Central Coast Climate Science Education
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A "Grand Solar Minimum" Would Not Cause a new "Little Ice Age"

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Background

As the sun goes through it sunspot cycle of about 11 years it passes through a "solar maximum" where it exhibits quite a few sunspots and then goes through a "solar minimum" where there may be long periods of time where no spots at all appear.

Complex changes in the local and overall solar magnetic field occur during these cycles. During the course of these cycles the sun changes its overall brightness *very slightly* over the course of these 11 year cycles, being brightest during the time of solar maximum. It might seem counter-intuitive that the sun is brightest when it has the most relatively darker spots, but that is more than compensated for by brighter than average regions on the sun during times of solar maximum.

For many years it has been realized that over the past hundreds of years there have been periods when this normal 11-year cycle was replaced by a period when hardly any spots appeared at all. The most famous such interval of such a "grand solar minimum" was called the "Maunder Minimum" (see: https://en.wikipedia.org/wiki/Maunder_Minimum) A somewhat less extreme case is referred to as the "Dalton Minimum" (https://en.wikipedia.org/wiki/Dalton_Minimum)

The Maunder Minimum occurred during roughly, but not exactly, the same period as the "Little Ice Age" during which western European temperatures were unusually cold. (See https://en.wikipedia.org/wiki/Little_Ice_Age .)

As discussed below, it is now possible to reproduce with some confidence the brightness of the sun going back over 1000 years, and the result of this research is that over this period there have been five notable "grand solar minima."

It has been suggested that the Maunder Minimum was the dominant cause of the "Little ice age." The preponderance of the evidence though, is that the "Little Ice Age", unlike the current human-driven warming, was not a global cooling *simultaneously affecting the entire globe.* The severest cooling was confined mainly to portions of Europe and North America. Moreover, it is not at all clear that solar dimming was the primary cause. An

increased level of volcanic eruptions during this period may have been a major contributor, since dust from eruptions has a cooling effect on the climate.
See this discussion: https://eos.org/articles/the-little-ice-age-wasnt-global-but-current-climate-change-is)

Similarly with the Dalton Minimum, which was certainly affected by the spectacular volcanic eruption of Mt. Tambora in 1815, the most powerful eruption in recorded human history. The ash spread around the world, blocking sunlight, and resulted in the infamous "year without a summer".

Nonetheless, it may have been that these Grand Solar Minima have caused significant widespread cooling of the earth, and there is some speculation that another Grand Solar Minimum may be in the offing and that we should therefore prepare for an impending period of cold weather. ***The main purpose of this essay is to argue that such a concern is unwarranted.***

A similar discussion of this topic has recently been posted on a NASA website and I recommend it; the conclusion reached is the same but I have included in this essay a more quantitative discussion than in this NASA post: https://climate.nasa.gov/blog/2953/there-is-no-impending-mini-ice-age/)

The Solar Cycle

What gives rise to the solar cycle with its sunspots and related phenomena? There are complex fluid motions in the sun, involving upwelling convective currents in the sun's outer third of the sun and these are strongly affected by the fact that the sun rotates, and at different speeds, depending upon location in the sun. Since the gas in the sun is completely ionized (i.e., electrons have been stripped from their atoms) the gas is an excellent conductor of electricity. These fluid motions can induce electric currents, which in turn generate complex magnetic fields. and it is the changing configuration of these magnetic fields which give rise to the solar cycle and associated sunspots.

I think it is fair to say that a full understanding of the solar cycle is therefore still not available and there is disagreement among solar astronomers about how intense the next solar cycle will be, let alone reliably predict whether or not we are headed for another Grand Solar Minimum.

For example, Dr. Irinia Kitiashvili, a solar astronomer at the NASA Ames Center, predicts that solar cycle #25, (the one now beginning,) whose peak is expected around 2025, *will be the weakest in 200 years.* Popular accounts of her work also quote her as predicting an impending Grand Solar Minimum, though I cannot find a direct reference to a publication or presentation of hers making such a prediction.

In any event, a panel of solar astronomers sponsored by NOAA and NASA drew a different conclusion regarding solar cycle 25:

"The panel has high confidence that Solar Cycle 25 will break the trend of weakening solar activity seen over the last four cycles. 'We predict the decline in solar cycle amplitude, seen from cycles 21 through 24, has come to an end' said Lisa Upton... panel cochair...'there is no indication we are approaching a Maunder-type minimum in solar activity' " (see https://www.weather.gov/news/201509-solar-cycle)

Nevertheless, let's assume that some sort of long term event like the Dalton or Maunder Minimum will shortly take place and see what its consequences might be. To avoid getting bogged down in the complex processes which affect the earth's climate I will make some simplifying assumptions about the earth's energy budget, for it is the changes in the flow of energy into and out of the earth which governs changes in the climate such as those which we are now experiencing.

Energy balance and energy imbalance

To a very high degree of accuracy, the only energy *input* into the earth's climate system is from the sun. But not all of this energy is absorbed by the earth's surface or atmosphere: reflective things like clouds, snow and ice reflect a fraction back to space. The average of this fraction is called the earth's *albedo*, symbolized by the Greek letter α. So $(1 - \alpha)$ is the amount of solar energy that *is* absorbed by the earth's surface and atmosphere.

The primary source of energy *output* from the earth's surface is infrared radiation, which depends upon the temperature of the earth's surface. Part of this radiation does not escape but is redirected back down to the earth's surface by the greenhouse gases and water vapor in the atmosphere.

(For the different role that water vapor plays from the "long lived, well-mixed" greenhouse gases like CO_2, see: http://www.centralcoastclimatescience.org/uploads/5/3/8/1/53812733/topic5_ghgs_stevek.pdf especially page 8.)

About 60% of this infrared energy radiated from the earth's surface escapes into space.

I will only consider carbon dioxide (CO_2) in comparing the relative importance of a grand solar maximum with the effect of the current level and rate of increase of greenhouse gases.

If, over a fairly long period of time, no significant change in either the sun's brightness or the amount of greenhouse gases occurs, then the long-term average surface temperature of the earth will adjust so the amount of escaping infrared radiation balances the amount of absorbed incoming solar energy. In other words, the earth will be in energy balance.

We can state this in words: Energy absorbed from the sun = infrared energy radiated back into space

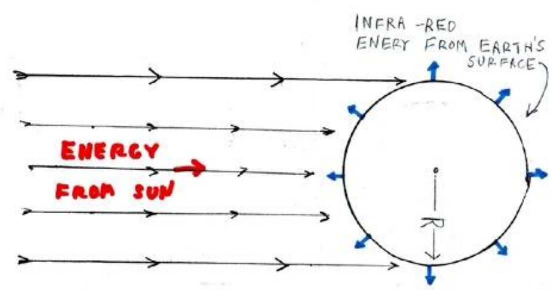
Or, in terms of mathematical language:

(1) $\pi R^2 F(1-\alpha) = 4\pi R^2 \sigma T^4 \beta$

Don't be intimidated by this equation--it is easy to understand.

The symbol R stands for the radius of the earth, while F stands for the rate at which solar energy falls on a square with an area of one square meter, with that square surface being perpendicular to the incoming solar energy. (A square meter is about 11 square feet). The value of F is about 1,361 watts for every square meter--a lot of energy: which is why there is so much interest in harnessing solar energy.

In the following diagram the edges of a circular bundle of solar rays which will intercept the earth is shown. Recall from geometry that the area of a circle is πR^2, so $\pi R^2 F$ is the total amount of solar energy intercepted by the earth every second.



Now let's consider the other side of equation #1: $4\pi R^2 \sigma T^4 \beta$. The small blue arrows in the figure indicate the outflowing infrared energy radiated from every square meter of the earth's surface. The amount of energy radiated from every square meter is approximately given by a basic law of physics called Stefan's law, or sometimes the Stefan-Boltzmann law. It says that the amount of this radiated energy is proportional to the 4th power of the surface temperature (which must be measured on the Kelvin temperature scale, starting from 'absolute zero'), multiplied by a numerical constant represented by the Greek letter σ.

That is where the σT^4 comes from. The "T" in this expression is an appropriate average, since of course the actual temperature varies over the surface of the earth.

Because of the greenhouse gases in the earth's atmosphere, not all of this energy escapes into space, as described above. Only a fraction of this energy does, and I have represented that fraction by the Greek letter β, which as I have noted above, is presently about 0.6. The value of 0.6 can be directly measured by measuring from space the escaping infrared radiation at the top of the atmosphere, compared to the amount radiated at the earth's surface. Since the surface area of a sphere is given by $4\pi R^2$, $4\pi R^2$ times $[\sigma T^4\beta]$ gives us the amount of energy radiated away by the earth. This will be equal to $\pi R^2 F(1-\alpha)$ *provided* the earth is in energy balance.

A lot of things cancel out on the left side and right side of equation one and after doing this and doing a bit of simple algebra we get the equivalent statement of the earth being in energy balance, written as equation two:

(2) $F(1-\alpha)/4 - \sigma T^4\beta = 0$

Note that we divided both sides of equation one by the "4" so 4 now divides the left side of equation 2.

Of course, the earth has never been precisely in energy balance. But over the last few thousand years, since the end of the last ice age, it has been very nearly so, as attested to by the very stable globally averaged climate over this time.

But the earth is now definitely out of energy balance. Why is this and how do we know? The 'why' is because humans have rapidly added CO_2 and other greenhouse gases to the earth's atmosphere. This has caused the fraction of escaping infrared radiation represented by β to *decrease* so that the earth is no longer in energy balance. We know this because we have measured the increased heat energy being stored in the various components that make up the earth's climate system, especially the ocean.

But because the oceans can store a huge amount of energy without having a large temperature increase, the resulting temperature has only increased slightly and cannot "keep up" with the increasing trapping of heat from continued increase of the greenhouse gases. (For an entertaining illustration of the huge "heat capacity" of the ocean, watch this short video:
https://www.jpl.nasa.gov/videos/oceans-of-climate-change)

We will represent this state of affairs by letting the letter E stand for the current energy imbalance. So, writing this statement as an equation it looks like:

(3) $F(1-\alpha)/4 - \sigma T^4\beta = E$

The energy imbalance E in equation (3) is currently a positive number: More solar energy is being absorbed by the earth than the earth is radiating out to space.

Climate scientists can directly measure the value of F as well as the albedo, α, and the amount of globally averaged escaping infrared radiation, $\sigma T^4\beta$, although these measurements are difficult.

The results of these measurements are that the value of the albedo turns out to be about 0.3 and that the earth is out of energy balance by about 0.8 watts per square meter.

(Another way of estimating the amount of this energy imbalance is to measure the rate at which the earth's climate system, especially the ocean, is accumulating energy.)

This value of 0.8 watts per square meter is just a tiny fraction compared to the total amount of incoming solar energy but it is what is driving the rapidly changing climate we are now seeing.

Now, (finally!) let's consider what would happen to the positive energy imbalance, E, if the sun were suddenly to enter into a "grand solar minimum."

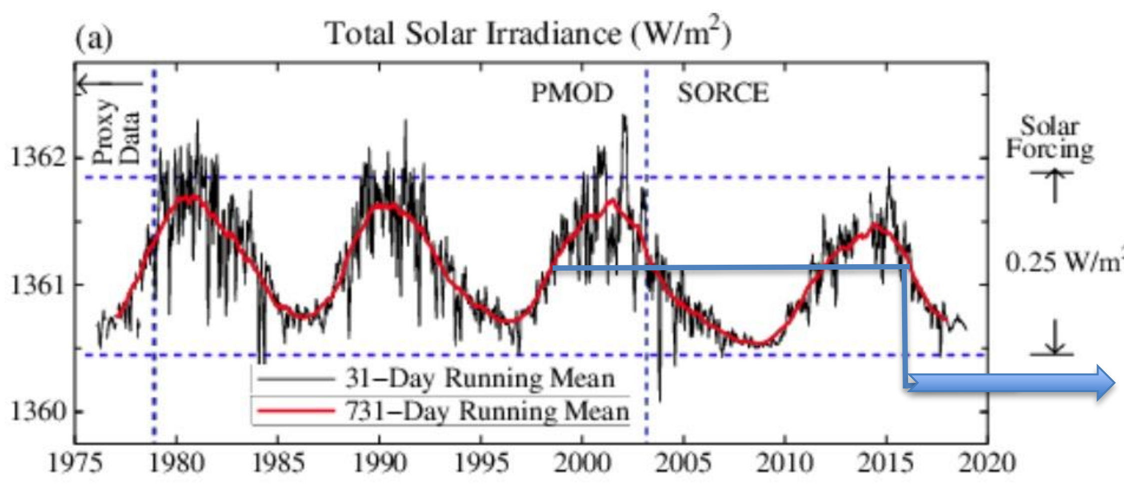
This will cause a change in equation (3) as F, the radiation per square meter from the sun, is suddenly changed, causing the energy imbalance to be suddenly changed. For the moment I will assume no change in the amount of trapping of greenhouse gases, so that there is no *change* in the quantity $\sigma T^4 \beta$ I will represent this situation by modifying equation (3):

(4) $(\Delta F)\ (1-\alpha)/4 = (\Delta E)$

(The capital Greek letter Δ is generally used to represent a small change in a quantity.)

Recent measurements and historical reconstructions of solar brightness

What is a reasonable value to assume for the decrease in solar brightness, (ΔF), for such a grand solar minimum? We don't really know for sure since it is only since the space age that accurate measurements of the sun's brightness have been made. These measurements are shown in the following graph. The scale on the left is the value of F. I will explain below the solid blue line and blue arrow I have drawn in.



You can clearly see the variation in solar brightness that roughly repeats about every 11 years. The important number is not the approximately 1361 watts per square meter but the *very small change from solar maximum to solar minimum relative to the average value.*

Since no such space-based measurements existed before 1975 and even accurate ground-based measurements in the 20th century were difficult, how can one reconstruct the history of solar energy going back centuries which can act as a guide for what one might expect from a new grand solar minimum?

The answer is that one uses 'proxies' for the solar energy. That is, measurements that were available, or can be recovered, that go back many centuries and act as indirect measurements for the solar energy. As noted near the beginning of this essay, a lot of progress has been made in developing two such 'proxies'.

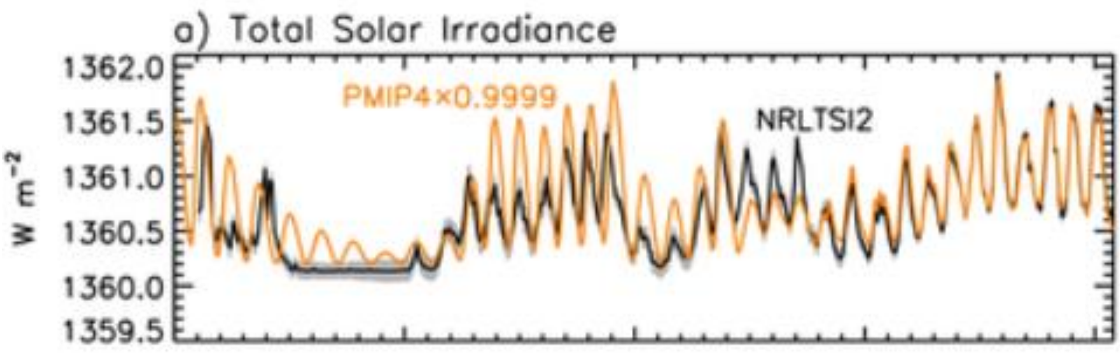
The first proxy is the number of sunspots recorded from year to year, and the invention of the telescope enabled astronomers to keep sunspot records from the early 1600's. By comparing recent sunspot records with the accurate space-based measurements the relation between sunspot number and solar brightness can be calibrated.

A second proxy makes use of the variation in cosmic rays reaching the earth from interstellar space as the change in the sun's magnetic field with the solar cycle causes changes in the shielding of these cosmic rays by the sun's far reaches of its magnetic field.

When these cosmic rays enter the earth's atmosphere and crash into the nitrogen or oxygen atoms making up most of the earth's atmosphere they may 'chip off' parts of the nucleus of these atoms ("spallation") producing rare types (isotopes) of the carbon atom (C^{14}) and the beryllium atom (Be^{10}.) The number 14 for carbon refers to the sum of the number of protons (6) and the number of neutrons (8) in that isotope of carbon, compared to the more common 6 protons and either 6 or 7 neutrons for carbon. Be^{10} has 4 protons and 6 neutrons compared to the common 4 protons and 4 neutrons of Beryllkum.

When these two isotopes are produced by cosmic rays, they are quickly incorporated in trees or ice and by counting tree rings or similarly the ice core yearly layers, it is possible to reconstruct the yearly variation in the intensity of cosmic rays and how they changed with the variable shielding with the sun's changing magnetic field. These can be calibrated against the sunspot record. These two proxies have revealed 5 grand solar minima over the last 1000 years or so.

Here is the result of the reconstructed solar brightness beginning with the year 1600.



To avoid including some extraneous material I have cut off some other graphs which included the scale of years. The plot starts at 1600 CE and ends at just past 2000, each larger tick mark is an interval of 100 years with the small ones at 10 year intervals. The orange and black curves show the results from two different reconstructions.

The Maunder minimum is very clearly marked and runs from around 1650 to 1700. The Dalton minimum is about as deep but of shorter duration, running from 1800 to 1840. The Maunder minimum drops to an average value of F of about 1360.2 Watts per square meter. Let's assume that the value of F in the hypothetical new grand minimum drops to this value

What value should we take for the current value of F for estimating the value of ΔF in equation (4)? Because of the large "sluggishness" of the ocean in responding to energy changes ("thermal inertia") it would be best to average over the value of F in the last couple of solar cycles and for that value from the graph of the recent space measures of solar brightness I have adopted 1361.2 This results in a value of ΔF of 1.0 Watts per square meter.

This is the origin of the solid blue line and arrow I have drawn in the graph of the space-based solar energy. So, the assumption we are making is that suddenly there was a drop of this magnitude in solar brightness and that it stays indefinitely at that level.

Consequences of a drop in solar brightness and continued CO2 emission

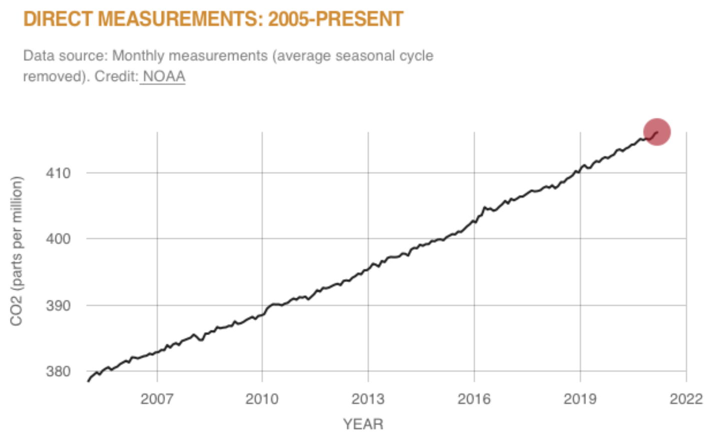
With (ΔF) being a negative number of 1.0 watts per square meter , and (1- α) = 0.7 and then dividing by 4, we get from equation 4 for ΔE a negative value of about -.175 Watts per square meter. Since before this imaginary grand solar minimum we started with a *positive* energy imbalance of 0.80 Watts per square meter, we would still be left with a *positive* (warming) energy imbalance of about 0.625 Watts per square meter.

In other words, even if β, the fraction of escaping infrared energy, had stayed the same, the earth would continue to warm, though at a slightly smaller rate.

But in fact, we are continuing to *increase* the amount of CO_2 and other greenhouse gases so β, the fraction of infrared radiation escaping, will continue to *decrease*, leading to more trapping of infrared heat. This will quickly offset the slight change in the energy imbalance brought about by the hypothetical grand solar minimum.

How quickly?

Here is a plot of the recent history of the change in the amount of carbon dioxide in the earth's atmosphere which NASA and others monitor:



From this graph I estimate that the amount of carbon dioxide is currently increasing at the rate of about 2.3 parts per million every year. The latest NASA measurement puts it at about 418 parts per million.

By calculating how the amount of heat trapping changes with increasing carbon dioxide (and verifying this by observations) climate scientists have worked out a simple formula for how the amount of escaping infrared energy changes as the amount of carbon dioxide changes. This change, the "radiative forcing" from carbon dioxide, is given approximately by a simple formula:

(5) Decrease in escaping infrared energy = 5.35 * ln(C/Co) in Watts per square meter.

(See this very good Wikipedia article, in particular section 3.2)
https://en.wikipedia.org/wiki/Radiative_forcing)

In this formula, "ln" stands for the natural logarithm, C is the amount of CO_2 in the atmosphere (in parts per million) at some time in the future and Co is the amount at some instant.

Normally the change in this 'radiative forcing' and other "forcings" are referred to some time at the beginning of the industrial revolution. (For a discussion of the concept of 'forcings' see
http://www.centralcoastclimatescience.org/uploads/5/3/8/1/53812733/topic2_forcings.pdf

But for this imaginary case, when the hypothetical dimming occurs, we will take the value of Co to be its present value of 418 parts per million. We can then calculate what value of C would be required for the change in the radiation forcing to offset the 0.175 watts per square meter decrease in the energy imbalance associated with our hypothetical solar dimming.

The answer is that the carbon dioxide level, C, would need to increase from 418 to about 432 parts per million. But from the graph of CO_2 above we conclude it is changing about 2.3 parts per million every year. *This means it would only take about 6 years for the initial decreased warming to be offset by increasing carbon dioxide. Subsequently, warming will have resumed at about the same rate as before the dimming and will continue to increase as long as we continue to increase the amount of CO_2 in the atmosphere.*

Concluding remarks

That a change in solar energy of an amount comparable to the variation from maxiumu to minimum during the solar cycle should have a rather small effect is not so surprising. A study by Professors Ka-Kit Tung (Univ. of Washington) and Charles Camp (Cal State Cal Poly) required a very sophisticated analysis of the recent surface temperature of the earth to extract the small solar cycle influence against the rising surface temperature record and its random fluctuations caused by phenomena like El Nino.
(See their paper here:
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2007GL030207)

As it happens (coincidentally) the decrease in solar brightness I chose in the illustrative example I have illustrated above is about the same as the typical difference between solar maximum and solar minimum. The Camp/Tung analysis found a temperature swing of only about 0.2 degrees C from maximum to minimum associated with the solar cycle. This back and forth swing of 0.2 degrees between solar maximum to minimum is about the same as the background increase in the average global temperature *per decade* since 1980, though the rate of global warming over the past decade 2010 to 2020 has been somewhat greater.

A caveat to this discussion is that the change in total solar brightness is not the only effect of the solar cycle on the climate. During the solar cycle there are changes in the amount of the sun's ultraviolet energy output which influences the ozone layer and thus the temperature of the stratosphere. This causes short term variations in regional climate but has not been demonstrated to contribute to an overall energy imbalance.

Recall from the discussion above that the solar cycle involves variations in shielding of cosmic rays as the sun's magnetic field changes. This enabled the 'proxies' of isotopes of carbon and beryllium to be used to estimate changes in solar brightness. It has been suggested that such changes in cosmic rays might influence the amount of cloudiness, hence the albedo of the earth and thus the energy balance (see equation 3.) But the evidence for this is not considered convincing by most climate scientists.

Incidentally, the small 0.2 degrees C "fingerprint" of the solar cycle that Camp and Tung found necessarily includes these two possible effects of the solar cycle, in addition to the slight variation in solar brightness, so their effects on global temperature cannot be very large.

From this discussion I conclude that we should not worry about a little ice age associated with a possible grand solar minimum. We should instead continue to try to reduce, and eventually eliminate, the rise in greenhouse gases caused by burning fossil fuels, knowing that we will also have to adjust to the continued warming and associated climate change which we cannot avoid.

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