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Changing Sun, Changing Climate?

This essay is partly based, by permission, on an essay by Theodore S. Feldman (PSDI, Bedford, Mass), “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>

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 lifetimes. 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 remained 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 future warming from the rise in greenhouse gases would far outweigh any solar effects.

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.¹ 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 such a connection, 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 the price of wheat had been high, he pointed out, presumably reflecting spells of drought.²

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

¹ Feldman (1993); Fleming (1990).

² Herschel (1801), pp. 313-16; see Hufbauer (1991).

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 in one century as in the last. That still left room for 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 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.⁴

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).

⁴ 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 (1950).

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. Over a term of years the more active Sun seemed 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.¹ 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.²

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.³ 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.

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."⁴ 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

¹ 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).

² Abbot (1967); Aldrich and Hoover (1954).

³ Fröhlich (1977).

⁴ Lamb (1997), pp. 192-93.

cycles that... draws all kinds of creatures out of the woodwork.”¹ (This was a robust tradition—into the 21st century, enthusiasts with weird or incomprehensible theories of solar-terrestrial connections, backed up by selected 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 they did exist, lurking somewhere in the data.²

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.³ “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.”⁴

Such thinking was still in circulation two decades later. 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 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.⁵ In the 1950s, 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...”⁶

Meanwhile 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.

¹ J. Eddy, interview by Weart, April 1999, AIP, p. 6.

² Nebeker (1995), p. 95.

³ Simpson (1934); Simpson (1939-40). Simpson cited A. Penck, who argued that the entire world had cooled and only solar changes could explain this.

⁴ Simpson (1939-40), p. 210.

⁵ Öpik (1958); “flickering” (due to uncertain convective changes): Öpik (1965), p. 289.

⁶ E.g., Brooks (1949), ch. 1; Shapley (1953); Wexler (1956), quote p. 494, adding that turbidity (from volcanoes) was equally important.

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.¹

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 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—so more sunspots would mean fewer of these particles. Either way there might be an influence on the weather. Meteorologists gave these ideas some credence.² 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.³

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-

¹ Willett (1949), pp. 34, 41, 50; see Lamb (1997), p. 193; the earlier hypothesis (not cited by Willett) is in Haurwitz (1946); glacier papers are cited by Wexler (1956), p. 485.

² 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.

³ Sellers (1965), pp. 220-23.

year cycle to the next). There were also matches to possible longer solar variation cycles.¹ 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. As the authors admitted, the conclusion would remain in doubt unless it could be verified by spacecraft entirely above the atmosphere.²

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 sheet, 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.³ 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.⁴

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.⁵ 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 (CO₂) would come on top of this rise, making for a dangerously abrupt warming.⁶

(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. The downturn in temperature since the 1940s, whether due to a variation in the

¹ Lamb (1977), pp. 700-704.

² Kondratyev and Nikolsky (1970); Fröhlich (1977).

³ 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.

⁴ Johnsen et al. (1970); see also Dansgaard et al. (1971); Dansgaard et al. (1973).

⁵ Broecker (1999).

⁶ Broecker (1975).

Sun's radiation or some other natural cause, could indeed change to a natural upturn that would add to greenhouse warming instead of subtracting from it. In fact that happened, beginning in the 1970s.)

The 1970s also brought 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.¹ 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 timescales 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 possibility that solar activity could 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 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."²

Evidence was accumulating, however, 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.³ He had followed this up in collaboration with the carbon-14 expert Hans Suess, confirming that the concentration of the isotope really 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

¹ 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...").

² Eddy (1977a), p. 92.

³ Stuiver (1961).

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.¹

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.² The early 1970s also brought claims that far slower variations in the Earth’s magnetic field correlated with 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.³

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 electrical charges that cosmic rays brought into the atmosphere somehow affected how 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 scientifically conceivable that changes in sunspots could have

¹ 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.

² Ralph and Michael (1974).

³ Wollin et al. (1971); Gribbin (1982), ch. 7.

something to do with changes in climate. Most experts, however, continued to consider the idea discredited if not preposterous.¹

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.

Read the details in our Interview with Eddy at <http://www.aip.org/history/climate/eddy1.htm>.

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 Herschel had noticed this prolonged dearth of sunspots. A 19th-century German astronomer, G.W. Spörer, had been the first to solidly 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.²

“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 heightened activity on the Sun's surface). Once his attention was drawn

¹ Dickinson (1975); a similar speculation, connecting cosmic rays with storminess, was offered by Tinsley et al. (1989); see also the solar activity-atmosphere connection reported by Wilcox et al. (1973). 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.

² 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 Wearth, April 1999, AIP, 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.

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.”¹

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 rather than solar physics. Meanwhile, however, it called into doubt the theoretical reasoning that said the Sun could not be a variable star.²

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 high carbon-14, and thus low 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 perish from starvation 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.”³

¹ 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, April 1999, AIP.

² Hufbauer (1991), pp. 269-78.

³ “benign,” Eddy (1977c), p. 69.

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 more definite, but it too had many local variations, not everywhere as important as in the North Atlantic region. 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.¹ 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.

Eddy worked hard to “sell” his findings. At a 1976 workshop where he first presented his full argument, his colleagues tentatively accepted that solar variability might be responsible for climate changes over periods of a few hundreds or thousands of years.² 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.”³

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 give a better match to temperature trends over the entire last millennium.⁴ 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.⁵

Meanwhile Stuiver and others confirmed the connection between solar activity and carbon-14, and this became a standard tool in later solar-climate studies.⁶ An example was a study that reported a

¹ Jones and Mann (2004), p. 20, see p. 7 and passim. See also note on the “hockey stick” graph in the essay on the modern temperature trend.

² 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, April 1999, AIP, p. 14.

³ Eddy (1977b), quote p. 173; for more extensive speculations and reflections, see Eddy (1977a).

⁴ Schneider and Mass (1975a); similarly, Schneider and Mass (1975b).

⁵ Hansen et al. (1981), using what was admittedly a “highly conjectural” (p. 93) measure of variability by D.V. Hoyt.

⁶ Stuiver and Quay (1980).

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.¹ 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.”²

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 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).³

Yet 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?⁴

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

¹ Wigley and Kelly (1990).

² Bradley (1985), p. 69.

³ Gilliland (1981), reporting 11- and 76-year variations in solar size; Gilliland (1982a); Gilliland (1982b), quote p. 128.

⁴ 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.

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.¹ 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.²

After 1988

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.³ A single decade of data was too short to support any definite conclusions about long-term climate change, but it was hard to see how such a slight variation could matter much.⁴ 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.”⁵

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, plus a theory to explain why there should be any connection at all

¹ 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>.

² Willson and Hudson (1988); Hickey et al. (1988).

³ Lee et al. (1995).

⁴ Hoyt and Schatten (1997).

⁵ Seitz (1992), p. 28, see p. 17.

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.”¹

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.²

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.”³ 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.”⁴

¹ Friis-Christensen and Lassen (1991); Kerr (1991); Young (1895), p. 162. Errors: Damon and Laut (2004).

² Baliunas and Jastrow (1990); Foukal (2003).

³ “More significant” (an “admittedly crude” analysis): Cliver et al. (1998), p. 1035.

⁴ Svensmark and Friis-Christensen (1997); Friis-Christensen and Svensmark (1997); the effect was also reported, less convincingly, by Pudovkin and Veretenenko (1995); Pudovkin and Veretenenko (1996). Errors: Damon and Laut (2004). Later studies: Marsh and Svensmark (2000); Pallé,(2001); Harrison and Stephenson (2006).

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 electrical circuit that circles the planet, and which varies in response to solar activity, might influence cloudiness.¹

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.²

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 temperature rise over that period? Whether any of the proposed solar mechanisms did in fact produce a noticeable effect on global climate was still no more than speculation. But 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. An increase in smoggy haze, dust from farmlands, smoke from volcanic eruptions and other aerosols had probably had something to do with the temporary cooling. 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

¹ Stratosphere and ultraviolet: Haigh (1994); 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 electrical circuit: Tinsley (1996); Tinsley (2000). Two reviews are Bard and Frank (2006) p. 5; Kirkby (2007).

² 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).

the Sun and the terrestrial atmosphere before we can understand the nature of the contemporary changes in climate.”¹

However, rough limits could now be set on the extent of the Sun’s influence. Average sunspot activity did not increase after 1980, and on the whole, solar activity during the half-century since 1950 looked little different from the half-century before. The continuing satellite measurements of the solar constant found it cycling within narrow limits, scarcely one part in a thousand. As for cosmic rays, they had been measured since the 1950s and likewise showed no long-term trend. Yet the global temperature rise that had resumed in the 1970s was accelerating at a record-breaking pace. 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.” The most advanced computer models now allowed for a presumed influence of solar variations on climate, and they calculated that since the 1970s that influence had increasingly dwindled in significance as compared with the rising effects of greenhouse gases. The modelers got a good match to maps of recent observed climate changes when they included the effects of the gases, but not if they tried to attribute it all to the Sun. For example, the stratosphere was cooling, which was exactly what models predicted would result from the greenhouse effect, but the reverse of what should result from a solar influence.²

When Foukal reviewed the question in 2006, he found no solid evidence that the Sun had played a role in any climate change back to the Little Ice Age. The cold spells of the early modern centuries, some experts suggested, might be explained by a spate of volcanic eruptions and other terrestrial factors. On the other hand, a study of deposits in a cave in China did find a solid correlation between weather and solar activity spanning the past two millennia—but the correlation broke down after 1960. The consensus of most scientists, arduously hammered out in a series of international workshops, flatly rejected the argument that the soaring temperatures since the 1960s could be dismissed as a mere effect 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

¹ 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).

² Tett et al. (1999); stratosphere: IPCC (2001), 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.” “Over the past 20 years”: Lockwood and Fröhlich (2007); another review: Bard and Frank (2006), on model sensitivity see p. 7.

responsible for all the global warming prior to 1970, at most 30% of the strong warming since then can be of solar origin.”¹

Some experts continued to believe that the Maunder Minimum of solar activity must have had something to do with the medieval cold spells. And some persevered in arguing that slight solar changes (which they thought they detected in the satellite record) had driven the extraordinary warming since the 1970s. A few groups pursued the study of possible mechanisms, for example devising experiments that they hoped would show an effect of cosmic rays on clouds. Yet even if somebody did finally manage to show how changes on the Sun could influence climate, the influence could not be very great. Greenhouse warming was bound to swamp any solar effects as the quantities of the gases in the atmosphere soared ever higher. Willson, the leader of the satellite experts, explained that in the future, “solar forcing could be significant, but not dominant.”²

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 did react with extreme sensitivity to almost imperceptible changes in the radiation arriving from the Sun? The planet would surely also be sensitive to greenhouse gas interference with the radiation once it entered the atmosphere. Some of the scientists who reported evidence of past connections between solar 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. A U.S. National Academy of Sciences panel estimated in 1994 that if solar radiation were to weaken as much as it had during the 17th-century Maunder Minimum, the effect would be offset by only two decades of accumulation of greenhouse gases. As one expert explained, the Little Ice Age “was a mere ‘blip’ compared with expected future climatic change.”³

For recent work on temperature changes over the past millenium or so, probably related to solar variations plus volcanic eruptions and perhaps other factors as well as the recent rise of greenhouse gases, see the conclusion and figure captions in the essay on The Modern Temperature Trend.

Related:

¹ Foukal et al. (2006); see Shindell et al. (2001), Shindell et al. (2003); other factors: e.g., change of surface brightness due to deforestation, Goosse et al. (2006). Chinese (from a single speleothem, sensitive to monsoon variations): Zhang et al. (2008). Consensus: International Panel on Climate Change (2001). “30%”: Solanki et al. (2004), p. 1087.

² Willson reported a brightening of 0.04 percent between the two most recent solar cycles, Willson (1997); this was controversial, see Kerr (1997b); similarly and more recently, Willson and Mordvinov (2003); discussed by Byrne (2003). Experiments: e.g., Svensmark et al. (2007) (which brought a strong press reaction but proved little). “Mere ‘blip’”: Nelson (1997).

³ National Research Council (1994), combining statements on pp. 3 and 4; blip: Wigley and Kelly (1990), p. 558. See www.usgcrp.gov/usgcrp/991118FO.html. For Gerard Bond’s warning about sensitivity see Pearce (2007c), p. 164; similarly Lockwood and Fröhlich (2007).

Past Cycles: Ice Age Speculations
The Modern Temperature Trend