Saving Earth

27 June 2019

James Hansen

I must finish *Sophie's Planet* this year, so I am writing few Communications. However, I make the draft of Chapters 31-34 available here, because my perspective of and conclusion about events in the 1980s differs from that of Nathaniel Rich in *Losing Earth*. I kept careful notes during that era and subsequent years, so I am confident that what I write is accurate, but I would welcome corrections.

Earth was not "lost" ln the 1980s. Earth is not lost today, but time for action is short.

Climate concerns in the late 1980s led quickly to the 1992 Framework Convention: all nations agreed to limit greenhouse gases to avoid 'dangerous anthropogenic interference' with climate. The problem was that neither the 1997 Kyoto Protocol nor the 2015 Paris Agreement directly addressed global energy policies. For the sake of young people, we must understand that failure and take appropriate actions.

It is wonderful that more people are waking up to the fact that we have a climate emergency. The emergency was clear more than a decade ago when it was realized that the long-term safe level of atmospheric CO_2 was less than 350 ppm[1]. Already, we were well into the dangerous zone.

Good policy-making requires an understanding of the time scales of change. The public tends to focus on extreme weather and climate events, because of their great practical importance. However, the 'existential threat' of climate change derives from long-term underlying climate change that affects sea level and the habitability of parts of the world, as well as the magnitude of extreme events.

In *Sophie's Planet* I argue that the climate system's inertia, i.e., its slow response to human-made changes of atmospheric composition, provides us the possibility to avert the existential threat of climate change. But to achieve that end we need to understand not only the climate system, but the time scales for change of the energy and political systems.

Why do I include political systems? My training in physics is relevant to climate and energy systems, but politics? I have witnessed a lot, and I took careful notes. The period includes the Clinton and Obama Administrations, which supposedly tried to address climate change. We need to understand the mistakes.

Political polarization makes solution of the climate problem more difficult. I doubt that political extremes represent most people. I make a case in *Sophie's Planet* for a third party in the United States, aimed at making America America again. American leadership is needed to address climate change.

It will be a lot of work. Polarization did not come about instantly, and it cannot be fixed quickly. Groundwork includes changing to a ranked voting system, so third party candidates are never 'spoilers.' That requires changing some state Constitutions. The party should decide whether/when it is ready to field a presidential candidate. A third party with even a few representatives in Congress can begin to have a big impact. Initially it may be only a force for changing the major parties, but that is a lot.

Our universities and democratic system in the United States have the innovation potential to move us and the world more rapidly to clean affordable energy. Our major parties, both on the take from special interests, share the blame for failing to provide the focus and incentives to develop that potential. In the near-term we must try to affect legislation and candidates for office, but this approach has been failing for decades, so I will argue for a third party that takes no funding from special interests.

[1] Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, 2008: Target atmospheric CO_2: Where should humanity aim? *Open Atmos. Sci. J.*, **2**, 217-231.

My aim here is to summarize the 'existential threat' caused by human-made climate change, what we know about its time scales, and the prospects for averting a disastrous outcome. The science is not settled. We need good science now, more than ever, to help us find a pathway.

I also want to thank the many people who contributed to Climate Science, Awareness and Solutions (CSAS) this year, which has allowed us to continue to function since the Two Gentlemen providing a large fraction of our funding died last year. As soon as the book is finished I must work harder on fund raising, because I believe our group can make some significant contributions. Before losing that long-term funding last year, I hired an oceanographer post-doc, Craig Rye – other team members are Pushker Kharecha (expert in carbon cycle and energy), Makiko Sato (physicist and expert in all data) and Eunbi Jeong (our program coordinator). CSAS also supports several legal cases, as noted below.

You can contribute to CSAS at https://ei.givenow.columbia.edu/#. Be sure to **enter** "Gift for Climate Science, Awareness and Solutions" in the Special Instructions box at Step 3—Payment Information page. If you do not explicitly indicate that the contribution is for our group, we will not see the funds. Alternatively, you can send a check to the following address: John Halpin, Major Gifts Officer, Earth Institute, Columbia University, Hogan Hall, Level A, 2910 Broadway, MC 3277, New York, NY 10025. Checks should be made **payable to** "The Trustees of Columbia University" and must be accompanied by **a note** that the gift is for "Climate Science, Awareness and Solutions." You can find full donation instructions on our support page: http://csas.ei.columbia.edu/support. Eunbi (ej2347@columbia.edu) also can provide assistance.

Delayed climate response[2] – it takes centuries for Earth to adjust to a change of atmospheric composition – is both our *bête noire* and our potential savior. On one hand, delayed response allows *potential* climate impacts to build up before the public notices that something bad is happening.

On the other hand, delayed response also allows the possibility of actions to avert a globally catastrophic outcome. By 'globally catastrophic outcome' I refer to the threat that the planet could become ungovernable over the next several decades, if we do not fundamentally alter our energy systems.

That threat derives mainly from two large-scale climate change impacts. First, low latitudes during the warm seasons could become so hot and inhospitable to human livelihood as to generate an unstoppable drive for emigration. That potential future is emerging into view for regions as populated as India, Bangladesh, Southeast Asia, and huge swaths of Africa. The tragedy would be that these regions are, in a 'less than 350 ppm climate,' among the most spectacular and livable regions on the planet.

The second climate impact is sea level rise, which is an ominous threat on multi-decadal time scales. This sea level threat may be less immediate than the low-latitude, over-heating, climate-change threat, but it is more 'non-linear,' implying that it has the potential to grow exponentially, becoming unstoppable and irreversible. Note that the sea level threat is near-global, because most of the world's large cities and infrastructure are located on coastlines. Nations that would be devastated by large sea level rise include the greatest economic powers of the 21st century, the United States and China.

These two climate impacts are the heart of the 'existential threat.' Current emigration pressure from Central America and the Middle East/Northern Africa, in part climate-driven, provides a tiny preview.

[2] Delayed response is caused by the ocean's thermal inertia and the time it takes for ice sheets to respond to climate change. It happens that amplifying feedbacks exceed diminishing feedbacks in our climate system. Predominance of amplifying feedbacks is why climate exhibits large swings from glacial to interglacial conditions on millennial time scales, even though the forcings that drive those changes are small.

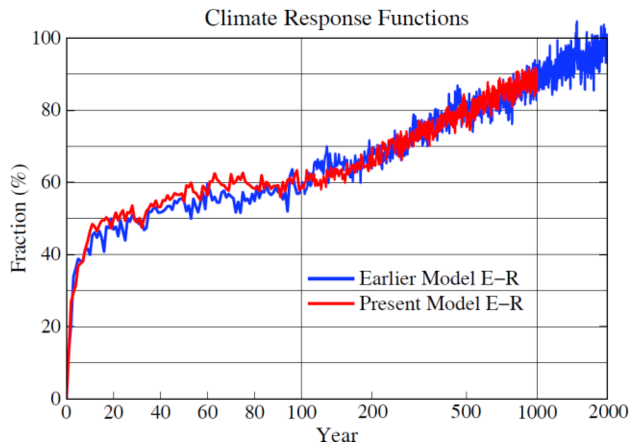

Figure 1. Climate response function, i.e., the fraction of the (fast feedbacks only) eventual (equilibrium) temperature change in response to a climate forcing (Fig. 4 of Hansen et al., 2016).[3] The time scale (horizontal axis) is linear for the first 100 years and logarithmic thereafter.

Discernable impact of global warming on local and regional extremes of the hydrologic cycle are also emerging. These include more extreme precipitation, floods and storms, on the wet side, and an expansion of arid regions, more intense heat waves and fires, on the dry side.

The bad news is that there is more warming in the pipeline, even if we stabilize atmospheric composition at today's level. We know quite accurately how much further warming is already 'in the pipeline,' because we are measuring Earth's energy imbalance, which is +0.75 ±0.25 W/m^2. Given global climate sensitivity of 0.75°C per W/m^2, well-established from Earth's paleoclimate history, that means there is additional warming of about 0.5°C (about 1°F) on the way.

That climate sensitivity, which is 3°C for doubled CO_2, accounts only for fast feedbacks. If we wait long enough for slow feedbacks to occur, such as change of ice sheet size, the warming will be larger.

The good news is that the time scales of these amplifications range from several decades to several millennia. Half of the fast-feedback warming occurs within several years after the gas is added to the air (Figure 1). The other half of this (fast-feedback) warming requires centuries (Figure 1).

This weird temporal response of surface climate change has a simple explanation related to ocean mixing. The second half of the warming requires the deep ocean to warm.

Most of the warming still 'in the pipeline' is associated with deep-ocean warming. Thus most of this 'in the pipeline' warming will not occur this century. This permits the possibility of avoiding most of that warming, if we reduce the amount of gases in the air on the time scale of a century or two.

The time scale(s) of additional warming associated with slow feedbacks is more complicated and uncertain. We[3] concluded that multi-meter sea level rise was likely on a timescale of 50-150 years, if business-as-usual (BAU) emissions continued to 2100. The BAU climate forcing reaches 8.5 W/m^2 this century, equivalent to quadrupled CO_2. Such climate forcing would leave the lower reaches of the ice sheets dripping in rainwater as well as meltwater. The world's coastal cities would likely be doomed, but it is difficult to predict the exact timing of ice sheet collapse.

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[3] Hansen, J., M. Sato, P. Hearty, R. Ruedy, M. Kelley, V. Masson-Delmotte, G. Russell, G. Tselioudis, J. Cao, E. Rignot, I. Velicogna, B. Tormey, B. Donovan, E. Kandiano, K. von Schuckmann, P. Kharecha, A.N. Legrande, M. Bauer, and K.-W. Lo, 2016: Ice melt, sea level rise and superstorms:/ evidence from paleoclimate data, climate modeling, and modern observations that 2 C global warming could be dangerous *Atmos. Chem. Phys.*, **16**, 3761-3812.

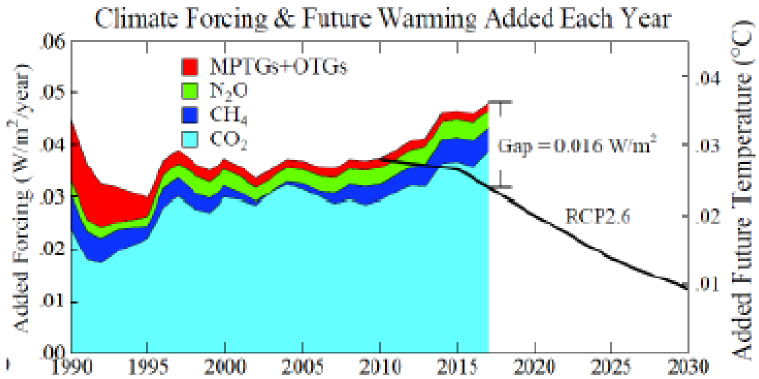

Figure 2. Annual growth of greenhouse gas climate forcing and (right scale) annual addition to equilibrium global warming under the assumption of 3°C global warming for doubled CO_2.

However, the world could and should do much better than BAU, i.e., produce a smaller climate forcing. Global warming in the neighborhood of 2°C or less relative to pre-industrial implies a climate forcing less than half that of BAU. In that event, the magnitude of slow feedbacks this century will be more limited. This pathway would provide a chance of bringing the system under control. We would not necessarily hand young people a climate system running out of control.

After all, the real world today is taking up almost half of human-made CO_2 emissions. With better agricultural and forestry practices, the soil, biosphere and ocean could take up even more CO_2. If we begin to reduce emissions, atmospheric CO_2 will begin to decline long before emissions approach zero.

The really bad news is that the annual growth of greenhouse gas climate forcing is not declining, it is accelerating! Accelerating growth is mainly from CO_2, but methane (CH_4) also contributes (Fig. 2).

The real world is rapidly diverging from the RCP2.6 scenario (Fig. 2) that IPCC (Intergovernmental Panel on Climate Change) devised as a pathway that keeps global warming at approximately 1.5°C.

The gap between reality and RCP2.6 can be closed by extracting CO_2 from the air. A realistic cost estimate for CO_2 capture and storage is now possible. The pilot industrial-scale plant of Keith et al.[4] yields a cost estimate of \$123-252/tCO_2 including the relatively small cost of storage.[5] This corresponds to \$451-924/tC (tC = ton of carbon).

Let us look at the cost of CO_2 extraction for a single year. In 2017 the excess growth of the climate forcing was 0.016 W/m^2. Atmospheric CO_2 must be reduced 1.14 ppm to achieve that forcing reduction.[6] Attaining a CO_2 reduction of 1.14 ppm requires extracting about 2 ppm from the air.[7] Thus we must extract 4.24 GtC (15.5 GtCO_2). The cost in 2017 would thus be \$1912-3918B. In rounder numbers the annual cost of extracting CO_2 is now about 2-4 trillion dollars, and rising. That is the ***annual*** cost.

So we won't do the extraction. Leave the mess for the next generation. It is 'young people's burden.'[8]

[4] Keith, D.W., G. Holmes, D. St. Angelo and K. Heidel, 2018: A process for capturing CO_2 from the atmosphere, *Joule*, **2**, 1-22.
[5] Hansen, J. and P. Kharecha, 2018: Cost of carbon capture: can young people bear the burden? *Joule* **2**, 1405-1407.
[6] Conversion factors: 1 ppm of CO_2 is 2.12 GtC and yields a forcing of 0.014 W/m^2. 1 GtC is 3.67 GtCO_2.
[7] For the same reason that only about half of CO_2 emissions shows up as atmospheric increase, negative emissions (equivalent to a reduction of net emissions) shows up as a reduction of airborne CO_2 by half that amount (for simple carbon cycle calculations and graphs thereof, see Hansen et al., *Plos One* **8**, e81648, 2013).
[8] 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 CO2 emissions. *Earth Syst. Dynam.*, **8**, 577-616, doi:10.5194/esd-8-577-2017.

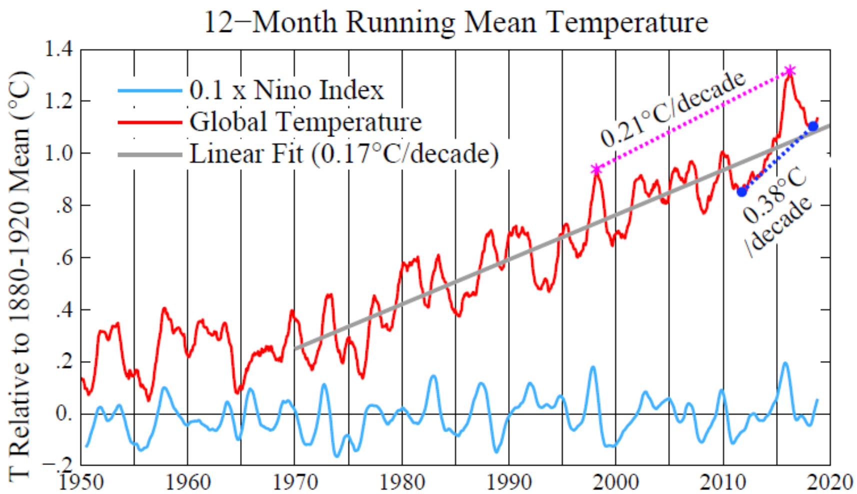

Figure 3. 12-month running mean of global surface temperature relative to preindustrial (1880-1920 mean).

Useful insight about future global warming is provided by the combination of Figures 1 and 2. The fact that about half of the global temperature response occurs in the first several years following introduction of the climate forcing (Figure 1) implies that the increased growth rate of greenhouse gas climate forcing this decade (Figure 2) should show up as an increase in the rate of global warming.

Figure 3 provides support of that expectation. Estimates of the recent warming rate based on global temperature peaks of the most recent super El Niños and the most recent La Niñas are notably higher than the rate of 0.17°C/decade that has characterized the past half century. The rate 0.38°C/decade based on the past two La Ninas is an exaggeration, because the last La Niña was weak. Based on the growth rate of the greenhouse climate forcing (Figure 2), the underlying global warming rate is now probably about a third higher than the average for the past half century, thus perhaps close to 0.25°C/decade.

Global warming over the next few decades will be based mainly on further increase of greenhouse gases in the air, not on 'unrealized warming' from gases added in the prior 150 years. That is an immediate implication of the climate response function shown in Figure 1.[9]

We can infer near-term global warming from the rate of climate forcing addition in the past few years (Figure 2) and extrapolation for several years, taking account of the inertia of global energy systems. Given the time required to replace energy infrastructure, we know that added forcing will not be close to the RCP2.6 line in Figure 2, but instead will be close to the recent range 0.04-0.05 W/m^2 per year. We also know that nobody will come up annually with \$2-4 trillion of loose change to fund CO_2 removal; even if they found the cash, there are no carbon capture facilities ready to capture CO_2 on that scale.

So, unfortunately, we can confidently predict that Earth will be warming at a rate of about 0.2°C per decade or slightly faster during the next two decades. That means the trend line of global temperature will breach 1.5°C by the late 2030s. The variability associated with the El Niño/La Niña cycle assures that the 1.5°C ceiling will be breached temporarily sooner than that.

[9] The response function in Fig. 1 was derived from the GISS (Goddard Institute for Space Studies) global climate model, but the shape of the function is based on the physics of ocean mixing and not dependent on the model. In the paper referenced in footnote 3, we compared the response function of the GISS model with that inferred for the models of two major modeling groups in the U.S. and one in the UK. These models all had slightly *slower* response than that of the GISS model, but the same shape for their response functions.

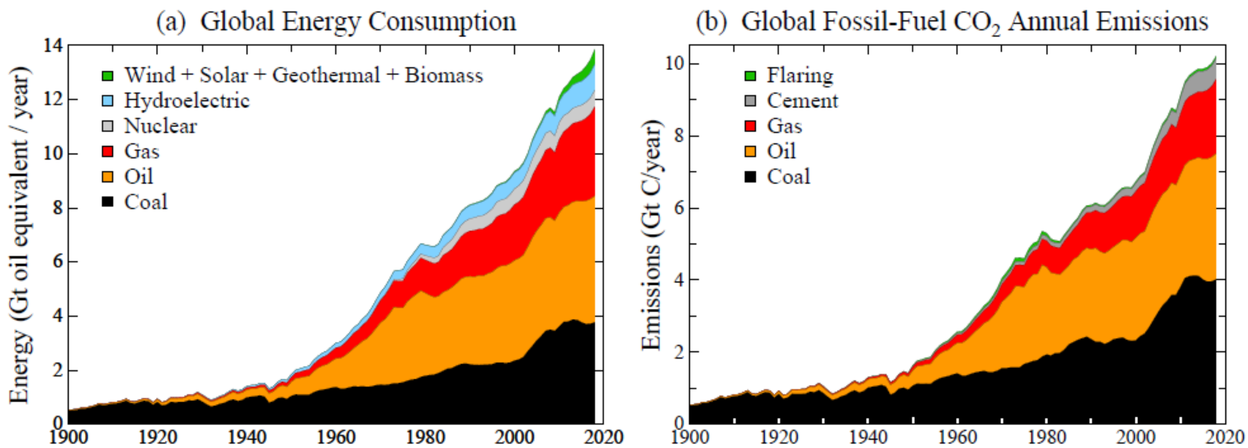

Figure 4. Global energy consumption and fossil fuel emissions. BP data are used since 1965 and Boden et al. data for prior years are adjusted to match BP in 1965.

Political leaders are perpetrating a hoax. Faced with realization that we could hand young people a climate system running out of their control, political leaders took the easy way out. With the Paris Agreement in 2015 they changed the target for maximum global warming from 2°C to 1.5°C.

A temperature 'target' approach is ineffectual. It has practically no impact on global emissions.

A target approach is also used for emissions. Yes, a nation should track its emissions accurately, but targets cannot substitute for policy. Global emissions ***accelerated*** after the 1997 Kyoto Protocol.

Do political leaders not understand what policy is needed? Or believe that it is too inconvenient?

Let's look at the history of emissions.

Fossil fuels powered the industrial revolution, raising living standards in much of the world. The industrial revolution began in the United Kingdom, and until the second half of the 19th century more than half of global emissions arose from that small nation (Figure 5).

Industrialization spread to Europe, then to the United States. Initial expansion in the United States was accomplished with the help of theft, urr, borrowing, of intellectual property from the UK. United States emissions grew rapidly, reaching about 50 percent of global emissions, from a nation with about 5 percent of global population. As other nations developed, the U.S. fraction of global emissions declined.

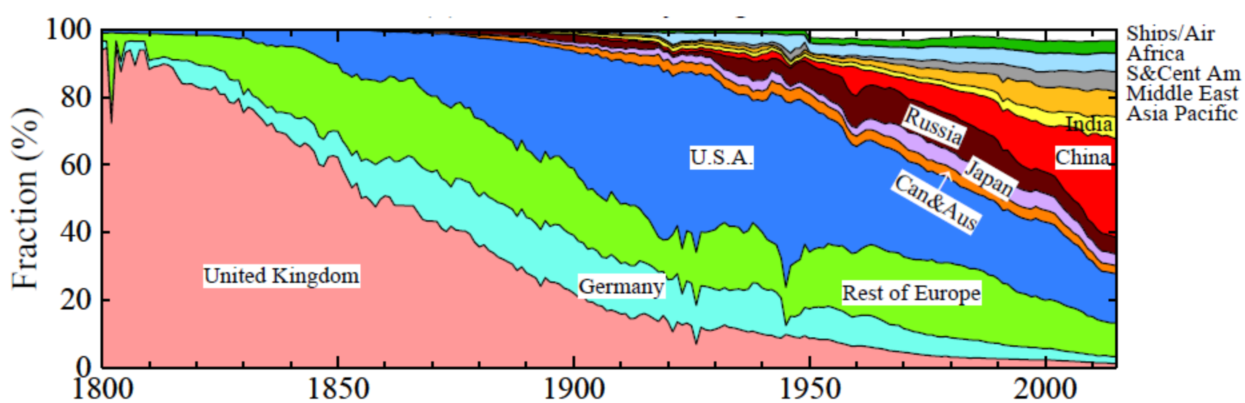

Figure 5. Fraction of fossil fuel emissions by nations and regions through 2015.

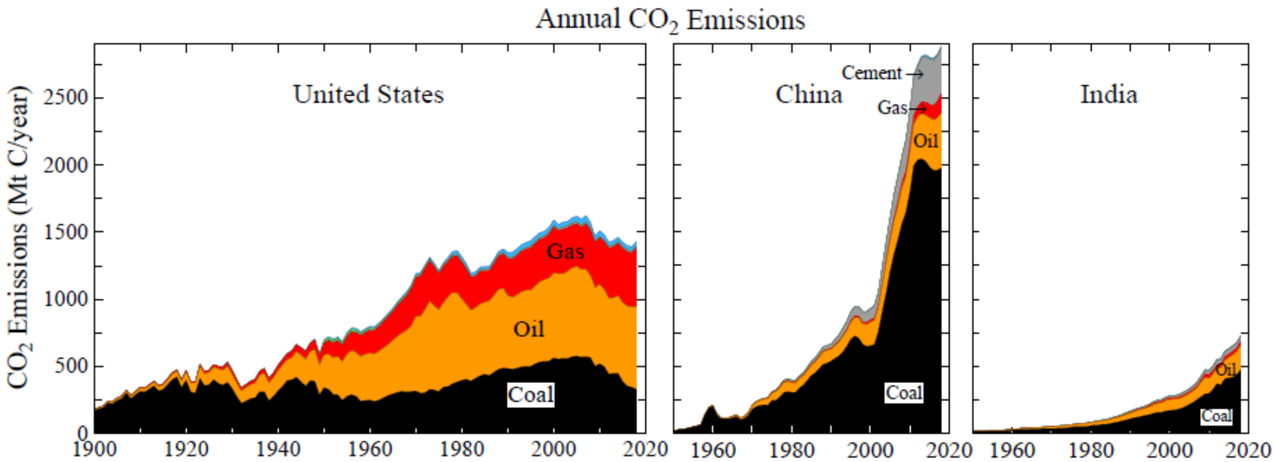

Figure 6. Fossil fuel CO_2 emissions by the three countries with largest current emissions.

By 1970 U.S. emissions were well over 1 GtC per year (Fig. 6). Fossil fuels helped raise the standard of living of the average American. The United States developed the largest, strongest economy in the world. U.S. emissions nearly stabilized thereafter, in part because of the growth of nuclear power, renewables and energy efficiency (Fig. 7).

Global emissions continued to increase rapidly (Fig. 4) as other nations developed. China's emissions, now more than double those of the United States (but about half on a per capita basis), may begin to stabilize, as there is a strong desire to reduce air pollution by moving to more nuclear power and renewable energies.

Other nations are at earlier stages of development. Emissions from India, Indonesia, Brazil, Saudi Arabia, Turkey, Thailand, for example, are rising fast: each has approximately doubled since 2000. India's population will pass that of China within the next few years. India is now the 3rd largest source of CO_2 emissions, and India's energy needs will grow much more as it seeks to raise its living standards.

Almost all nations give priority to their own development and to the well-being of their citizens. Nations therefore choose emission 'targets' consistent with their economic goals. So it should surprise nobody that the Kyoto and Paris agreements were ineffectual in restricting global fossil fuel emissions.

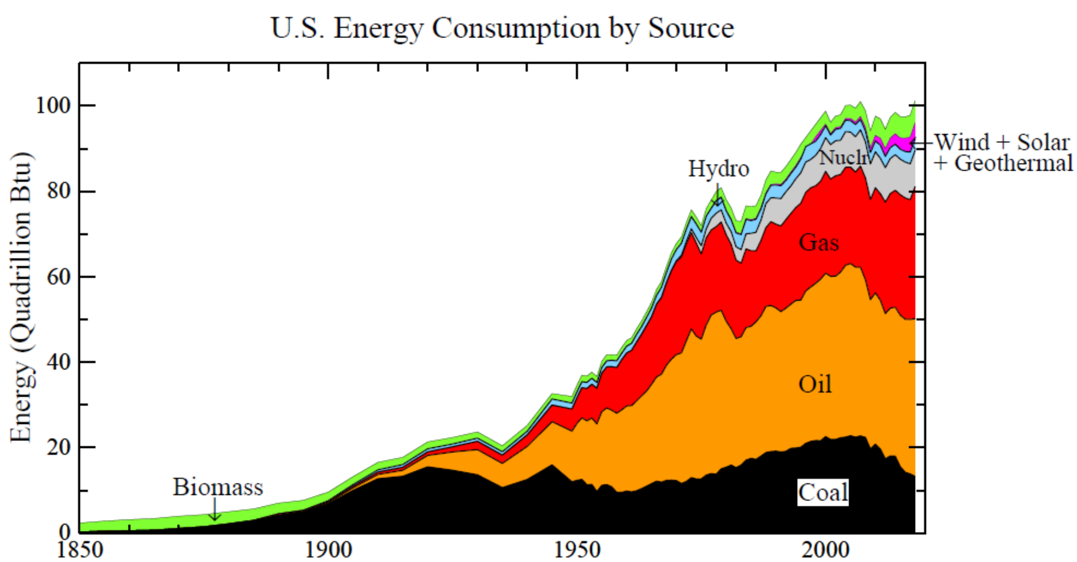

Figure 7. United States energy consumption (source: Energy Information Agency).

Global energy policies remain inconsistent with professed emission targets. Emission targets will never overrule the desire of nations to raise their standards of living. Effective energy policies, not professed targets, are the crucial requirement for phasing down fossil fuel emissions.

The two essential energy policy requirements are:
1) honest pricing of fossil fuels, i.e., the price must rise to include the cost of fossil fuels to society;
2) government support of breakthrough technologies, including clean energy research, development, demonstration and deployment programs.[10]

Deep decarbonization over a period of a few decades is plausible if both of these energy policies are adopted, but rapid decarbonization is unlikely if either of them is missing. Both are missing today.

A near-global carbon price can be achieved via a carbon fee, if the United States and China agree. China cannot be expected to impose an adequate carbon price until cost-competitive alternatives to fossil fuels exist for power generation, which is one reason that support of technology development is essential.

The missing technology for China, and now for India, was a clean source of power to replace coal in massive energy requirements for electricity and industrial heat. In their drive to lift their people out of poverty, these countries had to use coal, despite awareness that resulting air pollution sacrificed more than a million of their citizens' lives each year. Death from air pollution, as from smoking, is not pleasant.

Later this century, when scholars look back at what went wrong, the single sentence likely to stand out will be one uttered by President William Jefferson Clinton in his first State of the Union Address, almost three decades ago: "We are eliminating programs that are no longer needed, such as nuclear power research and development."

How could such a spectacularly bad decision have been reached? Readily available empirical data showed that nuclear power was the safest energy source, with the smallest environmental footprint. The climate issue was understood: Clinton's Vice President, Al Gore, had published "Earth in the Balance."

The story did not begin nor end with the Clinton Administration. I tell the story, as seen through my eyes, in *Sophie's Planet*. There is no villain, nobody with the intent of harming future generations. Yet our descendants are likely to view us with disdain, and they should – how could we have been so foolish? None of us come out looking good, least of all we scientists.

The story is still relevant. Nuclear engineers understand the potential of advanced generation nuclear technology. Today's nuclear reactors are a factor of ten more expensive than would be expected, given their amount of material and difficulty of construction. The potential for inexpensive, modular, ultrasafe reactors – built in a factory or shipyard – has not been developed.

Support for research, development, demonstration and deployment – lavished on renewable energies for decades – only recently has been initiated in a small way for modern nuclear power. That support should be ramped up rapidly, because advanced generation nuclear power is needed if we are to largely phase out fossil fuel emissions over the next half century.

One crucial need is to drive down the cost of nuclear power to a level competitive with fossil fuels. The best chance of obtaining that result soon may involve cooperation of the nuclear industry in the West with nations, such as China and India, that have large energy markets.

The possibility of cooperation among the great powers, although unlikely today, may become obvious tomorrow, i.e., once the reality of the global climate emergency is appreciated fully.

[10] Moniz, E.J., 2019: Innovating a green real deal, *Science* **364**, 1013.

SUMMARY

I should terminate this epistle about time scales. Saving Earth is a century-time-scale problem. There will be significant overshoot of global temperature as well as overshoot of atmospheric greenhouse gas amounts. We are already into overshoot territory, but not very far as yet. This is no time to give up.

The science of climate change is more important than ever. We must find a way to navigate back to a situation in which the planet is close to energy balance and climate is reasonably stable.

The most urgent task is to phase down fossil fuel emissions. There is no one simple solution to this. It will take a lot of positive actions, and also pressure on the fossil fuel industry, from multiple directions, pressure on them to become a clean energy industry.

One objective of Climate Science, Awareness and Solutions must be to help advance the date at which political leaders of the great powers recognize their need to cooperate on global energy policies.

We can help achieve that goal by clarifying the urgency of the situation, which is a mutual threat. We must stress the overall simplicity of the planet's energy balance, its carbon cycle, and the role of fossil fuels in altering the natural systems.

The potential to address global climate change will be much improved via active cooperation between China and the United States. That cooperation seems essential for both achievement of a global carbon fee and for development and world-wide deployment of breakthrough technologies.

I have visited China a few times in the past several years. The levels of academia and government at which I have interacted, which includes some of our former students, are open and eager for cooperation.

The legal approach must be pursued simultaneously with the political approach. As you are no doubt aware, our case against the federal government (*Juliana v. United States*), demanding that the government have a plan for phasing down fossil fuel emissions at a rate consistent with what the science indicates is required to protect the future of young people and later generations, has been slowed by the Trump Administration's continual legal maneuvers.[11,12]

At present the 9th Circuit Court of Appeals is considering objections of the Administration, which asserts that the Judiciary should not interfere in administrative matters. Trump's lawyers assert that the lawsuit attacks Constitutional separation of powers, that instead the public has the recourse of voting Congress and the President out of office.

The public has tried that recourse. They voted in Barack ('Planet in Peril') Obama and Albert ('Earth in the Balance') Gore. The accomplishments by those Administrations in addressing climate change, to use a favorite phrase of my mother, "did not amount to a hill of beans." Democrats and Republicans are both on the take from special interests, the fossil fuel industry. Both parties work with industry, approving and subsidizing fossil fuel extraction and use.

The result is that young people's Constitutional right to life, liberty and property is being violated, as is their right to equal protection of the law. I believe that the Court will allow the trial to go forward.

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[11] Judges give both sides a grilling in youth climate case against the government, J. Schwartz, *New York Times*, 4 June 2019.
[12] Youths sue for a livable climate, Julia Rosen, Los Angeles Times, 3 June 2019.

The legal approach is slow and no panacea, but it is an essential part of the solution. It was more than nine years ago, in 2010, when Mary Wood, author of "Nature's Trust," and I decided to work together. She organized a workshop later in 2010, in Eugene, Oregon, where I met her friend and colleague, Julia Olson. Julia formed Our Children's Trust and has done a remarkable, tireless job of driving legal cases for young people forward, while somehow also finding time to be friend and protector of all the young people.

My point is that the time scale for all of our avenues is long. That is why we must pursue all avenues simultaneously. CSAS is providing science support for several additional lawsuits, most of them employing attorney Dan Galpern, against industry and state and federal governments, lawsuits including opposition to expansion of coal mining and unconventional fossil fuels, and pipelines that would tend to lock in long-term development of especially high-carbon fossil fuels. (I will describe the several things that Dan and I are doing in a later Communication; this one is already too long.)

Conclusion: we should not dismiss the 3rd party concept on the basis that it is slow and hard work. A 3rd party may be a comparatively fast way to achieve effective action. Much of the public is *really* fed up with the present major parties.

I note that the 'expert reports' and 'declarations' for the legal actions are time consuming. They are the main reason for delay in finishing my book. An example is "Climate Change in a Nutshell."

I describe some of our ongoing research in the book, but I mention a few points here:

1. New climate simulations with a higher resolution model support the principal conclusions of our "Ice Melt" paper (footnote 3, page 3 above). Specifically, freshwater injection on the ocean due to mass loss of the Greenland and Antarctic ice sheets is already enough to cause slowdown of the Atlantic Meridional Overturning Circulation and cooling of the Southern Ocean. This latter cooling effect competes with greenhouse warming.

The good news is that the rate of mass loss by both the Greenland and Antarctic ice sheets slowed in recent years (Figure 8). Reduced melt on Greenland is associated with highly variable weather there during the brief summer melt season. Greenland ice sheet mass loss is expected to increase as the hemisphere continues to warm. There is a competition between increased snowfall (due to the warmer atmosphere) and increased melt (due to the higher temperature). Eventually ice melt wins out in warmer climate and the ice sheet will shrink; with shrinkage, amplifying feedbacks will accelerate mass loss.

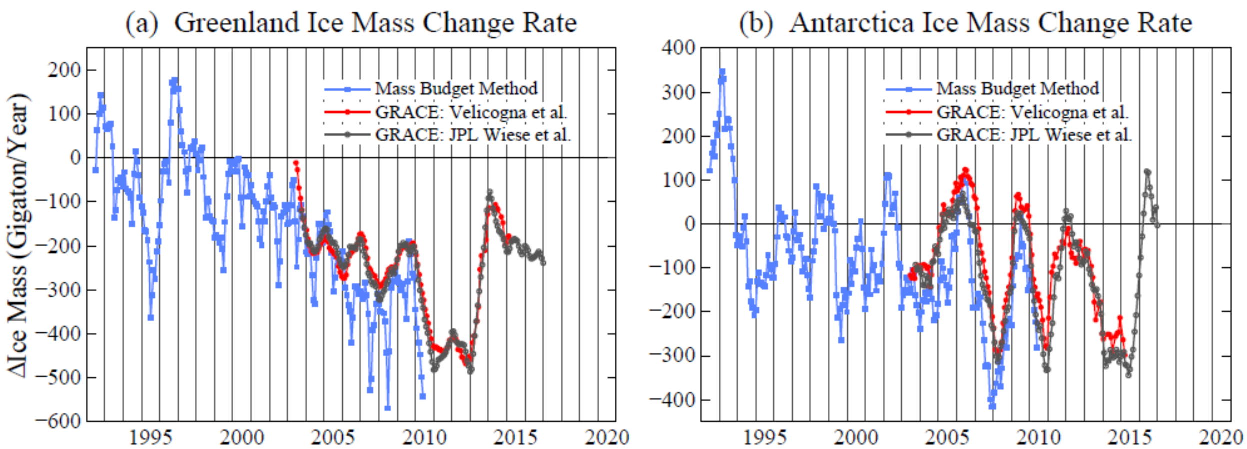

Figure 8. Greenland and Antarctic ice mass change (update of Fig. 30 in the "Ice Melt" paper, which provides the original data sources.)

Antarctica is larger and colder than Greenland. Reduced mass loss from Antarctica, with even mass gain in 2016, may be related to recent reduction of Southern Ocean sea ice cover, which allows moisture-bearing weather to penetrate inland and increase snowfall. That trend is unlikely to continue for long. We showed in the "Ice Melt" paper that, once Antarctic ice shelf melting reaches a sufficient rate, the freshwater injection causes a cooling of the Southern Ocean surface and expansion of sea ice area, which reduces snowfall over Antarctica. Ice shelf melt-rate depends on ocean temperature at depths abutting the ice shelves. This deep ocean temperature is increasing overall, but has dynamic variability.

It is important to monitor these processes to help understand the time scale on which ice sheet mass loss and sea level rise can accelerate. The GRACE (gravity satellite) mission is no longer functioning, but a gravity satellite follow-on mission has been launched, so the time series for Greenland and Antarctic ice sheet masses may soon be extended.

2. Human-made aerosols (fine particles in the air) are the largest uncertainty of all climate forcings. We hope to cooperate with Chinese colleagues in assessing the aerosol climate forcing and how it will change in response to changes of fossil fuel use. China is acquiring global satellite measurements of the polarization of reflected sunlight, which has the greatest potential for revealing aerosol physical properties and monitoring of how those are changing. Researchers in China include our former students and colleagues that we worked with on earlier research papers.

At the joint meeting of the Chinese Academy of Sciences and the American Geophysical Union last October I gave a presentation on aerosols that included climate simulations of purposeful solar radiation management (SRM). My Communication describing those climate model experiments included the standard concerns about "geoengineering." On the other hand, with the remarkable failure of governments to take serious steps to phase down fossil fuel use, such studies have become more than appropriate. "David Keith and Ted Parson," in arguing for research on SRM, persuaded an overwhelming majority of the audience of the propriety of such research (the link includes debate transcript and audience pre- and post-debate opinions). One of the merits of the research is to help wake the public up as to the seriousness of climate change implications.

We will write a paper on our aerosol experiments after I finish the book. The most interesting result is that injection of aerosols into the stratosphere over Antarctica and the Southern Ocean results in a cooling of the ocean off the coast of Antarctica at the depths that are presently warming most rapidly. Melting of ice shelves at these depths increases iceberg discharge and ice sheet mass loss.

3. Pushker Kharecha and Makiko Sato recently published a paper in *Energy Policy* quantitatively describing how energy choices in Japan and Germany following the Fukushima nuclear accident impacted human health and the environment. A summary of the paper for popular audiences is available here and the paper itself is available from our website.

4. We continue to cooperate with David Beerling's group in their research on the potential to obtain gigaton-scale increase of carbon storage in the soil. More on that subject later.