physics. Meanwhile, however, it called into doubt the theoretical reasoning that said the Sun could not be a variable star.[3]

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[1] Maunder (1890) attributes the discovery to Spörer; some authors now refer to a 17th-century Maunder Minimum and a 15th-century Spörer Minimum. Eddy chose "Maunder" to make a phrase that would be memorable: Eddy, interview by Weart, op. cit., p. 11. For history and references, see Eddy (1976); examples of neglect of Maunder: he was cited, but only for other work, in Abetti (1957); Kuiper (1953); Menzel (1949); the 17th-century paucity of sunspots was noted without any reference by Willett (1949), p. 35. On Eddy and sunspot cycles in general see Henderson (2018).

[2] The first published statement was an abstract for the March 1975 meeting of the American Astronomical Society Eddy (1975a); and next at a Solar Output Workshop in Boulder, Colo., Eddy (1975b); the famous publication was Eddy (1976), "defeat" p. 1200; "felt certain," Eddy (1977a), pp. 80-81. See Eddy, interview by Weart, op. cit.

[3] Hufbauer (1991), pp. 269-78.

Eddy's announcement of a solar-climate connection nevertheless met the customary skepticism. He pushed his arguments vigorously, stressing especially the Little Ice Age, which he memorably dubbed the "Maunder Minimum" of sunspots. The name he chose emphasized that he was not alone with his evidence. It is not unusual for a scientist to make a "discovery" that others had already announced fruitlessly. A scientific result cannot flourish in isolation, but needs support from other evidence and ideas. Eddy had gone some distance beyond his predecessors in historical investigation. More important, he could connect the sunspot observations with the carbon-14 record and the new doubts about solar stability. It also mattered that he worked steadily and persuasively to convince other scientists that the thing was true.

Pushing farther, Eddy drew attention to a spell of low carbon-14, and thus high solar activity, during the 11th-12th centuries. Remarks in medieval manuscripts showed that these centuries had been unusually warm in Europe. It was far from proven that those were times of higher temperatures all around the globe. However, scientists were (as usual) particularly impressed by evidence from the North Atlantic region where most of them lived and where the historical record was best known. Especially notable was the mild weather that had encouraged medieval Vikings to establish colonies in Greenland—colonies that had endured for centuries, only to be abandoned in the Little Ice Age. Eddy warned that in our own times, "when we have observed the Sun most intensively, its behavior may have been unusually regular and benign."[1]

(Decades later, after painstaking studies developed much fuller series of data covering the entire globe, these data showed a complex variety of periods of warmth and periods of cold. The so-called "Medieval Warm Period" when Iceland and Greenland were settled was a group of regional variations, significant but not as universal and extreme as the steep temperature rise felt around the world since the 1980s. The "Little Ice Age" was much clearer, but it was more a collection of regional cooling spells at different times than a coherent global phenomenon, not everywhere as obvious as around the North Atlantic. As one pair of experts remarked in 2004, "If the development of paleoclimatology had taken place in the tropical Pacific, Africa,... or Latin America, the paleoclimatic community would almost certainly have adopted other terminology." Instead of a Little Ice Age and Medieval Warm Period, scientists of the 1970s might have talked, for example, about great periods of drought. Still, Eddy's central point would stand: regional climates were more susceptible to perturbing influences, including small changes on the Sun, than most scientists had imagined.).[2]

Eddy worked hard to "sell" his findings. At a 1975 workshop where he first presented his full argument, his colleagues tentatively accepted that solar variability might be responsible for

[1] "Benign," Eddy (1977c), p. 69.

[2] It is uncertain why the Viking colonies collapsed, but climate change probably contributed—not cold but drought, according to Howley (2022). Jones and Mann (2004), p. 20, see p. 7 and passim; Neukom et al. (2019); PAGES 2k Consortium (2019). See also note on the "hockey stick" graph in the essay on the modern temperature trend.

climate changes over periods of a few hundreds or thousands of years.[1] Eddy pressed on to turn up more evidence connecting temperature variations with carbon-14, which he took to measure solar activity. “In every case when long-term solar activity falls,” he claimed, “mid-latitude glaciers advance and climate cools.”[2]

Already while Eddy’s sunspot figures were in press, other scientists began to explore how far his idea might account for climate changes. Adding solar variability to the sporadic cooling caused by dust from volcanic eruptions did seem to roughly track temperature trends over the entire last millennium.[3] Peering closer at the more accurate global temperatures measured since the late 19th century, a group of computer modelers got a decent match using only the record of volcanic eruptions plus greenhouse warming from increasing carbon dioxide—but they improved the match noticeably when they added in a record of solar variations. All this proved nothing, but gave more reason to devote effort to the question.[4]

Meanwhile Stuiver and others confirmed the connection between solar activity and carbon-14, and this became a standard tool in later solar-climate studies.[5] An example was a study that reported a match between carbon-14 variations and a whole set of “little ice ages” (indicated by advances of glaciers) that had come at random over the last ten thousand years.[6] Other studies, however, failed to find such correlations. As a 1985 reviewer commented, “this is a controversial topic... the evidence relating solar activity and carbon-14 variations to surface temperatures is equivocal, an intriguing but unproven possibility.”[7]

Scientists continued to report new phenomena at the border of detectability. In particular, Ronald Gilliland (another NCAR scientist) followed Eddy’s example in analyzing a variety of old records and tentatively announced slight periodic variations in the Sun’s diameter. They matched not only the 11-year sunspot cycle but also the 80-year cycle that had long hovered at the edge of proof. Adding these solar cycles on top of greenhouse warming and volcanic eruptions, Gilliland too found a convincing match to the temperature record of the past century. He calculated that the solar cycles were currently acting opposite to the rise in carbon dioxide, so as to give the world an equable climate until about the year 2000. This might lead to complacency about

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[1] Workshop: Zirin et al. (1976). White (1977), see Mitchell p. 21, Hays p. 89; note also the earlier, more doubting response of Mitchell (1976), p. 491. “Salesman”: Eddy, interview by Weart, op. cit., p. 14.

[2] Eddy (1977b), quote p. 173; for more extensive speculations and reflections, see Eddy (1977a).

[3] Schneider and Mass (1975a); similarly, Schneider and Mass (1975b).

[4] Hansen et al. (1981), using what was admittedly a “highly conjectural” (p. 93) measure of variability by D.V. Hoyt.

[5] Stuiver and Quay (1980).

[6] Wigley and Kelly (1990).

[7] Bradley (1985), p. 69.

greenhouse warming, he feared, which “could be shattered” when the relentlessly increasing carbon dioxide added onto a solar upturn. Most of his colleagues awaited more solid proof of the changes in diameter and the long-term cycle (and they continue to await it).[1]

More Sun-Climate Connections (1980s - 1990s)

How could changes in the number of sunspots affect climate? The most direct influence would come if the change meant a rise or fall in the total energy the Sun radiated upon the Earth, the so-called “solar constant.” The development of highly accurate radiometers in the 1970s raised hopes that variations well below one percent could be detected at last. But few trusted any of the measurements from the ground or even from stratospheric balloons. Rockets launched above the atmosphere provided brief observations that seemed to show variation over time, but it was hard to rule out instrumentation errors. Nor were many convinced by Peter Foukal when he applied modern statistical methods to Abbot’s huge body of old data, and turned up a faint connection between sunspots and the amount of solar energy reaching the Earth. Even if that were accepted, was it because the Sun emitted less energy? Or was it because ultraviolet radiation from solar storms somehow changed the upper atmosphere, which in turn somehow influenced climate, and thus affected how much sunlight Abbot had seen at the surface?[2]

To try to settle the question, NASA included an instrument for measuring the solar constant on a satellite launched in 1980. The amazingly precise device was the work of a team at the Jet Propulsion Laboratory led by Richard C. Willson. Soon after the satellite’s launch, they reported distinct if tiny variations whenever groups of sunspots passed across the face of the Sun. Essential confirmation came from an instrument that John Hickey and colleagues had previously managed to insert in the Nimbus-7 satellite, a spacecraft built to monitor weather rather than the Sun.[3] Both instruments proved stable and reliable. In 1988, as a new solar cycle got underway, both groups reported that total solar radiation did vary slightly with the sunspot cycle.[4]

Satellite measurements pinned down precisely how solar brightness varied with the number of sunspots. Over a sunspot cycle the energy radiated varied by barely one part in a thousand; measuring such tiny wiggles was a triumph of instrumentation.[5] A single decade of data was too short to support any definite conclusions about long-term climate change, but it was hard to see

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[1] Gilliland (1981), reporting 11- and 76-year variations in solar size; Gilliland (1982a); Gilliland (1982b), quote p. 128.

[2] Hufbauer (1991), pp. 278-80; for example, a 1978 workshop concluded that changes in stratospheric ozone due to ultraviolet radiation might influence climate McCormac and Seliga (1979), pp. 18, 20.

[3] Hickey et al. (1980); Willson et al. (1981); Hufbauer (1991), pp. 280-92. See also materials on the AGU history site, http://www.agu.org/history/sv/irradiance/index.shtml.

[4] Willson and Hudson (1988); Hickey et al. (1988).

[5] Lee et al. (1995).

how such a slight variation could matter much.[1] Since the 1970s, rough calculations on general grounds had indicated that it should take a bigger variation, perhaps half a percent, to make a serious direct impact on global temperature. However, if the output could vary a tenth of a percent or so over a single sunspot cycle, it was plausible to imagine that larger, longer-lasting changes could have come during the Maunder Minimum and other major solar variations. That could have worked a real influence on climate.

Some researchers carried on with the old quest for shorter-term connections. Sunspots and other measures plainly showed that the Sun had grown more active since the 19th century. Was that not linked somehow to the temperature rise in the same decades? People persevered in the old effort to winkle out correlations between sunspots and weather patterns. For example, according to a 1991 study, Northern Hemisphere temperatures over the past 130 years correlated surprisingly well with the *length* of the sunspot cycle (which varied between 10 and 12 years). This finding was highlighted the following year in a widely publicized report issued by a conservative group. The report maintained that the 20th-century temperature rise might be entirely due to increased solar activity. The main point they wanted to make was less scientific than political: "the scientific evidence does not support a policy of carbon dioxide restrictions with its severely negative impact on the U.S. economy."[2]

Critics of the report pointed out that the new finding sounded like the weary old story of sunspot work: if you inspected enough parameters, you were bound to turn up a correlation. As it happened, already by 2000 the correlation of climate with cycle length began to break down. Moreover, a reanalysis published in 2004 revealed that from the outset the only pattern had been a "pattern of strange errors" in the key study's data. Little more could be said without further decades of observations—and a theory to explain why there should be any connection at all between the sunspot cycle and weather. The situation remained as an expert had described it a century earlier: "from the data now in our possession, men of great ability and laborious industry draw opposite conclusions."[3]

The most straightforward correlation, if it could be found, would connect climate with the Sun's total output of energy. Hopes of finding evidence for this grew stronger when two astronomers reported in 1990 that certain stars that closely resembled the Sun showed substantial variations in total output. Perhaps the Sun, too, could vary more than we had seen in the decade or so of precise measurements? In fact, studies a decade later showed that the varying stars were not so much like the Sun after all. Still, it remained possible that the Sun's total luminosity had climbed enough since the 19th century to make a serious impact on climate—if anyone could come up with an explanation for why the climate should be highly sensitive to such changes.[4]

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[1] Hoyt and Schatten (1997).

[2] Seitz (1992), p. 28, see p. 17; see also Seitz et al. (1989).

[3] Friis-Christensen and Lassen (1991); Kerr (1991); Young (1895), p. 162. Errors: Damon and Laut (2004).

[4] Baliunas and Jastrow (1990); Foukal (2003).

A more promising approach pursued the possibility of connections between climate shifts and the slow changes in the Sun's magnetic activity that could be deduced from carbon-14 measurements. A few studies that looked beyond the 11-year sunspot cycle to long-term variations turned up indications, as one group announced, of "a more significant role for solar variability in climate change... than has previously been supposed."[1] In 1997 a pair of scientists drew attention to a possible explanation for the link. Scanning a huge bank of observations compiled by an international satellite project, they reported that global cloudiness increased slightly at times when the influx of cosmic rays was greater. Weaker solar activity apparently meant more clouds. Later studies and reanalysis of the data found severe errors, and the authors themselves shifted from claiming an effect on high-level clouds to claiming an effect on low-level clouds. But the study did serve to stimulate new thinking.

The proposed mechanism roughly resembled the speculation that Dickinson had offered, with little confidence, back in 1975. It began with the fact that in periods of low solar activity, the Sun's shrunken magnetic field failed to divert cosmic rays from the Earth. When the cosmic rays hit the Earth's atmosphere, they not only produced carbon-14, but also sprays of electrically charged molecules. Perhaps this electrification promoted the condensation of water droplets on aerosol particles? If so, there was indeed a mechanism to produce extra cloudiness. A later study of British weather confirmed that at least regionally there was "a small yet statistically significant effect of cosmic rays on daily cloudiness."[2]

Other studies meanwhile revived the old idea that increased ultraviolet radiation in times of higher solar activity might affect climate by altering stratospheric ozone. While total radiation from the Sun was nearly constant, instruments in rockets and satellites found the energy in the ultraviolet varying by several percent over a sunspot cycle. Plugging these changes into elaborate computer models suggested that even tiny variations could make a difference, by interfering in the teetering feedback cycles that linked stratospheric chemistry and particles with lower-level winds and ocean surfaces. By the end of the 1990s, many experts thought it was possible that changes in the stratosphere might affect surface weather after all. Meanwhile others speculated about mechanisms through which the powerful electric circuit that circles the planet, and which varies in response to solar activity, might influence cloudiness.[3]

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[1] "More significant" (an "admittedly crude" analysis): Cliver et al. (1998), p. 1035.

[2] Svensmark and Friis-Christensen (1997); Friis-Christensen and Svensmark (1997); the effect was also reported, less convincingly, by Pudovkin and Verentenenko (1995); Pudovkin and Veretenenko (1996). Errors: Damon and Laut (2004). Later studies: Marsh and Svensmark (2000); Pallé,(2001); Harrison and Stephenson (2006).

[3] Stratosphere and ultraviolet: Haigh (1994); Rind and Balachandran (1995) ; Haigh (1996); McCormack et al. (1997); Shindell et al. (1999); Labitzke and van Loon (1999) for discussion, see Wallace and Thompson (2002); more recently, White (2006). Global electric circuit: Tinsley (1996); Tinsley (2000). More recent work by Tinsley and others is reviewed by Ram et al. (2009). Arnold (2002) is an example of the complexity of the arguments and provides historical references. Two reviews are Bard and Frank (2006) p. 5; Kirkby (2007).

While the physics of how solar activity could affect clouds remained obscure, it was now undeniable that possible mechanisms could exist. And while the data were noisy, a growing variety of evidence, some of it going back thousands of years, showed credible correlations between solar activity and one or another feature of the climate. Whatever the exact form solar influences took, most scientists were coming to accept that the climate system was so unsteady that many kinds of minor external change could trigger a shift. It might not be necessary to invoke exotic cosmic ray mechanisms, for the system might be sensitive even to the tiny variations in the Sun's total output of energy, the solar constant. The balance of scientific opinion tilted. Many experts now thought there was indeed a solar-climate connection.[1]

The Sun vs. Greenhouse Gases (2000s)

When a 1999 study reported evidence that the Sun's magnetic field had strengthened greatly since the 1880s, it brought still more attention to the key question: was increased solar activity the main cause of the rise in average global temperature over that period? As the 21st century began, most experts thought it likely that the Sun had driven at least part of the previous century's warming. Most convincingly, the warming from the 1880s to the 1940s had come when solar activity had definitely been rising, while the carbon dioxide buildup had not yet been large enough to matter much. A cooling during the 1950s and 1960s followed by the resumption of warming also correlated loosely with changes in solar activity. How far the solar changes had influenced climate, however, remained speculative. The temporary cooling had probably been at least partly related to an increase in smoke from smoggy haze, dust from farmlands, volcanic eruptions, and other aerosols. It was also possible that the climate system had just swung randomly on its own. One senior solar physicist insisted, "We will have to know a lot more about the Sun and the terrestrial atmosphere before we can understand the nature of the contemporary changes in climate."[2]

By the early 21st century, however, evidence of connections between solar activity and weather was strengthening. Extremely accurate satellite measurements spanning most of the globe revealed a distinct correlation between sea-surface temperatures and the eleven-year solar cycle. The effect was tiny, not even a tenth of a degree Celsius, but it was undeniable. Similarly weak but clear effects were detected in the atmosphere near the surface and, somewhat stronger, in the thin upper atmosphere.[3] The practical significance of these effects was minor—after all, if the

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[1] For example, correlations of cosmic rays (as an indicator of solar activity) with Asian monsoons, Neff et al. (2001); Wang et al. (2005); and with North Atlantic Ocean events, Bond et al. (2001).

[2] Lockwood et al. (1999). Reviewing various claims, including some based on observations of variations in supposedly Sun-like stars, three experts concluded in 2004 that "Any relationship" between long-term solar variations and climate "must remain speculative," Foukal et al. (2004). Know a lot more: Parker (1999); cf. criticism by Hoffert et al. (1999).

[3] Reid (1991); White (1998); White et al. (1997); Lean and Reid (2001); upper atmosphere: van Loon and Shea (2000).

sunspot cycle had a truly powerful effect on weather, somebody would have proved it much earlier. The new findings, however, did pose an important challenge to computer modelers. A climate model could no longer be considered entirely satisfactory unless it could reproduce these faint, but theoretically significant, decade-scale cycles.

Rough limits could now be set on the extent of the Sun's influence. For average sunspot activity decreased after 1980, and on the whole, solar activity had not increased during the half-century since 1950. As for cosmic rays, they had been measured since the 1950s and likewise showed no long-term trend. The continuing satellite measurements of the solar constant found it cycling within narrow limits, scarcely one part in a thousand. Yet the global temperature rise that had resumed in the 1970s was accelerating at a record-breaking pace, chalking up a total of 0.8°C of warming since the late 19th century. It seemed impossible to explain that using the Sun alone, without invoking greenhouse gases. "Over the past 20 years," a group reviewing the data reported in 2007, "all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures." It was a stroke of good luck that the rise of solar activity since the 19th century halted in the 1960s. For if solar activity had continued to rise, global temperatures might have climbed slightly faster—but scientists would have had a much harder job identifying greenhouse gases as the main cause of the global warming.

The most advanced computer modeling groups did manage to reproduce the faint influence of the sunspot cycle on climate. Their calculations showed that since the 1970s that influence had been overtaken by the rising effects of greenhouse gases. The modelers got a good match to maps of the climate changes observed over the past century, but only if they included the effects of the gases, and not if they tried to attribute it all to the Sun. For example, if they put in only an increase of solar activity, the results showed a warmer stratosphere. Adding in the greenhouse effect made for stratospheric cooling (since the gases trapped heat closer to the surface) . And cooling was what the observations showed.[1]

What about global Sun-climate correlations farther back through time? Paleontologists' studies of isotopes stemming from cosmic rays continued to show a rough connection with the Medieval and Little Ice Age climate anomalies. And an especially neat study of deposits in a cave in China found a solid correlation between weather and solar activity spanning the past two millennia. However, the correlation had broken down after 1960, just when greenhouse gases began to kick in—evidently overwhelming weaker influences . Painstaking studies simply failed to find any significant correlation between cosmic rays and cloudiness. The consensus of most scientists, arduously hammered out in a series of international workshops, flatly rejected the argument that

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[1] Tett et al. (1999); stratosphere: IPCC (2001a), p. 709. Benestad (2005) reports that "...comparison with the monthly sunspot number, cosmic galactic rays and 10.7 cm absolute radio flux since 1950 gives no indication of a systematic trend in the level of solar activity that can explain the most recent global warming." Similarly see Wang et al. (2005). "Over the past 20 years": Lockwood and Fröhlich (2007); another review: Bard and Frank (2006), on model sensitivity see p. 7.

the soaring temperatures since the 1960s could be dismissed as a consequence of changes on the Sun. In 2004 when a group of scientists published evidence that the solar activity of the 20th century had been unusually high, they nevertheless concluded that "even under the extreme assumption that the Sun was responsible for all the global warming prior to 1970, at most 30% of the strong warming since then can be of solar origin."[1]

When Foukal reviewed the question in 2006, he found no decisive evidence that the Sun had played the central role in any climate change, not even the Little Ice Age. The cold spells of the early modern centuries, experts were beginning to realize, could be at least partly explained by other influences. For one, a spate of sky-darkening volcanic eruptions had triggered a period of increased sea ice which reflected sunlight from the North Atlantic region. In addition, there was evidence that the CO_2 level in the atmosphere had dipped during those centuries (possibly because of changes in human populations and agriculture). The greenhouse effect, even then, looked like a main factor in climate change.

Still, many experts thought it likely that the Maunder Minimum of solar activity could have had something to do with the early modern climate anomalies, contributing perhaps a couple of tenths of a degree of cooling. One theory, for example, held that the changes in ozone (less ultraviolet = less ozone = less warming in the stratosphere) would have had a strong effect on the Northern Hemisphere jet stream. This particularly affected the weather in Europe, the classic location of Little Ice Age cold spells: perhaps low solar activity did make for colder winters there. Whatever the mechanism, a group convened in 2012 concluded that solar ultraviolet variations had mainly regional effects and could "contribute very little to global temperature variations."[2]

A few scientists persevered in arguing that much smaller solar changes (which they thought they detected in the satellite record) had driven the extraordinary warming since the 1970s. But even among these outlying groups, leaders admitted that in the future, "solar forcing could be significant, but not dominant." Nevertheless the argument that solar activity was the true cause of global warming continued to circulate. It was one example of the indestructible "zombie" theories that plagued discussions.

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[1] Isotopes (carbon-14 and beryllium-10): Bard et al. (2003). Chinese (from a single speleothem, sensitive to monsoon variations): Zhang et al. (2008). Cosmic-ray studies: e.g., Krissansen-Totton and Davies (2013), Kulmala et al. (2010). Consensus: International Panel on Climate Change (2001), and again in 2007 and 2013. "30%": Solanki et al. (2004), p. 1087; their contention that recent solar activity was unprecedented in the past eight millennia was disputed by Muscheler et al. (2005).

[2] Foukal et al. (2006). Volcanoes: Shindell et al. (2001), Shindell et al. (2003), Miller et al. (2012), Slawinska and Robock (2018); for lower CO_2 level see Indermühle et al. (1999) , Ruddiman (2005); other factors: e.g., change of surface brightness due to deforestation, Goosse et al. (2006). On Sun-weather mechanisms see Meehl et al. (2009). Low solar activity correlates with cold European winters: Lockwood et al. (2010); also, low UV brings cold European and N. American winters: Ineson et al. (2011). Contribute very little: National Research Council (2012).

As it happened, solar activity sank to historic lows after 2005. Some prominent people in the opposition to regulating greenhouse gas emissions now publicly predicted rapid global *cooling*. But a dispassionate look over the past half-century would see no connection between solar activity and global temperatures. The supposed correlation with cosmic rays, in particular, faded away. In 2013 several papers appeared reporting studies that sought a statistical connection between cosmic rays and various types of climate data. Finding none, the papers (as a journalist remarked) “put the final nail in the cosmic rays–global warming coffin.”

When temperatures climbed to a new record in the 2010s while solar activity remained unusually low, only the ignorant or disingenuous could persist in denying that greenhouse gases were the only plausible cause. By the mid 2010s the study of “solar-terrestrial relations” (as scientists called the topic) had settled down to teasing out thee complex ways solar activity might possibly exert a subtle influence on specific regional weather patterns. Such research required, first, assembling and standardizing vast collections of weather data, and second, adapting one or another of the elaborate supercomputer models of the atmosphere to test hypotheses for mechanisms like ozone interactions. The research was pursued vigorously as part of the perpetual enterprise of improving short-term weather predictions, but it was scarcely relevant to climate change.[1]

The import of the claim that solar variations influenced climate was now reversed. Critics had used the claim to oppose regulation of greenhouse gases. But what if the planet really was at least a bit sensitive to almost imperceptible changes in the total radiation arriving from the Sun? The planet would surely react no less strongly to changes in the interference by greenhouse gases with the radiation after it entered the atmosphere. Some of the scientists who reported evidence of past connections between the Sun and climate changes warned explicitly that their data did not show that the current global warming was natural—it only showed the extreme sensitivity of the climate system to small perturbations.

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[1] Willson (1997), reporting a brightening of 0.04 percent between the two most recent solar cycles; this was controversial, see Kerr (1997b); similarly Willson and Mordvinov (2003), discussed by Byrne (2003). A few groups pursued the study of possible cosmic ray mechanisms, for example elaborating theories of how changes in the atmosphere’s electric circuit, which varies with the flux of cosmic rays, affected precipitation in the Arctic, see Ram et al. (2009) , or devising experiments that they hoped would show a direct and strong effect of cosmic rays on clouds, e.g., Svensmark et al. (2007) (which brought a strong press reaction but proved little). Later experiments entirely refuted the claim that cosmic rays affect cloud formation, Dunne et al. (2016). For reviews see Dudok de Wit et al. (2015) and Mironova et al. (2015).“Final nail:” Dana Nuccitelli, “Cosmic Rays Fall Cosmically Behind Humans in Explaining Global Warming,” *The Guardian* (Nov. 12, 2013), online at https://www.theguardian.com/environment/climate-consensus-97-per-cent/2013/nov/12/global-warming-humans-not-cosmic-rays, q.v. for a brief account of the papers. Data: Dudok de Wit et al. (2018).

Back in 1994 a U.S. National Academy of Sciences panel had estimated that if solar radiation were to weaken as much as it had during the 17th-century Maunder Minimum, the entire effect would be offset by another two decades of accumulation of greenhouse gases. A 2010 study reported that with the growing rate of emissions, by the late 21st century a Maunder-Minimum solar effect would be offset in a single decade. As one expert explained, the Little Ice Age "was a mere 'blip' compared with expected future climatic change."[1]

For more on temperature changes over the past millennium or so, see the conclusion and figure captions in the essay on The Modern Temperature Trend.

Related:
Past Cycles: Ice Age Speculations
The Modern Temperature Trend

[1] For Gerard Bond's warning about sensitivity see Pearce (2007c), p. 164; similarly Lockwood and Fröhlich (2007). National Research Council (1994), combining statements on pp. 3 and 4; late 21st century: Feulner and Rahmstorf (2010); "blip:" Nelson (1997); similarly see Wigley and Kelly (1990), p. 558.