Sun-Earth Connection

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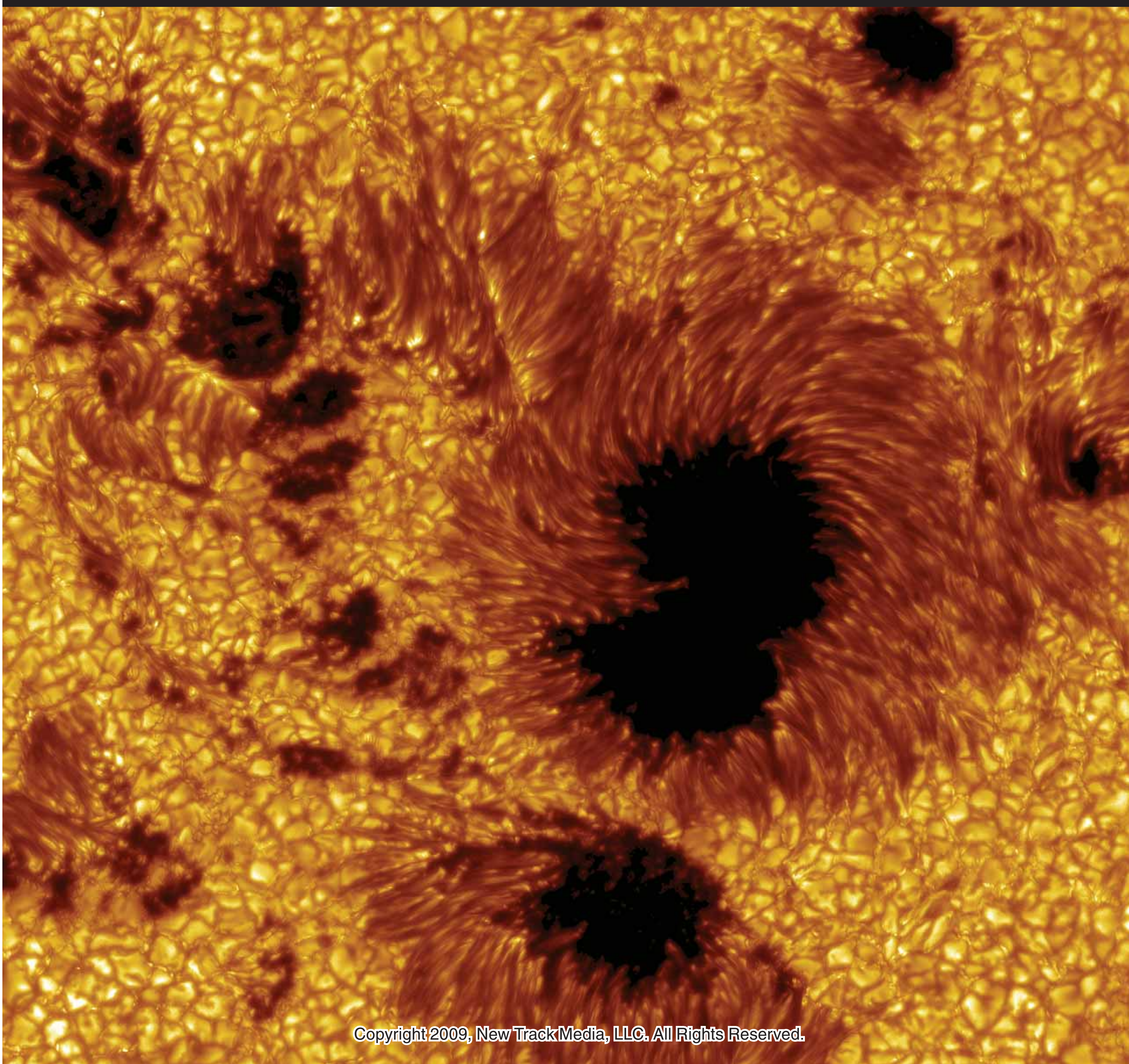
SOLAR IMPACT

Variations in the Sun's output influence Earth's climate in ways scientists are still trying to discern.



From Earth, the Sun appears as a smooth, glowing disk, its intense shine warming our planet. But if we could float just above that scorching orb, we would see a seething cauldron of gigantic bubbles. In the churning sea of 10,000°F (5,500°C) gas, dark eddies materialize, lasting for hours to months, and appear to slowly rotate across the Sun.

Through filtered telescopes and sometimes without magnification, these sunspots look like splatters of ink against the pale disk. More than just a cosmetic disturbance, the waxing and waning of the spots signal that the Sun's chaotic moods may influence Earth's climate.

Fire in the Sky

While searching for the imaginary planet Vulcan in the mid-1800s, German astronomer Heinrich Schwabe linked sunspots to a cycle that rises and falls. These cycles average about 11 years, and each has a sunspot maximum and minimum. Only a handful of small sunspots appear during the low point, while dozens of larger ones arise in groups during solar maximum. Half a century later, George Ellery Hale used a spectroheliograph to correctly infer that sunspots have strong magnetic fields, linking the 11-year sunspot cycle to a magnetic cycle.

In the past 30 years, satellites have examined the Sun's magnetic cycle in greater depth. The European-NASA Solar and Heliospheric Observatory (SOHO) has made exquisitely detailed measurements for a full 11-year cycle, while the Japanese-American spacecraft Hinode has taken some of the highest-resolution images of the Sun since its launch in September 2006.

The Sun's magnetic field, which pervades the entire solar system, arises from a dynamo process operating in the interior. A number of motions maintain the dynamo, including the Sun's rotation and the flow of material from the equator to the poles. These motions cause bubbles of hot, electrically charged gas (plasma) to rise up to the Sun's visible surface (the photosphere) and expand into the corona, producing localized magnetic fields that alter a region's temperature. These processes modify the Sun's energy output. Although scientists accept the dynamo as the driving force of the Sun's magnetic cycles, modeling its intricate workings is fiendishly complex.

Magnetic-field lines often coalesce and tangle, suppressing the upward flow of energy, creating sunspots. Because sunspots block the flow of energy from deeper down, they are a few thousand degrees cooler than the rest of the photosphere, and thus appear darker than their surroundings.

Although sunspots are places of reduced temperature, their presence ironically signals a more energetic Sun. During solar maximum, bright active regions called *faculae* (Italian for "little torches") and nearby *plage* areas also increase in numbers. The enhanced energy output from these bright regions is twice as large as the reduced energy from sunspots, resulting in an overall brightness increase during solar maximum.

Satellites have shown that the Sun brightens in visible light during solar maximum by approximately 0.1% and radiates considerably more energy in ultraviolet light and X rays, which are absorbed in Earth's upper atmosphere. The active regions responsible for these changes also give rise to magnetic eruptions that produce flares and coronal mass ejections higher in the solar atmosphere.

The Little Ice Age

In 2003 Gerald North (Texas A&M University) showed that Earth's surface temperatures vary in a way that correlates to the 11-year sunspot cycle, but only by about 0.1°C. Mathematician Ka-Kit Tung (University of Washington) later found a change of about 0.2°C. "At the 11-year time scale there is a detectable signal, but it's very tiny. It doesn't have any consequences for humans," says North.

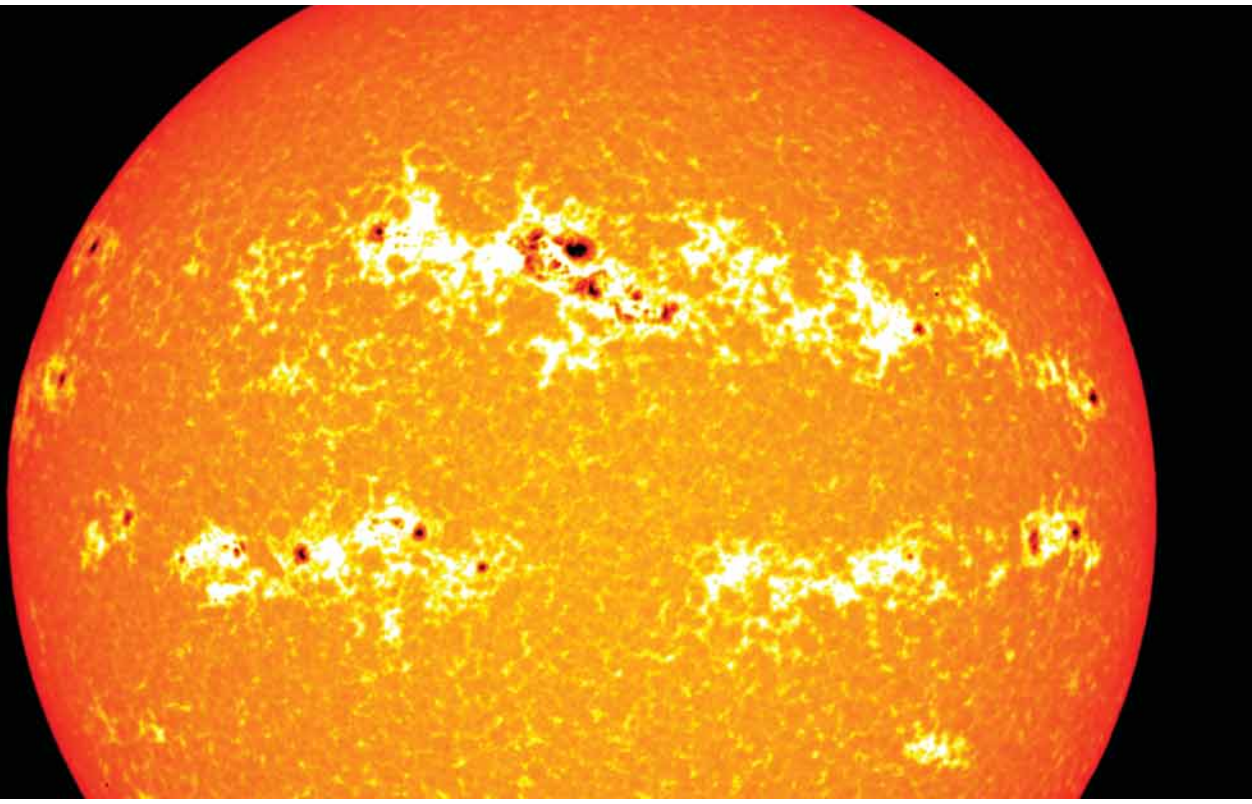
Though the effect of this difference on climate appears to be modest, scientists point to a puzzling time in Earth's history when several unusually low sunspot cycles occurred in succession. During the 1614 solar peak there were well over 100 sunspots. But from 1645 to 1715 there was a sustained period when sunspots were nearly absent. This period is named the Maunder Minimum after English astronomer Edward Maunder, who first noted this trend retrospectively in 1893. It was closely followed by the Dalton Minimum, which lasted from about 1795 to 1825.

Around this time, extremely cold spells were so pronounced, especially in Northern Europe, that some researchers have dubbed the period from roughly 1450 to 1850 "the Little Ice Age." The Maunder Minimum coincided with the coldest part of the Little Ice Age — when in many regions of Europe glaciers expanded, warm summers disappeared, and rivers, harbors, and canals froze. Climate models based on temperature reconstructions suggest a global cooling of about 0.2°C, and as much as a full degree or more in certain parts of Europe.

A scarcity of sunspots indicates a sluggishly inactive Sun, of which the Maunder and Dalton minimums are just the most recent examples. Since sunspots have been recorded only since around 1610, scientists have looked

The 1-meter Swedish Solar Telescope captured this sunspot group in 2002, near solar maximum. The largest sunspot is nearly 20% larger than Earth. The intense magnetic activity of sunspots blocks heat rising from the interior, leading to a temperature 2,300 to 3,200°F (1,300 to 1,800°C) cooler than the surrounding gas.

ROYAL SWEDISH ACADEMY OF SCIENCES



This color-enhanced image from the Precision Solar Photometric Telescope, taken in 2001 near solar maximum, shows the bright light from faculae beating out the darkening from sunspots. The graph at the upper right shows that the Sun is generally slightly brighter at times of high sunspot activity. Although Earth receives slightly more solar energy at solar maximum, it's not enough to have any noticeable effect on climate.

NASA / GSFC SCI VISUALIZATION STUDIO / SOURCE DATA: HAO & NSO PSPT

at other indirect measurements to try to understand how solar activity has changed during past millennia.

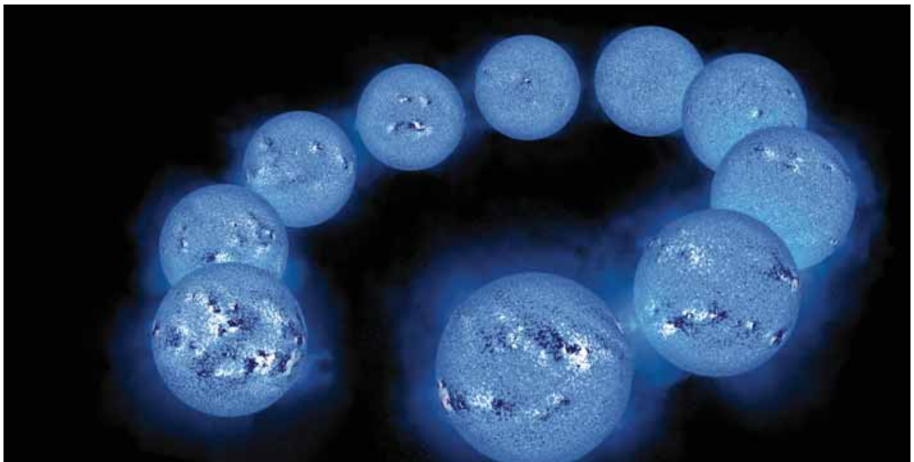
When the Sun is magnetically active, the solar wind is stronger and deflects the high-energy galactic cosmic rays that constantly bombard Earth. Conversely, when solar activity is less energetic, more cosmic rays strike our atmosphere and create isotopes such as carbon-14 and beryllium-10. These isotopes eventually end up in tree rings and ice cores, respectively. Studies showing that more carbon-14 accumulated in tree rings led to the discovery of the Spörer Minimum, from about 1450 to 1550, which marks the onset of the Little Ice Age.

"The beryllium and carbon records are a little ambiguous in these minima," says solar-terrestrial physicist Judith Lean (U.S. Naval Research Laboratory). Perhaps the prevalence of these isotopes is not just influenced by solar activity, but also by climate, so the record is not straightforward. Local weather can also cause variations.

"There is no clear physical process that can be invoked to explain a strong global cooling as a result of the Maunder Minimum," adds climate modeler Chris E. Forest (MIT). But he cites enhanced volcanic activity as a possible reason. Europe's and North America's "Year Without a Summer" in 1816 corresponded to the 1815 catastrophic volcanic eruption of Tambora in Indonesia, which spewed hundreds of megatons of heat-reflecting dust, rock, and aerosols into the atmosphere. It also occurred in the midst of the Dalton Minimum.

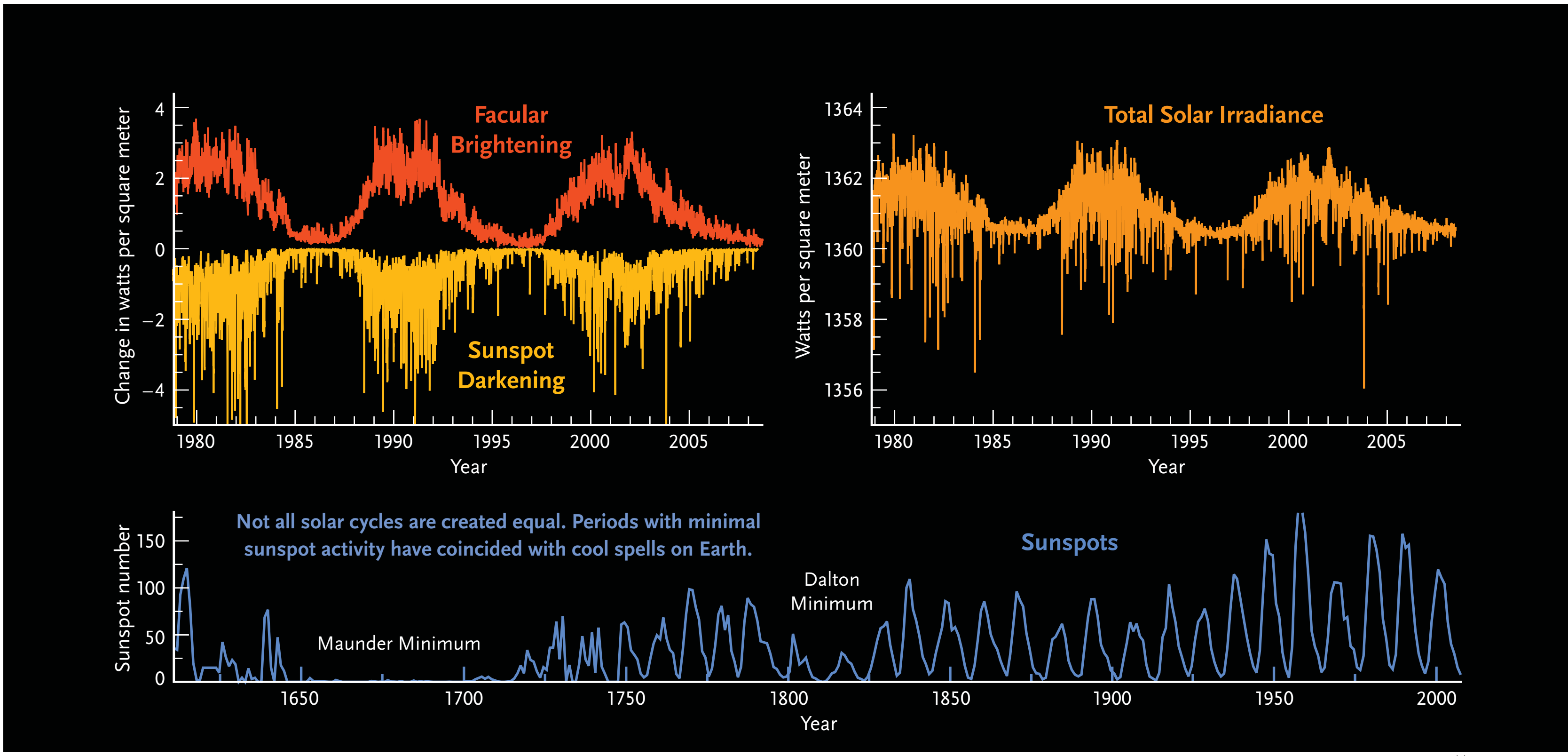
"The Little Ice Age can be explained in the models through a combination of the fairly intense volcanic activity and the relatively low solar output," says climatologist Michael Mann (Penn State University). "When you decrease solar output by the amount we think took place during the Maunder Minimum, the models predict that has enough influence on the North Atlantic jet stream to cool parts of Europe a couple of degrees Celsius, even though that same change in solar output cooled global temperatures by only a tenth as much."

"The solar influences on Earth's climate over the last several decades have been very small," adds Thomas Karl, director of the National Oceanic and Atmospheric Administration's National Climatic Data Center. But he affirms that solar cycles are potentially extremely important, as evidenced by the Little Ice Age, when sunspots disappeared. "The data have a lot of interpretation, but nevertheless there's some pretty good evidence to suggest there was less solar irradiance, and it did influence weather."



These images from the National Solar Observatory's Vacuum Tower Telescope show solar activity falling and rising from 1992 to 2001.

LOCKHEED MARTIN SOLAR & ASTROPHYSICS LABORATORY / NATIONAL SOLAR OBSERVATORY / AURA / NSF



JUDITH LEAN / U.S. NAVAL RESEARCH LABORATORY (3)

But for the major ice ages, climate models show that the orbital mechanics of Earth's revolution around the Sun and changes in Earth's axial tilt were responsible for the major wax and wane of the glacial advances.

Solar Activity and Today's Climate

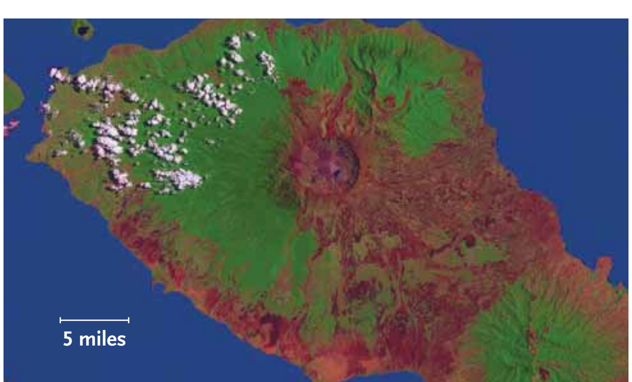
Research on extreme past climate conditions also raises the question of whether solar variations play any role in recently observed global climate changes. The large majority of climate scientists agree that anthropogenic activities have a greater effect on these shifts than do variations in solar activity. But climatologists don't completely understand the ways in which solar variation affects Earth, so they have difficulty reaching a consensus on how much solar variations contribute to climate changes.

Although reconstructions of solar brightness based on sunspots and isotope records point to a slight increase in solar output since the beginning of the 1900s, most experts say that trend has tapered off after about 1950. Aside from SOHO, measurements of the Sun's total solar irradiance — the total energy from the Sun across different wavelengths — have mainly come from the Solar Maximum Mission, the Upper Atmosphere Research Satellite (UARS), Nimbus 7, the Earth Radiation Budget Satellite (ERBS), ACRIMSAT, and particularly the current Solar Radiation and Climate Experiment (SORCE) mission, which carries state-of-the-art solar radiometers that monitor both the total energy and spectrum.

"Since the late 1970s, the global temperature increase has been pretty constant," says Karl, by almost 0.2°C per decade, as measured by a land and sea monitors. "Since then we've seen very little overall change in the energy from the Sun based on direct satellite measurements."

Because these satellites provide absolute measurements, their results must be compared to one another, which leaves room for interpretation. "Irradiance is a difficult measurement because it's absolute," says Lean. "You rely on the radiometers being stable and you have to cross-calibrate." Researchers hope to acquire a long-term record of irradiance from SORCE and its follow-on missions, Glory and NPOESS, which will carry solar radiometers. "We need to know how irradiance changes from cycle to cycle and if long-term trends are really occurring," says Lean. "Without the long-term data, it's impossible to validate the historical reconstructions of solar brightness changes that climate researchers currently use."

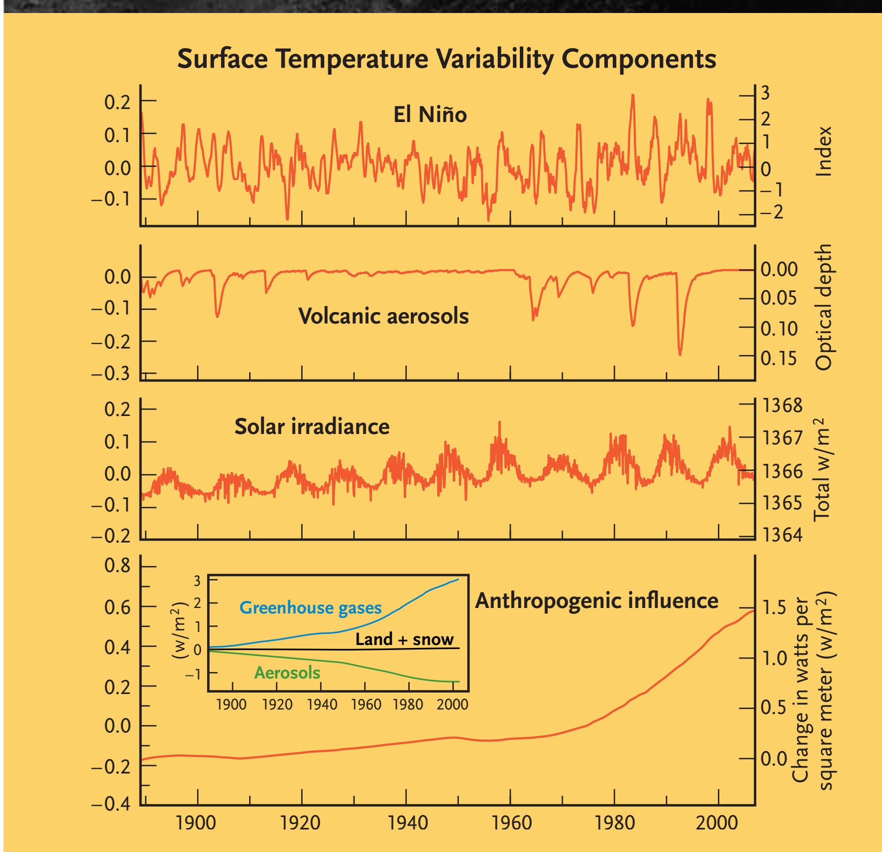
Climate models do take into account the slight increase of



USGS

Volcanoes can profoundly influence Earth's climate. This Landsat image shows Tambora, on the Indonesian island of Sumbawa. In April 1815 Tambora unleashed the most powerful volcanic eruption of the past millennium, killing more than 70,000 regional inhabitants and contributing to 1816's "Year Without a Summer."

Top and bottom left: The effects of global climate change are easily seen in glaciers such as McCall Glacier in Alaska's Brooks Range. Many glaciers are receding extremely rapidly on a geologic timescale as polar regions become warmer. *Center left:* The graphs compare various factors and their associated temperature changes (orange lines) that influence Earth's climate: El Niño, volcanic aerosols, solar irradiance, and human activities. The inset in the bottom graph shows how greenhouse gases, tropospheric aerosols, and changes to surface reflectivity combine to yield the net human factor. In the bottom main graph, the orange line's recent steep upward slope shows that human activities, mainly greenhouse-gas emissions, play the dominant role in the overall global warming measured in recent years. Natural processes play too small a role to account for most of that trend.



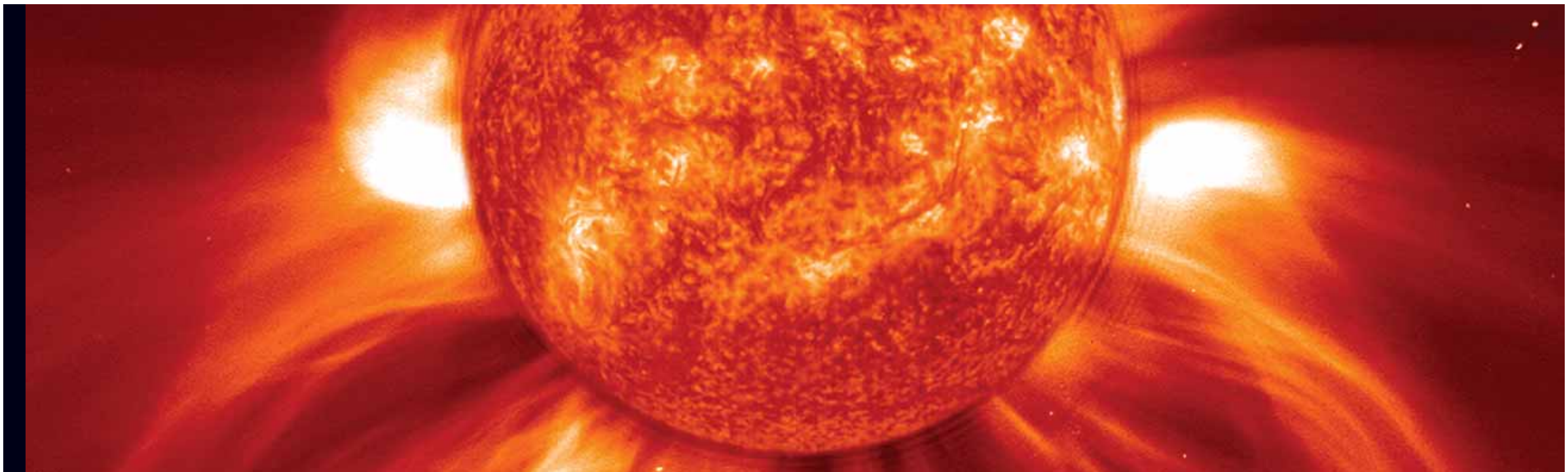
TOP PHOTO: AUSTIN S. POST / GRAPH SOURCE: JUDITH LEAN / BOTTOM PHOTO: MATT NOLAN (UNIVERSITY OF ALASKA, FAIRBANKS) / BOTH PHOTOS COURTESY NATIONAL SNOW AND ICE DATA CENTER

solar output in the early 20th century. "Models indicate that solar forcing can explain about 0.1 to 0.2°C of the warming in that early period. Since the net trend is close to 1°C, solar output increase can probably only explain about 20% of 20th-century warming," says Mann. "If you don't put human impact in the models, and you just include solar and volcanic activity, you can't explain the 20th-century warming; you get a slight cooling."

Taking Earth's reflectivity and geometry into account, recent solar cycles have produced a variation of about 0.2 watt per square meter at the surface. In addition to this direct surface heating, the more advanced climate models factor in solar-cycle ultraviolet effects in the atmosphere. But human greenhouse-gas emissions have led to the equivalent of about a 2.5-watts-per-square-meter increase since preindustrial times, which is only partially offset by an approximately 1-watt-per-square meter cooling from industrial aerosols injected into the troposphere. As a result, most models suggest that the past century's pronounced warming is mainly caused by human factors.

A more controversial hypothesis on how solar activity influences Earth's climate points to the solar wind. Physicist Henrik Svensmark (Danish National Space Institute) and others suggest that the increased ionization in the troposphere from cosmic rays may affect cloud coverage. The ionization may stimulate the formation of clouds, which reflect heat back into space. The group speculates that when solar activity is weaker, more cosmic rays hit Earth and cloud formation builds up, decreasing the heat that reaches Earth's surface.

The group compared data from satellites and cosmic-ray monitors. "We found a correlation of cosmic rays with low clouds within the first couple of kilometers of the troposphere," says Eigil Friis-Christensen, director of Denmark's National Space Institute, where the team is testing Svensmark's hypothesis. By building an artificial cloud chamber, the researchers found evidence that ion-



THE NEXT MAUNDER MINIMUM?

When might the Sun enter another Maunder Minimum? Mark Giampapa (National Solar Observatory) and his colleagues have studied the magnetic behavior of stars in the open cluster M67 that are similar to the Sun in mass, composition, and age. This program suggests that Sun-like stars spend about 17% of the time in a very-low-activity phase. Studies of tree rings and ice cores yield similar results. Since the Sun spent about 70 years in the Maunder Minimum, and that was 300 years ago, these studies suggest we might have to wait a century or longer for another low-activity phase.

SOHO / ESA / NASA

ization by cosmic rays leads to an increased formation of ultra-fine aerosol particles, which are the basis for the formation of cloud condensation nuclei in the atmosphere. The team is currently testing its hypothesis by trying to stimulate the formation of ultra-fine aerosols in an abandoned coal mine, where no cosmic rays can reach.

Looking Ahead

While each solar cycle has a sunspot minimum and maximum, no one knows why the Sun and other middle-aged solar-type stars have this ebb and flow, ranging from 8 to 15 years.

In early 2010 NASA plans to launch the Solar Dynamics Observatory (SDO). Equipped to peer beneath the Sun's surface, image sunspots, and measure the Sun's magnetic field, SDO is the first mission in NASA's Living with a Star program to better understand solar variability. SDO will image the Sun's corona at a range of temperatures in the extreme ultraviolet six times a minute for five years.

"This is the next big thing — it will bring more data by a factor of a thousand," says Karel Schrijver (Lockheed Martin Solar and Astrophysics Laboratory), who helped develop SDO. Although SDO will not measure solar irradiance, it will record the Sun's extreme ultraviolet and X-ray emission, which heats Earth's upper atmosphere.

Scientists have only fully measured the total solar irradiance in the last two solar cycles. Interestingly, "irradiance changes in [the just-ending] Cycle 23 were about the same as Cycle 22, even though the sunspot numbers were different," says Lean.

Related faculae are also a source of irradiance variation, and sunspots by themselves are incomplete indicators of the solar cycle. To figure out how the Maunder Minimum influenced climate, scientists would need to know what was happening with faculae, but such records don't exist. "The key is understanding the solar-activity cycle, which produces magnetic fields. Sunspots we use as a generic indicator, but really we have to understand the other things that are related, like the bright faculae," says Lean. "Solar activity can change, but it's the proportion of sunspots and faculae that determine how the irradiance changes." Once scientists understand how irradiance varies from cycle to cycle, they will be able to better understand if there are longer-term trends as well.

To listen to a podcast with solar-terrestrial physicist Judith Lean, visit SkyandTelescope.com/skytel.

The Next Cycle

Astronomers are currently noticing a delayed start to Cycle 24. Cycle 23 has lasted for a full 12 years, longer that the two prior cycles, but similar to Cycle 20. Until November 2008, professionals and amateurs went months without a single sunspot sighting. While it's presently far too early to liken this delay to the Maunder Minimum, a recent study by National Solar Observatory scientists suggests that sunspots may be growing cooler and less magnetic since 1990, and they hypothesize that sunspots may soon disappear.

These results are potentially exciting, says Yi-Ming Wang (U.S. Naval Research Laboratory), but he cautions that we are still in the low part of Cycle 23 and more measurements are needed during the next solar maximum to distinguish a long-term trend from a solar-cycle variation.

Predictions vary about what will happen in the upcoming cycle, which should peak around 2012. Some solar physicists are forecasting the upcoming cycle to be one of the highest on record, while others claim it will be unusually low. Refining our understanding of the solar cycle and studying the Sun in closer detail may eventually aid in determining — and perhaps anticipating — what consequences the shifting Sun has on Earth. ✦

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