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Solar Variability and Climate Change

by Dr. Willie Soon
January 10, 2000

The purpose of this article is to give you some details about the research which my colleagues (especially Sallie Baliunas and Eric Posmentier) and I have done in studying the controversial relationship between the Sun's energy output and Earth's temperature, in short, the sun-climate connection. Despite what you may have heard before about sun-climate studies, there are in fact demonstrable connections between our Sun's changing energy outputs and Earth's climate. This paper will use the best information currently available to explain what we do and do not know about the many aspects of the sun-climate connection.

My presentation consists of three parts.

1. The first part is a brief introduction on the physical aspects of the Sun, which normally vary over time.
2. The second part discusses the direct effect of the Sun's variable radiant energy on the changes in the Earth's surface temperature over the last 100 years or so.
3. The third part gives an illustration of how changes in the solar wind (that is, the flow of charged particles - protons and electrons - from the sun) and cosmic rays (the faster and more energetic charged particles from outside the solar system), may affect variables like temperature and clouds in the troposphere (the lowest 10 km of Earth's atmosphere).

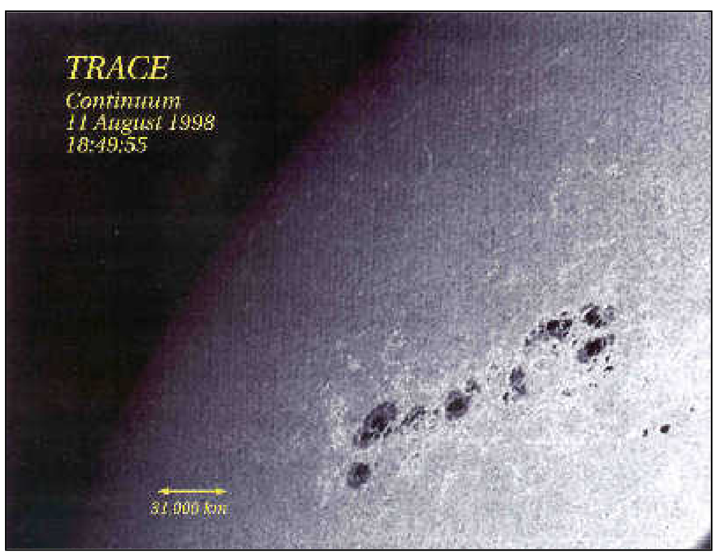

Figure 1

Here is a close-up view of the Sun's surface. Most noticeable here are the dark areas. These are sunspot regions, fields of intense magnetism 1,000 to 10,000 times as strong as that of the Earth. The yellow arrow gives the scale of this satellite photo. 31,000 km is about 2.5 times diameter of Earth, so you can see that sunspots are quite large.

Also noticeable in the background are the bright regions called *faculae*, which means "small torches" in Latin. Faculae are also magnetic fields but their field strength is significantly weaker than that of sunspots. For the sake of simplicity here, we may consider faculae as bright spots. We shall return to the role of the faculae in a minute.

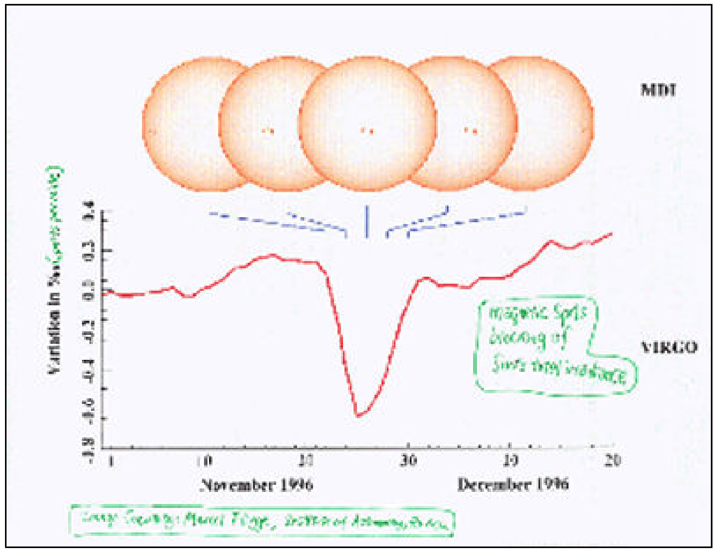

Figure 2

Here is what happens when a large sunspot or group of sunspots rotates past the central meridian facing Earth. We have determined that the total output of light energy from the Sun’s surface drops significantly, but the key question remains: does this light blocking effect of sunspots, which is caused by the 27-day rotation of the Sun, also affect year-to-year changes in solar energy output?

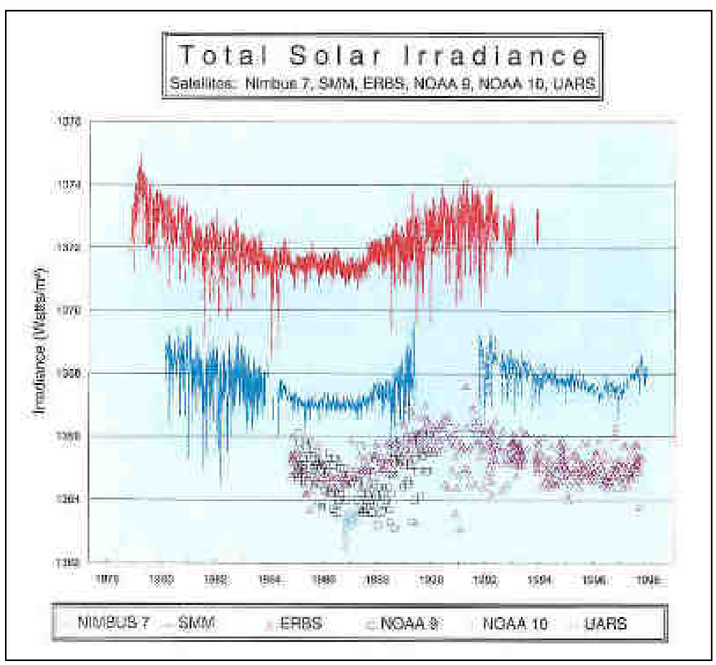

Figure 3

We learned some surprising new facts in the 1980s. Shown here is the total sunlight energy measured by different instruments onboard six different satellites.

First, these figures show an effect that runs counter to intuition. Observe the period between 1980 and 1990: this is a period of what is called "solar activity maxima," when there are more sunspots than usual. Also remember that sunspots occur in well-documented 11-year cycles. But in this chart, we see that during sunspot activity maxima, that is, with more sunspots blocking the sunlight, the Sun is actually brighter rather than dimmer! This is why I said this observed fact is counter-intuitive, since the implications from the previous chart [Figure 2] do not apply here. Apparently, when the Sun's magnetic activity is high, the area covered by the magnetic field of faculae increases even more than the dark spotted area. So the net effect is that the total light output of the Sun tends to be higher during activity maxima than activity minima.

This chart makes clear another fact: despite our best efforts, we cannot measure the total solar light energy precisely - the range of unknown is something like 7 to 10 W/m^2. There are important implications here for signal detection in Earth's climate (like determining the impact level of CO_2 arising from human activity) but that is beyond the scope of my discussion here.

The third thing to note from this chart is that we have only some twenty years of data. This may or may not be enough to say anything useful about longer-term variations, such as changes over the last hundred years. I emphasize this because our current knowledge of solar physics has not allowed us to develop adequate theories or empirical rules to tell us much more. So we could use some help from other sources.

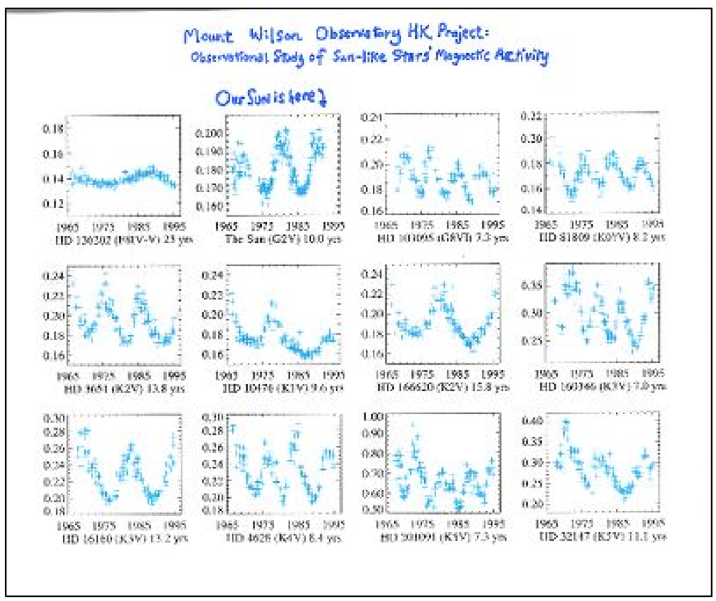

Figure 4

This chart demonstrates one of the most promising and practical ways of getting information on long-term changes in the Sun's total light energy. The principle is simple: our Sun is one of many so-called "lower main-sequence" stars. By carefully and patiently observing a group of stars with physical properties similar to the Sun, we may be able to deduce some likely behaviors of our Sun, based on statistical probabilities and guided, of course, by our understanding of physics.

Shown here are the fruits of some thirty years of dedicated effort at the Mount Wilson Observatory (led by my colleague Sallie Baliunas): this is the HK Project, named after the two specific spectra lines of ionized calcium which allow us to derive the information on magnetic variations. In this chart, I have plotted the variation in magnetic activity of twelve sun-like stars, including the Sun. Indeed, we observe that sun-like stars display a range of magnetic variability similar to what our Sun has shown (through sunspot records) over the last 350 years. The behaviors include cyclical change, such as our sun is presently displaying, and the flat or non-varying Maunder's Minimum-like activity of the mid- to late- 17th century. (A Maunder's Minimum period is a time when almost all the sunspots disappear from the surface of the Sun. The best-known Maunder's Minimum period lasted from about 1645 to 1715. This is quite distinct from the times of sunspot activity minima, where the spots disappear only for a few months.)

By collaborating with several of our astronomer colleagues, we have been able to collect enough information on both magnetic and total light variability of sun-like stars to tell us something about what could have happened on our own Sun. We came up with numbers in the range of 0.2% to 0.7% change in solar light output for the type of variation likely to occur during a Maunder minimum period and during the 1900s.

The range of uncertainty of our results for sun-like stars is also large, but let us posit a mean change of 0.4 to 0.5% in the Sun's brightness over the last 100 years in a climate model to see what happens.

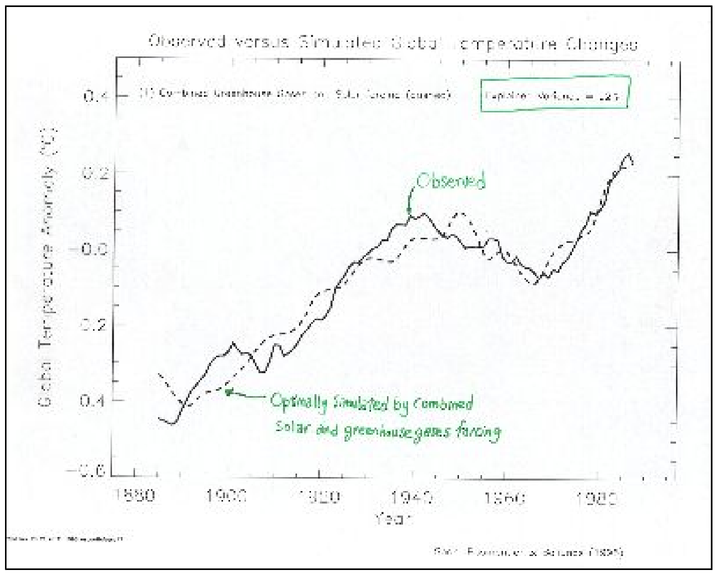

Figure 5

Here are the results. In this model experiment, we have considered both the changes in the energy inputs from the Sun and the greenhouse gases created by human activity. The 92% best-possible correlation to the known worldwide surface temperature readings (considering only these two parameters) is quite remarkable. Of course, here we are studying the slower response of the climate system to the changes caused by Sun's light and man-made greenhouse gases on time scales of decades to centuries, which is why you do not see the bumps and wiggles of interannual changes. We shall come back to this point later on.

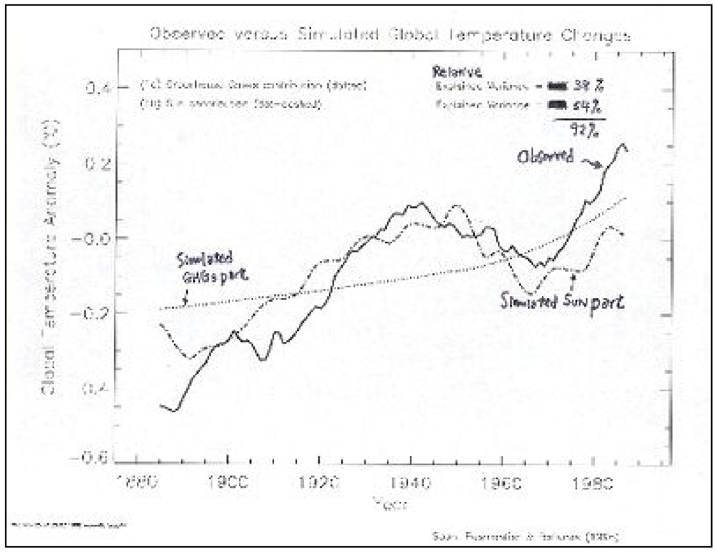

Figure 6

As for the split between solar energy imput and greenhouse gases, here is what we get: almost half of the explained variance comes from the Sun, while greenhouse gases contribute the remainder.

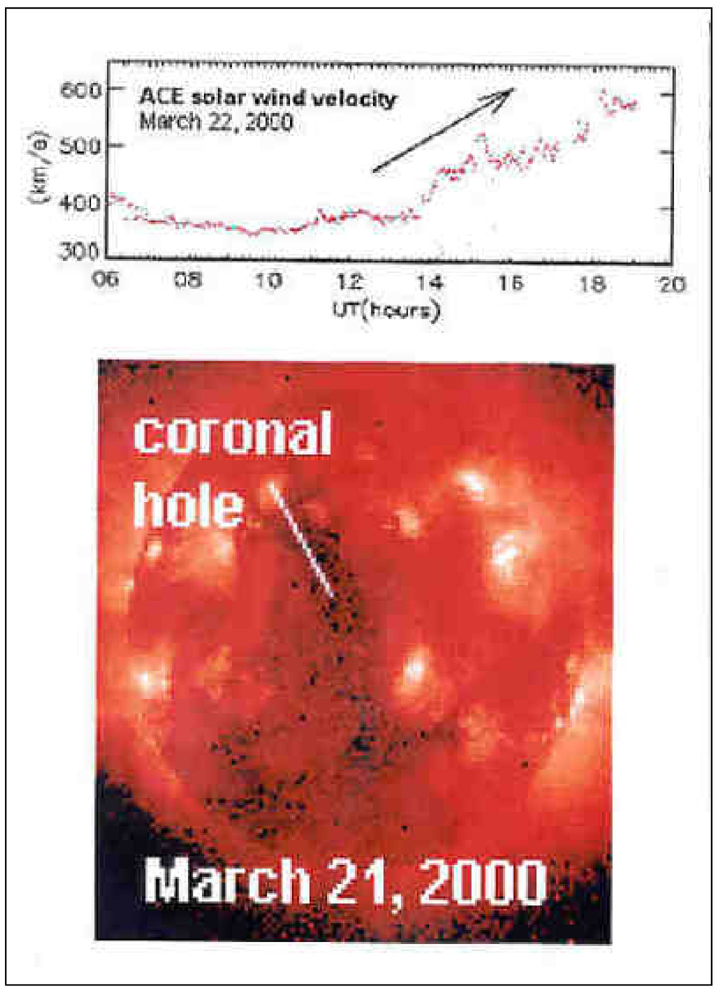

Figure 7

We now move on to the final part of the talk. It has long been understood that light energy output is not the only aspect of the Sun that changes. Let us now examine the Sun by means of x-rays to illustrate the most dramatic feature of the corona, the one- to two-million degree outer layer of the solar atmosphere. The particular feature emphasized in this picture is the coronal hole, which is simply a region of opened magnetic field lines (lines of force) that project from the Sun out into the solar system. Sunspots, on the other hand, are closed magnetic field regions.

Much of this hot gas can escape into the solar system through the coronal holes with their opened magnetic field lines and this gaseous material actually reaches the Earth. In contrast, the gases near sunspots are confined within the Sun itself by the closed magnetic field lines.

I would like to point out that size of the coronal hole and the number of sunspots are inversely related. This means that when the solar magnetic activity is at a maximum, there are more sunspots, as mentioned before, but the coronal hole area becomes smaller. In the times of activity minima, coronal holes tend to be larger while there are fewer sunspots on the Sun's surface. We are still trying to fully explain this empirical fact, but apparently the opened magnetic field structures (represented by coronal holes) and the closed magnetic field structures (represented by sunspots) tend to crowd each other out. I hope this explanation is sufficient for now.

The most important fact to remember is that coronal hole is the point of exit for the fast solar wind, a hot stream of charged particles flowing at about two million miles an hour. By contrast, the normal speed of the solar wind is about one million miles per hour.

For the purpose of this article, it is also important to note that the changes in open magnetic field structure of the coronal hole can either deflect or enhance some of the cosmic rays coming from deep space and thus controlling the amount of cosmic rays which can enter the earth.

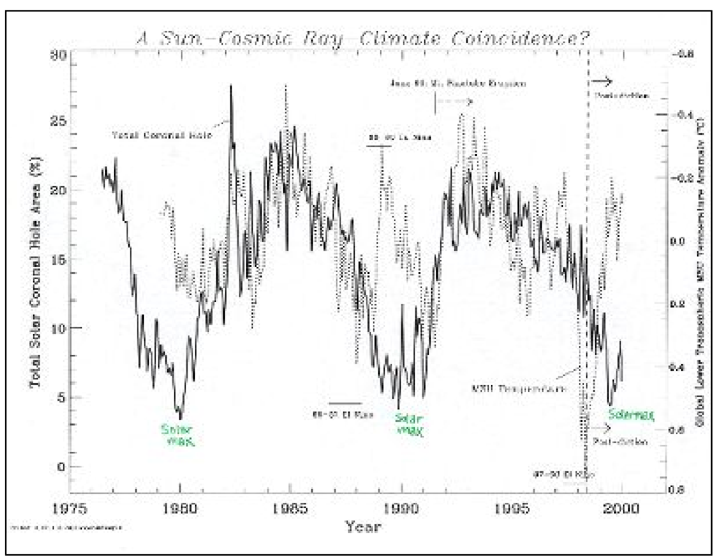

Figure 8

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What else can we say about the Sun’s coronal hole? Here, I show a most interesting correlation between the coronal hole and the temperature of the Earth’s lower troposphere. This data is taken from the well-known satellite records of atmospheric temperature constructed by Drs. John Christy of the University of Alabama and Roy Spencer of NASA-Huntsville.

Note that the temperature scale is inverted in this chart, so cooler is up and warmer is down. I have also marked the time when the correlation is first seen (around April-June 1998), so that all future disagreements or agreements can be examined impartially. Note also that the correlation in this chart is weaker since 1999 but as discussed below, this disagreement may be expected near solar maxima.

There are 3 more things to note in this chart.

First, the obvious instances of weak or nonexistent correlations: here we see changes due to El Niño in 1997-1998, La Niña in 1988-1989, and the June 1991 eruption of Mount Pinatubo. These are known climatic variations that can be readily explained by internal factors of the climate system. So we may be relieved that this study shows that solar changes don’t cause all climatic problems on Earth!

Second, note that there may be hints of symmetry in the timing of correlations and non-correlations. Periods of poor correlation appear near solar maxima, when coronal holes are smaller and formed more sporadically over the solar surface; for this reason we would expect their effect to be less. Periods of good correlation are found around activity minima. These are indeed the times when we see very large and stable coronal holes and we would expect greater effect from these holes.

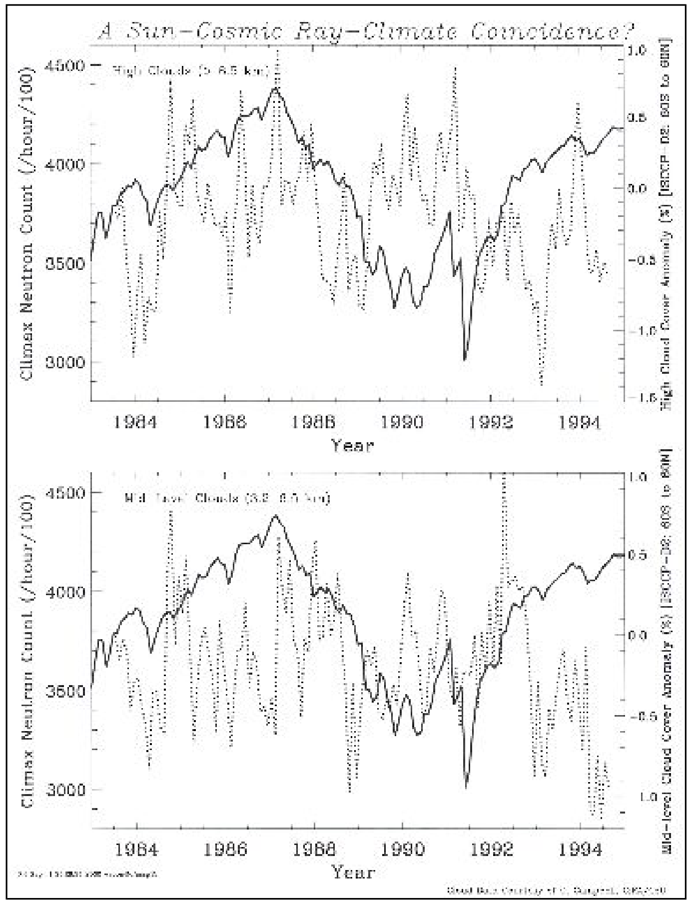
Third, note that the correlations shown in this chart suggest that the global lower troposphere temperature gets cooler during activity minima. These are times when we observe more charged particles from the fast solar wind and especially more cosmic rays.

As I said earlier, cosmic-ray charged particles travel near the speed of light and so they are a lot faster than charged particles from the solar wind. It is also important to note that their faster speed allows cosmic rays to penetrate much deeper into the Earth's atmosphere. In fact, as these cosmic rays interact with the molecules in our atmosphere, they create significant ionization of the air. Along with terrestrial sources of concentrated radioactivity like radon, cosmic rays are the primary cause of ionization in the troposphere. We shall see that this sometimes-neglected fact may turn out to be quite relevant for the discussion of climate change.

This search leads to two more questions:

1) How can we explain the observed correlations?

2) Is there any additional evidence to support this novel idea that cosmic and solar charged particles influence Earth’s climate?



Figures 9 and 10

We should note two negative results, in conformity with proper scientific practice. In this chart, we are looking for any link between cosmic rays and other important climatic variables like clouds.

We plotted the cosmic ray time series (as measured by the neutron counts shown as a solid line in the chart) versus the best currently available satellite-generated cloud cover data (dotted curve). Nothing interesting happens for the high-altitude and mid-level clouds.

But when we examine the low-level clouds, we find another surprise. The low-level clouds appear to be very closely linked to the cosmic ray flux. More cosmic rays may be related to greater ionizing flux for the lower atmosphere, which ultimately stimulates the formation of low clouds. (The complicated details are likely to be described in terms of the role of atmospheric ionization in affecting the growth and production of aerosol particles.) Without going into detail, we do know that low clouds like marine stratus clouds reflect a lot of incoming solar radiation, overwhelming the effects from other cloud types, and so cool the lower atmosphere.

Thus, more incoming charged particles during solar activity minima correlated with more low clouds and hence a relative cooling. This is consistent with what we just saw.

We are very fortunate that the checking does not just end here. We can ask if there are any other ways to test whether energetic charged particles influence the lower atmospheric variables. In today's case, we are happy to point to the work of our colleague, Dr. Wes Lockwood of Lowell Observatory in Arizona. Dr. Lockwood has been patiently recording the changes in brightness of the planet Neptune for almost twenty-five years now. What is most interesting in this record is the clear indication of a correlation between changes in Neptune's brightness and the number of sunspots, which Dr. Lockwood used as an activity indicator for changes in cosmic rays. As you may know, Neptune's brightness is caused primarily by reflection from its white methane clouds. In Dr. Lockwood's record, we may be seeing a cosmic ray modulation of the methane cloud albedo or areal coverage or both. This is consistent with what we have just seen about Earth's liquid water and ice clouds.

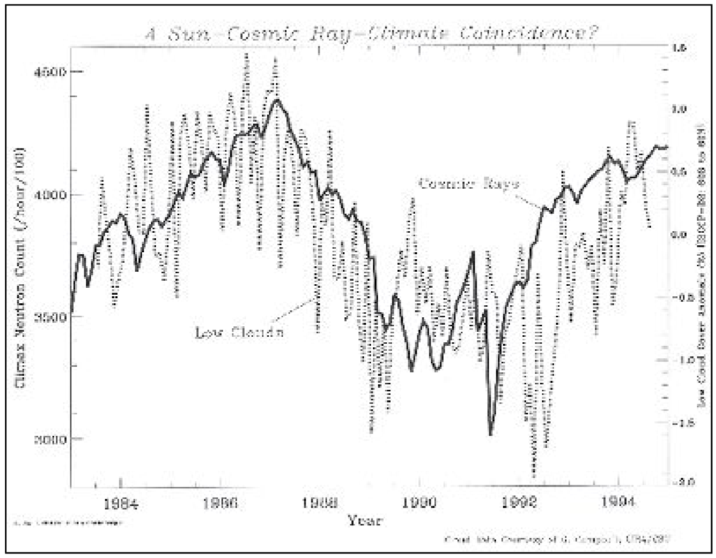


Figure 11

But of course, skeptics may still object that these are just statistical freaks. In this case, let me read you a sensible response written some 25 years ago by a distinguished solar-terrestrial relation researcher:

> "Would it then be fair to conclude with Solomon that there is no new thing under the Sun? Not entirely - for, although in one sense additional correlations may add nothing new, they may lead to an acceptable mechanism for the necessary interaction between the Sun and the lower atmosphere of the earth. If only this could be defined, the whole controversial field might be rapidly translated into realm of high respectability."
>
> "A Hundred Years of Controversy over Sunspots and Weather" A. J. Meadows, *Nature* (1975), vol. 256, p. 97

Let me summarize. I hope I have shown that the search for the physical linkages of sun-climate relations is very much ongoing and alive today. We are just beginning to amass sufficient data about physical mechanisms of climate change to be able to subject them to a proper scientific process of hypothesis formulation and, more importantly, hypothesis falsification.

Most of the research I have discussed today is less than five years old and some of it, such as the section on cosmic-ray ionizing flux modulation of low clouds, is indeed work in progress. We have been very fortunate to benefit from advances in observational capability in order to study important variables in both the Sun's energy output and the Earth's climate system. I should also like to emphasize the value of studying of sun-like stars to better understand the dynamics of our own Sun and solar system.

I hope that you will now agree with the Professor Jack Meadows' conclusion that it is premature to dismiss all these statistical correlations. Our intent was to define and investigate relevant physical links between Sun and climate, as have many other researchers. I suggest that after more than one hundred years of controversy, these correlations have been detected too frequently and too clearly to be mere coincidences. Further analysis of these data should help us learn how changes in the radiant and particle energy of our Sun affect Earth's climate. This research is especially important if we are to have a clear understanding of how climate behaves on many timescales.

Most important of all, if we wish to establish a scientific hypothesis of global warming relating to human activity and a public policy based on this, we must accelerate our research on this source of natural climate change. And to establish a scientific hypothesis, we must continue to work strenuously to investigate all possible physical mechanisms affecting the sun-climate relation and *try to rule them out*. This statement may be surprising, but this is the necessary scientific procedure.

To leave you with a more encouraging note in support of future studies on the sun-climate connection, I would like to borrow a few lines from Mark Twain:

"It's not the things [we] don't know that fool [us].

It's the things [we] do know that ain't so."

ENDNOTE

I am publishing my first popular book with a colleague from Ericsson Radio System of Stockholm, Mr. Steven Yaskell, on the sun-climate connection. If you are interested, here are the specifications (or email me at wsoon@cfa.harvard.edu for more details):

Title: Cycles of the Sun: The E. Walter Maunders and the Maunder Minimum

Scope: Not intended as a textbook, but good as adjunct reading in college-level astronomy, astrophysics, or environmental/atmospheric science courses

Publisher: Harcourt/Academic Press

Sponsoring Editor: Jeremy Hayhurst, Senior Editor (jhayhurst@acad.com)Expected Publication Date: March 2001

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