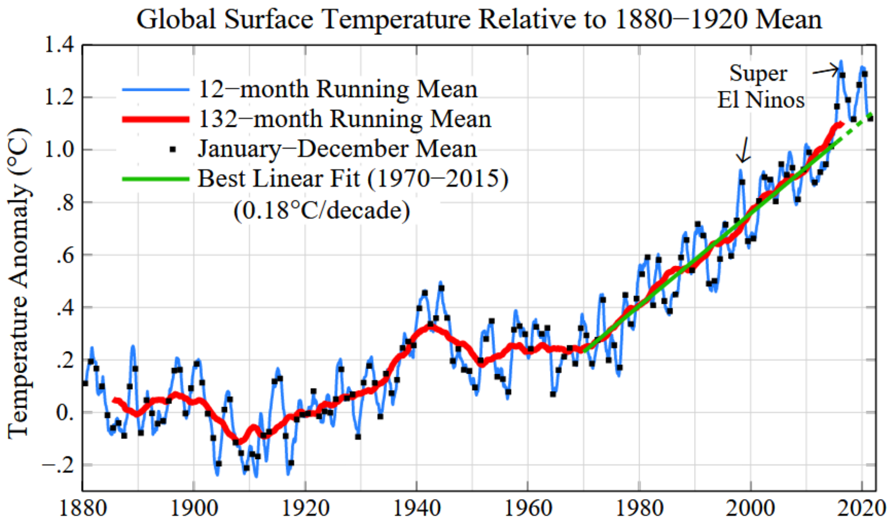

Fig. 1. Global surface temperature relative to 1880-1920 average.

Global Temperature in 2021

13 January 2022

James Hansen, Makiko Sato and Reto Ruedy

Global surface temperature in 2021 (Fig. 1) was +1.12°C (~2°F) relative to the 1880-1920 average in the GISS (Goddard Institute for Space Studies) analysis.[1,2,3] 2021 and 2018 are tied for 6th warmest year in the instrumental record. The eight warmest years in the record occurred in the past eight years. The warming rate over land is about 2.5 times faster than over the ocean (Fig. 2). The irregular El Nino/La Nina cycle dominates interannual temperature variability, which suggests that 2022 will not be much warmer than 2021, but 2023 could set a new record. Moreover, three factors: (1) accelerating greenhouse gas (GHG) emissions, (2) decreasing aerosols, (3) the solar irradiance cycle will add to an already record-high planetary energy imbalance and drive global temperature beyond the 1.5°C limit – likely during the 2020s. Because of inertia and response lags in the climate and energy systems, the 2°C limit also will likely be exceeded by midcentury, barring intervention to reduce anthropogenic interference with the planet’s energy balance.

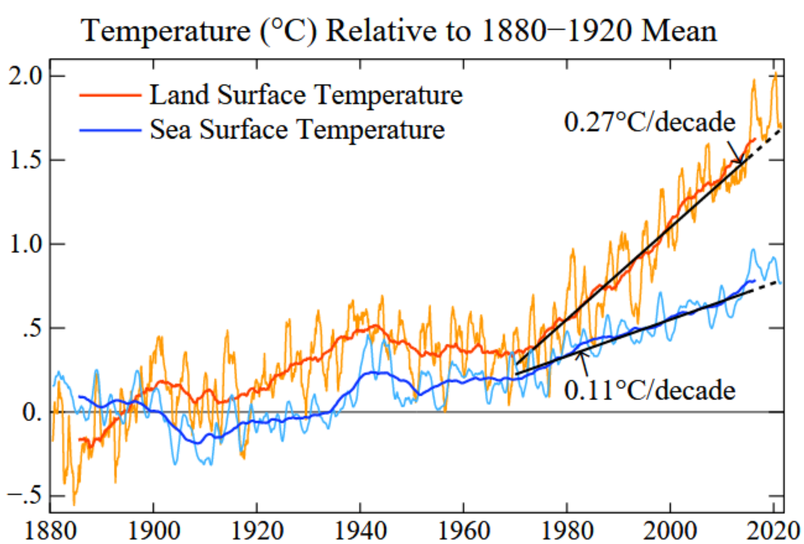

Fig. 2. 12-month and 132-month (thick curves) running-mean land and ocean temperatures.

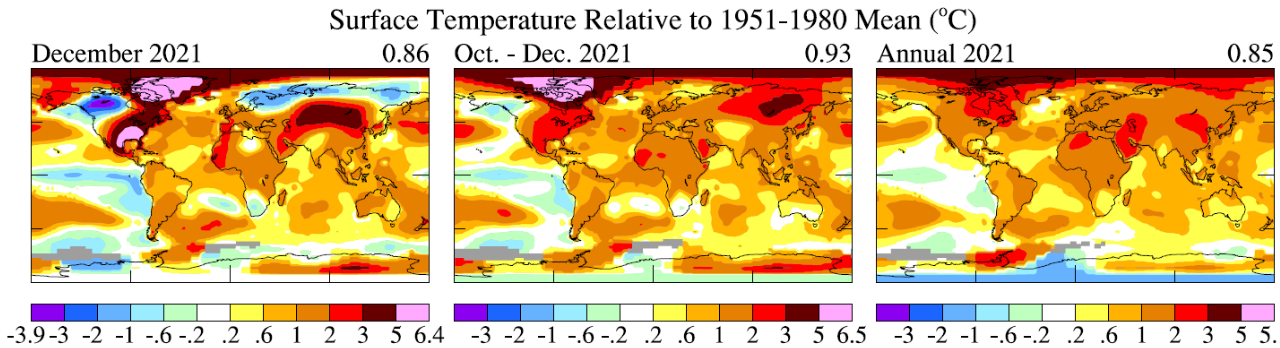

Fig. 3. December, final 3 months, and annual 2021 surface temperature anomalies.

Most interannual variability of global temperature (Fig. 1) is related to the El Nino/La Nina cycle. However, there are two anomalies that stand out and warrant comment: the warming jumps in 1940-1945 and 2015-2021. The 1940-45 warming seems to be largely an artifact of changing, inadequate ocean observations during World War II, as suggested in *Young People's Burden*.[4] This conclusion receives confirmation from Fig. 2: There's no 1940-45 anomaly in the temperature over land, where the thousands of meteorological stations provided time-consistent data from a sufficient number of locations even during the war. If there were such a large anomaly of ocean surface temperature, it would affect temperatures over land, but there is no indication of that in Fig.2. It would be great if data experts (hint to NOAA) would figure out and correct the data problem causing the unphysical hot spots in the ocean during World War II shown in Fig. A2 of *Young People's Burden*.

Accelerated warming of the past seven years requires an explanation. The big jump above the trend line (Fig. 1) is not caused by the ocean exhaling heat. On the contrary, ocean heat content and Earth's energy imbalance increased markedly. As discussed in July Temperature Update: Faustian Payment Comes Due[5] last August, that accelerated warming seems to be caused by a decrease of human-made aerosols; the moderately increased growth rate of greenhouse gases (GHGs) in the past several years cannot account for the observed large increase of Earth's energy imbalance.

Warming over land is much larger than warming over the ocean. The warming rate over land in the past several decades is 2.5 times larger than over the ocean (Fig. 2). Larger warming over land helps explain why climate impacts are becoming much more noticeable even though global warming is now "only" about 1.2°C (mean for past 7 years).

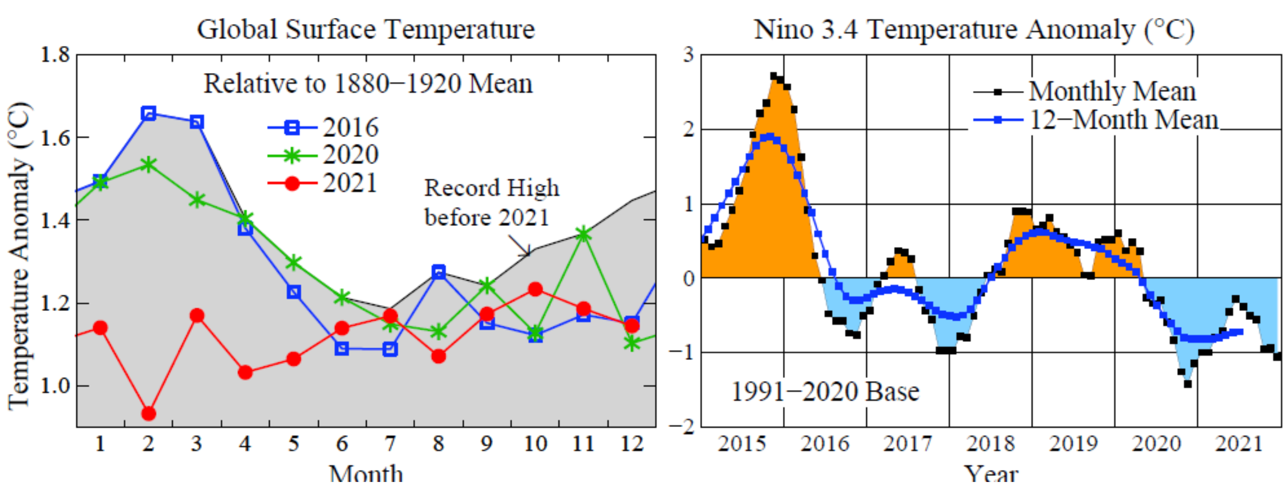

Fig. 4. Monthly global temperature anomaly. Right: Nino3.4 temperature anomaly for past 7 years.

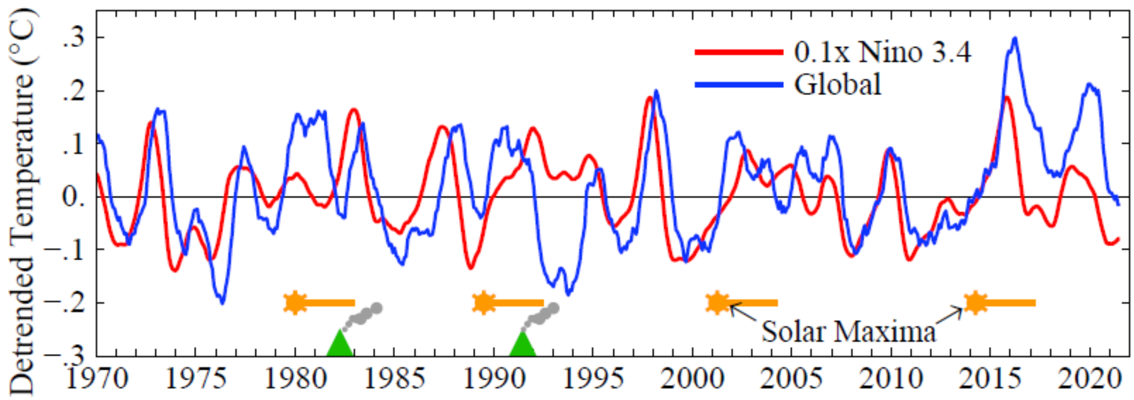

Fig. 5. Correlation of global and Nino temperatures is 60 percent with global temperature lagging the Nino3.4 anomaly by 5 months.

It was unusually warm in the Southeast U.S. and Greenland in December, the monthly average anomaly exceeding +5°C (+9°F) (Fig. 3). Note that La Nina cooling increased at the end of the year consistent with the ongoing double-dip La Nina shown by the Nino3.4 index in Fig. 4.

What are global temperature prospects in the near-term (1-2 years)? The chaotic El Nino/La Nina cycle rules near-term, with exceptions for large volcanoes such as Pinatubo and a small effect of the solar cycle, as discussed in November Temperature Update and the Big Climate Short.[6] Fig. 5, updated from that communication shows the consistent gap in the period 2015-2021 between actual global temperature and what would be expected given the Nino cycle. We will soon be able to see whether this gap continues, disappears, or grows, but near-term global temperature change will be dominated by the Nino cycle.

NOAA's National Weather Service Climate Prediction Center provides a 6-second video that nicely helps us think about near-term prospects. It shows the equatorial temperature anomaly versus depth, which this week shows a positive temperature anomaly at depth 200m propagating from west to east as a manifestation of a downwelling eastward-propagating Kelvin wave. The warm anomaly should arrive at the South American coast in March, which would seem nicely timed to initiate an El Nino later in the year, if the fickle winds of Spring cooperate with an adequate westerly wind anomaly. In that event, given the lags in the system, 2023 will be set up to break prior records for global temperature. Let's look at those lags.

Global temperature, Nino3.4 temperature, and the temperature of the upper 300 m of the equatorial (longitude 100W-180W) ocean are compared in the upper part of Fig. 6 (for the period with data for all three). The Nino3.4 and 300 m temperatures are highly correlated; the Nino3.4 temperature lags by the 4 months that it takes for the temperature anomaly to surface and reach the Nino3.4 area. The Nino3.4 and 300 m temperatures are about equally good predictors of global temperature, both with correlations a bit less than 60 percent. The 300 m temperature provides a longer lead time for a prediction.

Based on the eastward-propagating anomaly in the 6-second video and the 9-month lag, we might say that there is a good chance of an El Nino warming beginning late in 2022 Coupled with the unusual positive global climate forcings discussed in the next section, that El Nino is likely to make 2023 the warmest year in the instrumental record. Even if it's just a little futz of an El Nino – like that in 2018-19 (see Fig. 4) – it could lead to record global temperature.

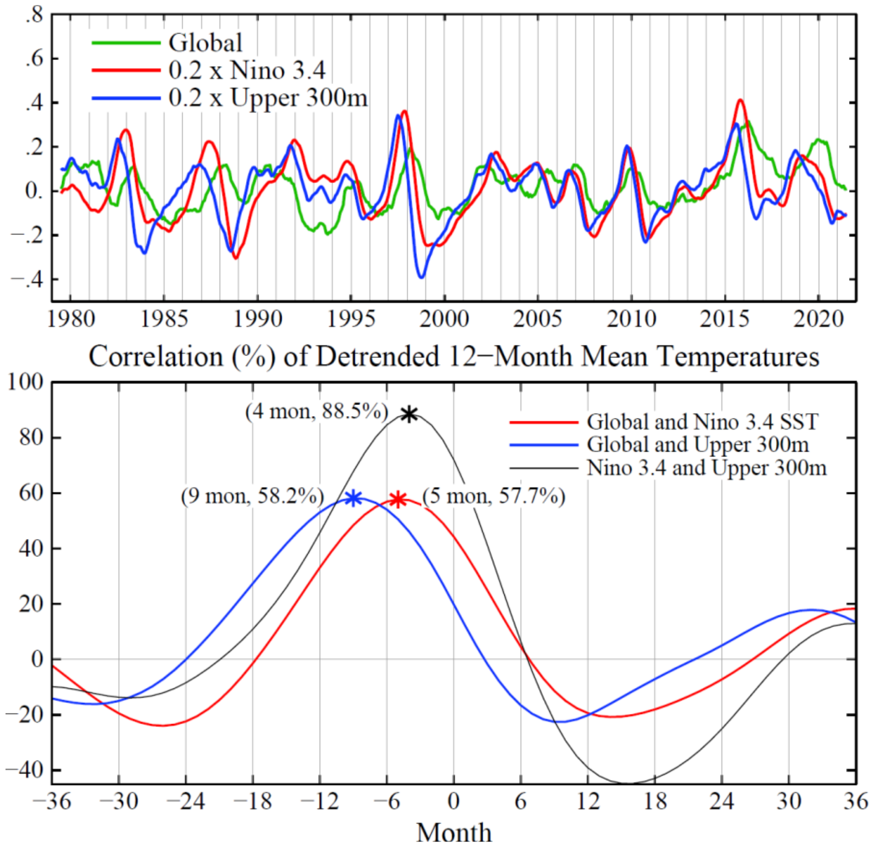

Fig. 6. Global, Nino3.4, and Nino-region upper 300 m 12-month running-mean detrended temperature anomalies and their correlation. Global temperature lags Nino3.4 by 5 months and the 300 m mean temperature by 9 months.

Let's look at NOAA's forecast: Fig. 7. Hmm, no El Nino in their forecast. Mark Cane once said that it's a crapshoot: Nature rolls the dice in the (NH) Spring. Outcome depends on fickle, hard to predict variable winds, especially winds in the central Pacific Ocean. A sufficient westerly wind anomaly can weaken the Bjerknes feedback that tends to keep the system in La Nina mode. Normally, easterly trade winds draw up cold deep water near South America and push cold water westward in the equatorial region. The resulting east-west temperature gradient affects atmospheric pressure so as to strengthen easterly trade winds (the Bjerknes feedback). But if wind anomalies weaken the easterly trade winds, warm water in the west tends to slosh back toward South America, weakening the temperature gradient, weakening the Bjerknes feedback, and reducing upwelling of cold water. That should be basically right – no time to check with Mark. The point is that conditions may be ripe for an El Nino that would begin late in 2022 with a big impact on 2023 global temperature. But El Nino depends on fickle wind anomalies. Prediction for the longer run is easier.

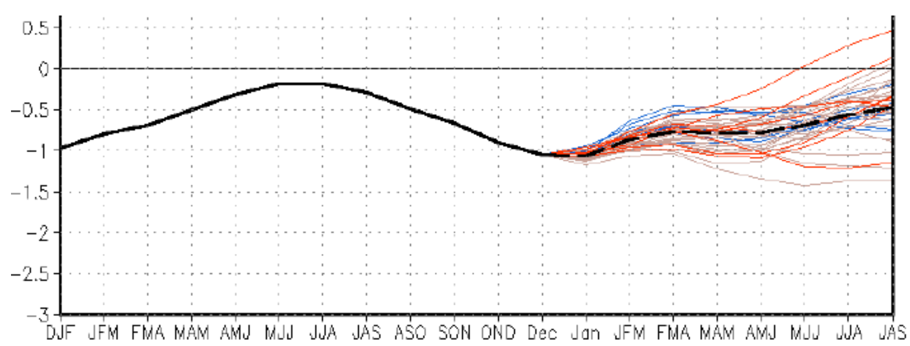

Fig. 7. Latest NCEP forecast.[7] In August the ensemble mean is still in La Nina mode(<0.5C).

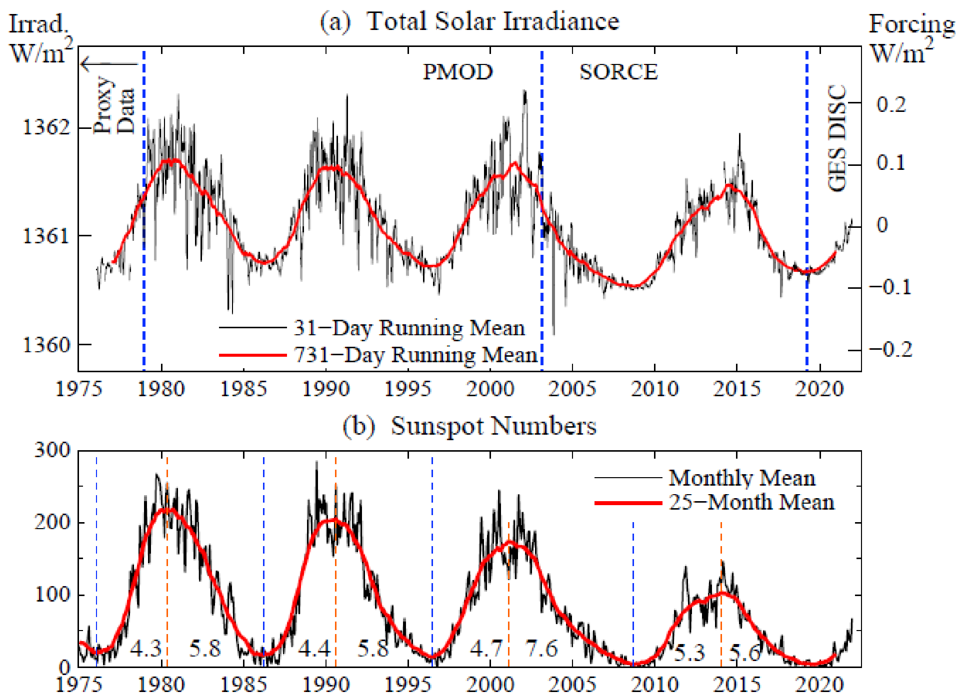

Fig. 8. Solar irradiance and sunspot numbers (data sources are here) .

Long-term global temperature change is driven by natural and human-made forcings. A forcing is an imposed perturbation of Earth's energy balance. For example, if the Sun's brightness increases, the Earth is temporarily out of energy balance – more energy coming in than going out – so it will warm over time (with a lag due mainly to the ocean's thermal inertia) to restore balance.

We have been measuring solar irradiance accurately for almost half a century and have not found a long-term change, but there is a cyclic variability with the solar magnetic cycle of about 0.1 percent (Fig. 8). Earth absorbs about 240 watts per square meter of solar energy (averaged over Earth's surface). So the full amplitude of this cyclic variability of the solar forcing is ~0.25 W/m^2. This should induce a cyclic variability of global temperature with full amplitude only of the order of 0.1°C. That cyclic temperature variability does show up in the temperature record, but it's hard to see because of larger changes associated with other forcings and the variability caused by El Ninos.

A much larger forcing is caused by increasing greenhouse gases (GHGs), i.e., gases that absorb infrared (heat) radiation. Earth's radiation to space emerges from all levels in the atmosphere and the surface, because the opacity of the atmosphere varies with wavelength in the infrared. If the amount of GHGs increases, the opacity increases and the radiation emerges from a higher level in the atmosphere (it emerges mainly from the level where the opacity ~ 1, but you don't need to worry about that). Temperature falls off with height, so the radiation to space decreases when GHGs increase, and the planet will warm up to restore energy balance. It's easy to calculate the energy imbalance (i.e., the climate forcing) caused by any increase of GHG amount – it's a simple radiation calculation, well tested in the laboratory and theory.

The total human-made GHG forcing – from preindustrial time to 2022 – is about 4 W/m^2. This is partially offset by the negative forcing of human-made aerosols (fine airborne particles) that mainly increase Earth's reflectivity, the aerosol forcing being about –1.5 W/m^2.[8] Of the net forcing of

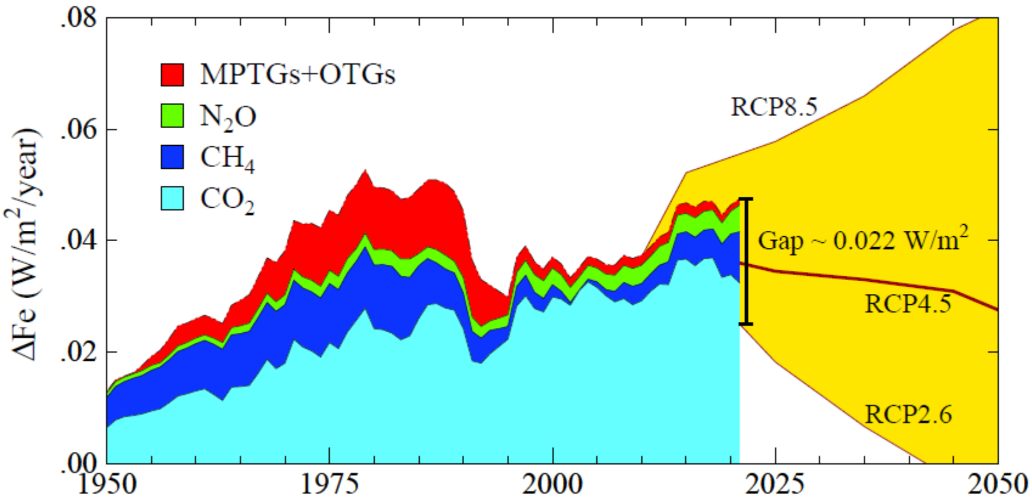

Fig. 9. Annual growth of greenhouse gas (GHG) climate forcing (red is trace gases, mainly CFCs). RCP2.6 is a greenhouse gas scenario designed to keep global warming below 2°C.

about 2.5 W/m^2, about 1.5 W/m^2 has been "used up" in causing the observed global warming of 1.2°C. The remaining 1 W/m^2 is Earth's present energy imbalance.

If we stabilized atmospheric composition at today's GHG amounts, we would get about 0.5-1°C further warming, depending on how long we wait. More on that topic later. The big problem is that we are not stabilizing GHG amounts in the air.

The colorful "truth" diagram (Fig. 9) provides a simple, precise measure of how the largest human-made drive of global warming is changing. This diagram shows how much additional climate forcing is being added each year by the still growing amount of GHGs in the air. It's more than 0.04 W/m^2 per year – that's almost half a watt per decade, and it is not declining. [This diagram is easy to compute because NOAA makes the GHG amounts available promptly, thanks especially to Ed Dlugokencky. Hint to NOAA: you should be pushing for a major award for Ed Dlugokencky, as he provides invaluable service to researchers and humanity.]

At the time of the Paris Climate Accord (2015), popular GHG scenarios were RCP2.6, 4.5 and 8.5, where the numbers are the GHG forcing in 2100. RCP2.6 was designed to keep global warming below 2°C. RCP2.6 has the net growth of GHGs becoming negative during the 2040s. There is a huge gap between the path that the real world is following (the top edge of the red area) and the scenario to keep warming below 2°C. We could close that gap by extracting CO_2 from the air and burying it, but the cost for extraction has reached $2.5-5.1 trillion for the single year (2021).[6]

Of course, these implausible extraction scenarios (negative emissions scenarios that IPCC employs) are not happening and won't happen. This allows us to call out bulls**t when government leaders claim that keeping global warming below 1.5°C is still possible. Even 2°C is practically locked in, barring intervention to reduce anthropogenic interference with the planet's energy balance.[9] That does not mean that the problem is unsolvable, indeed, a bright future for young people is possible, as one of us (JH) wrote[9] and summarized[10] recently.

[1] Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Rev. Geophys.*, **48**, RG4004, doi:10.1029/2010RG000345.

[2] Lenssen, N.J.L., G.A. Schmidt, J.E. Hansen, M.J. Menne, A. Persin, R. Ruedy, and D. Zyss, 2019: Improvements in the GISTEMP uncertainty model, *J. Geophys. Res. Atmos.*, **124**, no. 12, 6307-6326, 10.1029/2018JD029522.

[3] The current GISS analysis employs NOAA ERSST.v5 for sea surface temperature, GHCN.v4 for meteorological stations, and Antarctic research station data, as described in references 1 and 2.

[4] Hansen, J., M. Sato, P. Kharecha, K. von Schuckmann, D.J. Beerling, J. Cao, S. Marcott, V. Masson-Delmotte, M.J. Prather, E.J. Rohling, J. Shakun, P. Smith, A. Lacis, G. Russell, and R. Ruedy, 2017: Young people's burden: Requirement of negative CO_2 emissions. *Earth Syst. Dynam.*, **8**, 577-616, doi:10.5194/esd-8-577-2017.

[5] Hansen, J. and M. Sato, July Temperature Update: Faustian Payment Comes Due, www.columbia.edu/jeh1, 13 August 2021.

[6] Hansen, J., M. Sato and P. Kharecha, November Temperature Update and the Big Climate Short, www.columbia.edu/jeh1, 23 December 2021.

[7] NOAA National Center for Environmental Prediction forecasts are available and updated weekly. A new ensemble of climate model runs is made each week. The blue lines in Fig. 7 are the result of model runs in the most recent release, 10 January 2022. The quantity on the vertical axis in Fig. 7 is the temperature anomaly in the NINO3.4 region. Anomalies colder than – 0.5°C are La Nina conditions; warmer than +0.5°C is El Nino.

[8] Hansen, J., Foreword: uncensored science is crucial for global conservation, in Conservation Science and Advocacy for a Planet in Peril: Speaking Truth to Power, ed. D.A. DellaSala, Elsevier, 2021.

[9] Hansen, J., A Realistic Path to a Bright Future, www.columbia.edu/~jeh1, 3 December 2021.

[10] Hansen, J., "Don't Look Up," the American Dream, and An Appeal, 10 December 2021.