

Fig. 1. Global surface temperature anomalies (relative to 1880-1920) in 2016 and 2020.

## Global Warming Acceleration

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**Abstract.** Record global temperature in 2020, despite a strong La Niña in recent months, reaffirms a global warming acceleration that is too large to be unforced noise – it implies an increased growth rate of the total global climate forcing and Earth’s energy imbalance. Growth of measured forcings (greenhouse gases plus solar irradiance) decreased during the period of increased warming, implying that atmospheric aerosols probably decreased in the past decade. There is a need for accurate aerosol measurements and improved monitoring of Earth’s energy imbalance.

November 2020 was the warmest November in the period of instrumental data, thus jumping 2020 ahead of 2016 in the 11-month averages (Fig. 1). December 2016 was relatively cool, so it is clear that 2020 will slightly edge 2016 for the warmest year, at least in the GISTEMP analysis.

The rate of global warming accelerated in the past 6-7 years (Fig. 2). The deviation of the 5-year (60 month) running mean from the linear warming rate is large and persistent; it implies an increase in the net climate forcing and Earth’s energy imbalance, which drive global warming.

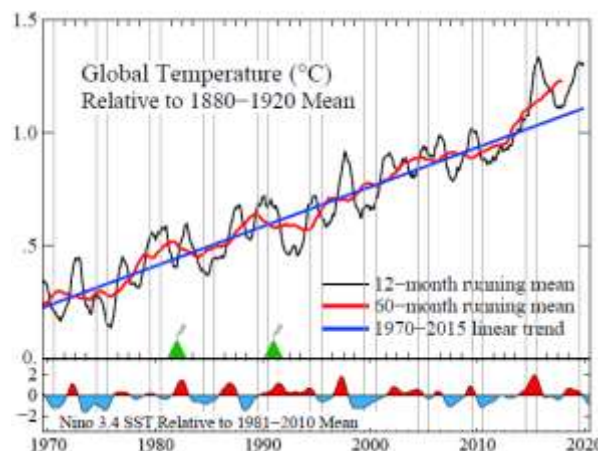
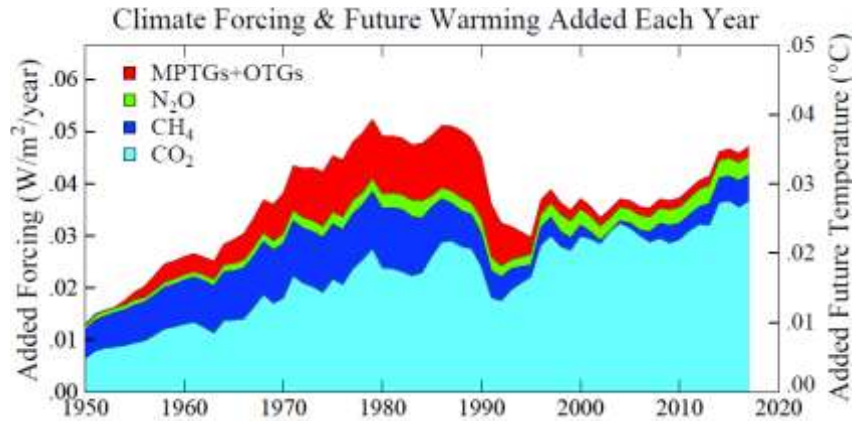


Fig. 2. Global temperature and Niño3.4 Index through November 2020.

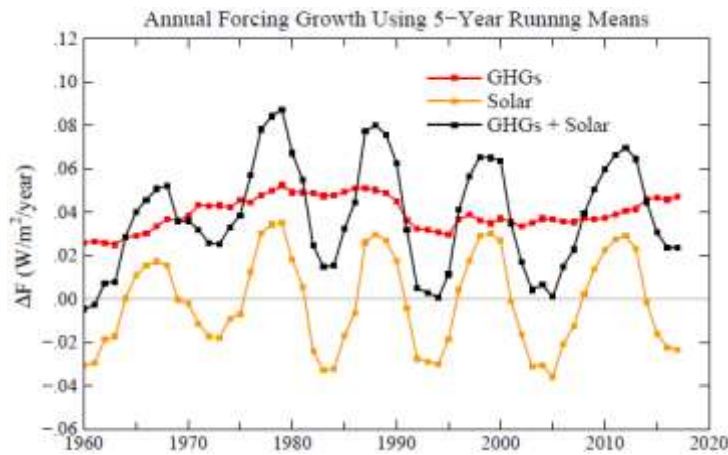


**Fig. 3. Annual growth of GHG climate forcing (red is trace gases, mainly CFCs).**

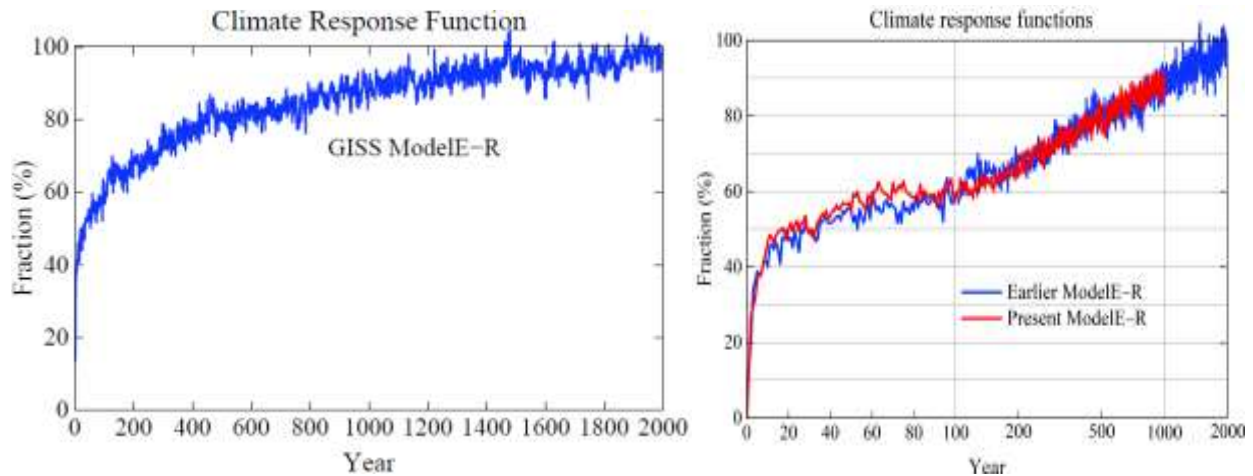
Variability of the 12-month running mean about the linear warming trend in the past 50 years is mainly unforced variability associated with ENSO (El Niño Southern Oscillation). The two largest deviations of the 60-month (5-year) running mean are forced deviations. The 1980s bump is from the CFC bump in the greenhouse gas (GHG) climate forcing growth (Fig. 3). The early-mid 1990s valley is the cooling due to the volcano of the century (Mt. Pinatubo).

The GHG climate forcing growth rate has accelerated in the past decade (Fig. 3), but not enough to account for the observed acceleration of the global warming rate. The validity of this conclusion becomes clearer when we look at the total measured climate forcing – the black curve in Fig. 4 – which is the sum of the GHG and solar climate forcings. During the period of global warming acceleration – 2015-2020 – the climate forcing growth rate due to measured forcings was a minimum.

Global warming is driven both by Earth’s current energy imbalance than by the recent growth of net climate forcing. The most recent several years have the largest effect on current warming. Even if you are not a physicist or mathematician, this is easy to understand – and by taking the trouble to understand, you can say that you understand Sir Isaac Newton’s calculus.



**Fig. 4. Black curve is the net annual change of measured climate forcings, GHGs + Solar.**



**Figure 5. Climate model's response function: fraction of the final response versus time. In the graph on the right the first 100 years are expanded with a log scale for remaining years.**

Fig. 5 shows the response function for GISS model E-R based on a 2000 year run for an instant CO<sub>2</sub> doubling with fixed ice sheets, vegetation distribution, and other long-lived GHGs. The expanded time scale for the first 100 years in the graph on the right shows that about a third of the response is obtained within the first 5 years. The remaining 2/3 is recalcitrant (slow).

The climate response function,  $R(t)$ , is the fraction (%) of equilibrium surface temperature response to an applied forcing as a function of time. Expected global temperature change is the forcing added this year times response function for year 1, plus forcing added last year times the response function for year 2, plus the forcing added the year prior times the response function for year 3... You get the idea. In equation form we write

$$T(t) = \int S R(t) [dF/dt] dt,$$

where  $T(t)$  is temperature anomaly at time  $t$ ,  $S$  is climate sensitivity ( $\sim 3/4^\circ\text{C}$  per  $\text{W}/\text{m}^2$ ),  $R(t)$  is the response function at year  $t$ , and  $dF/dt$  is the forcing added in year  $t$ .  $dt$  is just one year if you are adding up the pieces in one-year blocks – with a computer, we let  $dt$  be smaller. This simple calculation is very accurate (Hansen, 2008) as long as the ocean overturning circulation does not shut down, in which case you need a full atmosphere-ocean model.

We are showing the response function to explain how we know that if the only forcing changes were the GHGs and the Sun (black curve in Fig. 4) there would be no acceleration of global warming in the past five years – indeed, there should be a decrease in the warming rate. The real-world acceleration tells us that there must be another forcing, which is unmeasured. There is only one good candidate: aerosols. Although NASA chose not to measure the aerosol climate forcing (Chapter 33 of Sophie's Planet), some aerosol models suggest that global aerosol amount has decreased in the past decade (Bauer et al., 2020).

BTW, the enquiring mind is probably saying “well if the forcing change in the past five years is expected to leave a significant signature, should we not expect the solar cycle to show up in observed global temperature?” Indeed, the solar curve (yellow curve in Fig. 4) and observed



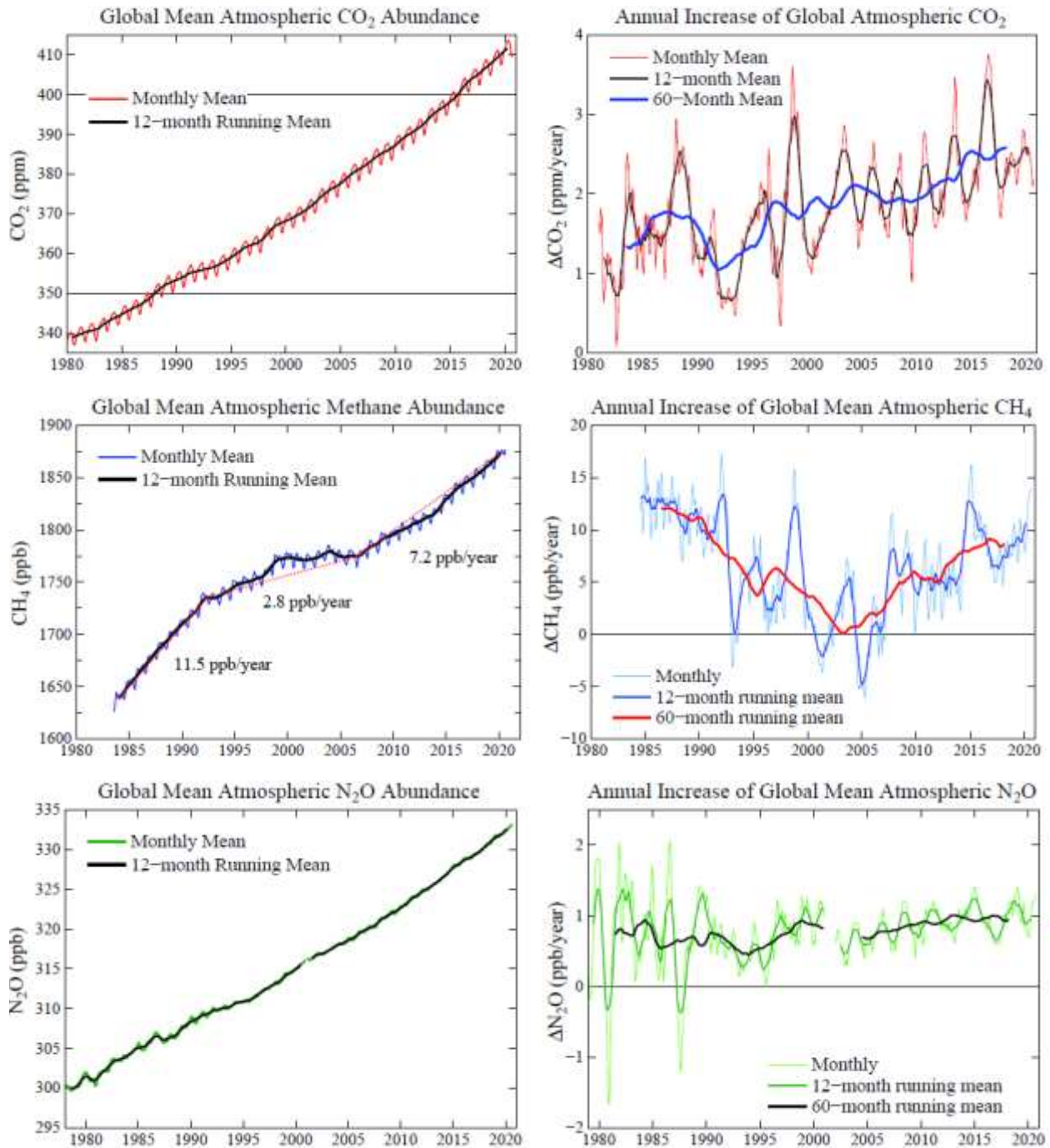
Figure 29. The Faustian bargain. Humans have enjoyed the fruits of the industrial revolution and avoided a large cost in climate change, as aerosol cooling has mitigated greenhouse warming. Payment comes due when humanity realizes that it cannot tolerate the further exponential growth of air pollution that would be needed for continued mitigation of global warming.

Figure 6. Chart 20 of Bjerknes lecture (Hansen, 2008).

global temperature curve have maximum correlation of 47% with temperature lagging the solar forcing by 1-2 years. If Earth were an all-land planet the lag should be  $\sim 0$  years; if an all-ocean planet the lag would be  $\sim$  quarter of the solar cycle, i.e.,  $\sim 3$  years; real world it should be 1-2 years. So, it works out right, despite the large volcanoes in that period.

How large is the aerosol forcing? In recent IPCC reports the GCMs (global climate models) tended to use aerosol forcings in the range  $-0.5 \text{ W/m}^2$  to  $-1.0 \text{ W/m}^2$ , despite the fact that the IPCC radiative forcing chapters suggest a larger (more negative) aerosol forcing, with a direct aerosol forcing  $\sim -0.5 \text{ W/m}^2$  and an indirect aerosol forcing (via cloud effects)  $\sim -1 \text{ W/m}^2$ , with large uncertainty bars. Consistent with the radiative forcing chapters, we (Hansen et al, 2011) made a strong case that the actual aerosol forcing is  $-1.6 \pm 0.3 \text{ W/m}^2$ . We also infer why most GCMs (including the GISS model) “need” a smaller aerosol effect – if they want to match observed global warming in the past century. The reason is that the models mix heat too efficiently into the ocean – so to match observed warming the models need a larger net forcing, which they achieve by omitting some of the negative aerosol forcing.

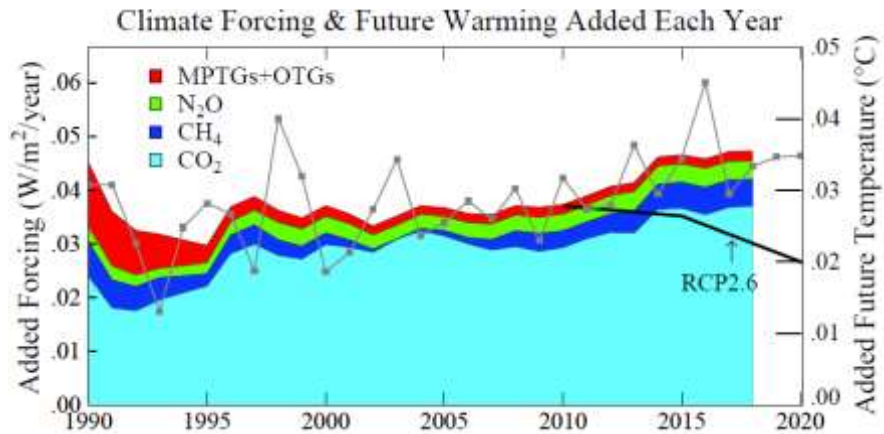
Is this important? Yes. It means that the little blip of extra warming that we got in the past five years is only a down payment on the penalty that young people will pay for our Faustian bargain. Mephistopheles is coming, but it is our grandchildren that he will be dragging off.



**Figure 7. CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O amounts and growth rates.**

Note that the current GCM modeling associated with IPCC, CMIP6 models, include model responses to instantaneous forcing (Smith et al., 2020). It will be possible to infer response functions of different models, and it should be easier to interpret model results.

**Aerosol summary.** Continued ignorance of the aerosol climate forcing, given the importance of aerosols for future climate change, should be unacceptable. The required measurements need to define the aerosol and cloud particle microphysics in detail. We know how to achieve that



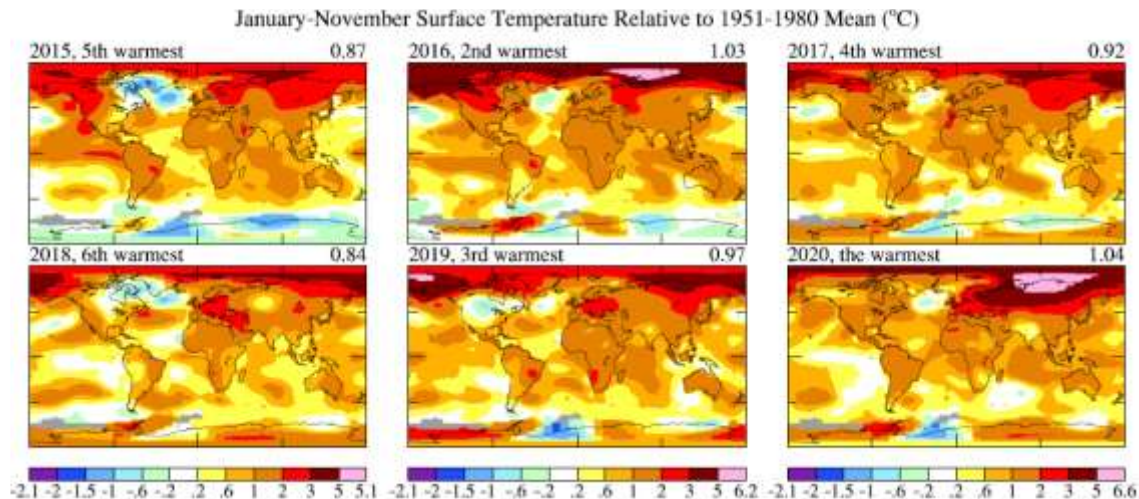
**Figure 8. Annual growth of GHG climate forcing (red is trace gases, mainly CFCs).**

detail – it requires multi-spectral, multi-angle, polarimetric observations of reflected sunlight from space with the polarization measured to an accuracy  $\sim 0.1$  percent (Mishchenko et al., 2007). There should be a dedicated small satellite monitoring program to quantify and monitor the aerosol direct and indirect climate forcings. This is one of the handful of essential measurement – which include GHGs, Earth’s gravity field, and Earth’s energy imbalance – that are needed to interpret climate change and impacts. Earth’s energy imbalance requires maintenance and improvements to the Argo float observations, especially in the regions around the Antarctic ice shelves (von Schuckmann et al., 2020)

**How are greenhouse gas forcings doing, up-to-date?** Are growth rates starting to decline? Not exactly – see Fig. 7. CO<sub>2</sub> growth is down a bit this year, and it should go down substantially in 2021, as the expected response to the strong La Niña now underway. CH<sub>4</sub> growth rate is shooting up, presumably as a result of “fracking,” increased venting at oil wells, and global warming feedbacks from warming wetlands and permafrost. N<sub>2</sub>O growth rate continues to increase slowly (the oscillations in growth rate presumably are variability of the stratospheric sink, related to stratospheric dynamics and stratosphere-troposphere exchange).

Slower CO<sub>2</sub> growth offsets increased CH<sub>4</sub> and N<sub>2</sub>O growth, so our estimate for the added GHG forcing in 2020 is essentially the same as in 2019. The annual forcing increase is shown by the dots on the gray line in Fig. 8. We use the 5-year running mean (in Fig. 3 and Fig. 8) for the colored portion of the chart to minimize oscillatory changes.

Note that the gap continues to grow between the actual growth of GHG forcing and the RCP2.6 scenario that would keep global warming to about 1.5°C. As discussed in our “Young People’s Burden” paper (Hansen et al. 2017), the cost of CO<sub>2</sub> removal to get back on track is likely to be in the trillions of dollars.



**Figure 9. Global temperature anomalies in the first 11 months of each of the past six years.**

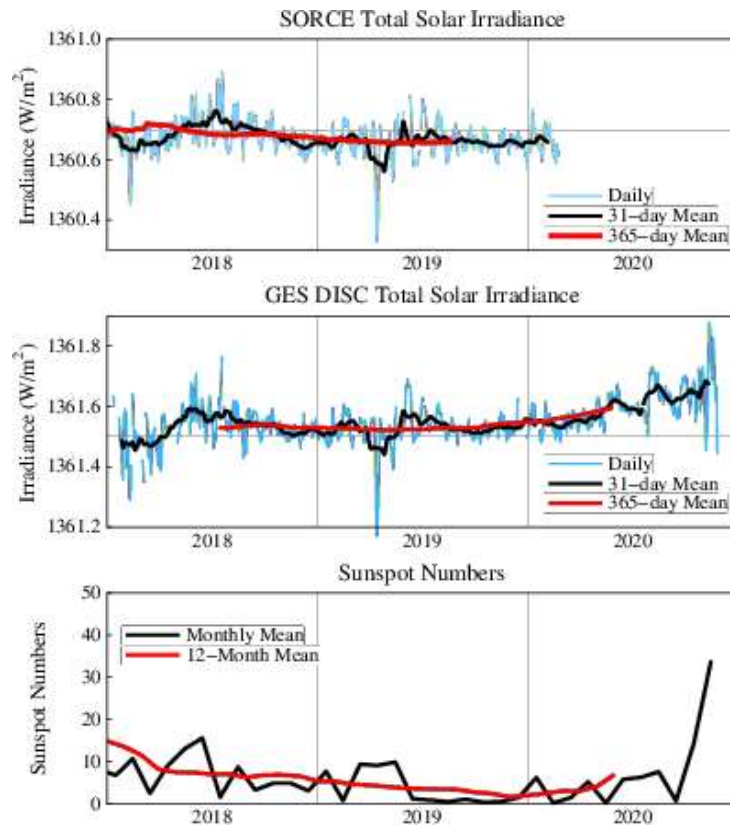
**Temperature maps.** Siberia and the Arctic Ocean had the largest warm anomalies in 2020, but it was warmer than the 1951-1980 average almost everywhere (Fig. 9). The global maps employ 1951-1980 as base period so that good global coverage of data is available for the base period.

**One more thing.** Remember the cry of the climate deniers? Many of them were counting on the Sun to go into a new, prolonged Maunder Minimum. That was possible, although the resulting negative climate forcing (cooling) would be small compared with the human-made GHG forcing.

It turns out that, on the contrary, we are now entering the next solar cycle. Solar minimum was late 2019. The uptick in irradiance is small so far, but the predictions from some solar models are that the coming maximum will be a strong one.

The impact of solar irradiance on global temperature lags solar irradiance by 1-2 years, so we are still at the point where we are getting maximum cooling from the solar cycle. Maximum added push of the solar cycle toward a warmer climate will be in mid-decade, i.e., in about 5 years.

Global temperature prognostication: 2021 will be cooler than 2020, because of the lagged effect of the current strong La Niña. When the next El Niño occurs, perhaps about mid-decade, hang onto your hat. Global emissions of GHGs had better be trending down by then!



**Fig. 10. Satellite measured solar irradiance (top 2 panels) and sunspot numbers. Solar minimum occurred in 2019.**

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