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Climate Change is All About Energy

By Drew Shindell

Climate change is all about energy, a subject familiar to any physicist. Climate changes are driven by changes in the Earth's energy balance with space, either as the result of variations in the distribution or intensity of incoming solar radiation reaching the Earth, the fraction of that radiation that is reflected, or the emission of thermal radiation back to space. The greenhouse effect alters the latter, trapping outgoing terrestrial radiation. A reduction in emissions during recent decades at exactly the wavelengths where greenhouse gases (GHGs) absorb has been directly measured from space, so there is no question about this effect. Thus the relevant question is how sensitive is the Earth's climate to changes in the planetary energy balance?

Climate records from the distant past show that the Earth's climate is not immutable, but in fact is rather sensitive, especially at long timescales. Climate models are not given credence by the climate science community unless they exhibit sensitivity consistent with paleoclimate evidence. Given a sensitive climate, the increasing greenhouse effect should be causing our planet to warm up substantially. Modern measurements show that indeed the Earth as a whole has unquestionably warmed since the industrial revolution. However, climate records don't indicate causality on their own. Instead, a combination of climate data and understanding of the many potential drivers of energy changes is required to attribute cause and effect. Perhaps surprisingly, this is often easier to do in the distant past than in more recent times, as the potential sources of energy balance changes were far fewer prior to large-scale industrialization.

With this in mind, we can explore the relative roles of natural factors and human contributions to the warming since the industrial revolution. The strength of past solar variations is not well known (the timing is known, but not the amplitude), so while the global mean warming of the early 20th century can be at least partially reproduced in models by imposing increased solar output, this by itself tells us little. Climate variations over the past several centuries provide a more useful constraint, and indicate that given what we know about climate sensitivity, solar variations very likely were the dominant driver of long-term (multi-decadal and longer) climate variations during the last millennium. Models are able to match the hemispheric average temperature changes and large regional changes, such as the 17th and 18th century cooling in Europe and parts of North America that gave rise to the name 'Little Ice Age', best when we assume past variations in solar output were extremely small, only ~0.1-0.2%. Such small variations imply that solar forcing (here forcing means an "external" change affecting the climate system's energy balance) may have contributed to the warming of the early 20th century, but that it was too small to be the sole driver.

How about the more rapid warming of the last 40 years? Much of this time the sun has been monitored by satellites, and there has been no substantial increase in its output. Tellingly, solar increases would heat the stratosphere more than the surface, and observations show instead that the stratosphere has been cooling rapidly. This cooling is partially due to ozone depletion, but is also present at altitudes where there has been little ozone change, and stratospheric cooling is a well-known response to GHG increases. Thus the spatial structure of atmospheric temperature change doesn't fit the impact of solar increases. Instead, it bears the signature of increased GHGs. However, GHGs trap so much energy that were they the only important factor the planet would be warming even more rapidly than observed. It's clear that the enhancement of the greenhouse effect is being partially offset by aerosols (particulates), though details of these are poorly understood at present. Hence as for the early 20th century, the uncertainty in the forcing limits the value of comparing models with observations of global mean temperature trends. One can put in increasing GHGs and then offset the right amount with aerosols to reproduce the late 20th century global mean trend, but little is learned. A more convincing reason to trust the climate models is that when these are driven with increasing GHGs and other forcings, they are capturing more and more of the regional response of temperature and precipitation seen in observations, including cooling in certain regions and decreased rainfall in much of the subtropics.

Though aerosols have been offsetting a poorly quantified but certainly substantial portion of GHG forcing, they are unlikely to continue doing so. For one, GHG forcing is growing ever larger, so to offset a constant fraction would require ever larger aerosol emissions. Instead, aerosol emissions have been decreasing in the developed world as a result of air quality legislation, and are projected to do so in the developing world during the next 10-40 years. So while poor understanding of aerosols is sometimes cited as a reason to doubt warming projections, in fact the crucial point about aerosols is that their influence will almost certainly decrease, making the future prospects for warming even worse than one would estimate considering GHGs alone.

Thus climate science tells us several key things. Our planet is warming. The abundance of GHGs in the atmosphere is increasing due to human activities, and these are enhancing the greenhouse effect. Natural forcings appear not to have increased during recent decades, and only minimally during recent centuries. The Earth's climate sensitivity is constrained well enough from studying the Earth's history to know that the enhanced greenhouse effect will lead to substantial warming in the absence of offsetting effects, and future offsetting effects (primarily from aerosols) are likely to decrease. So global warming during the 20th century is very likely largely caused by the GHG increases, and warming in the future is very likely to increase. Most estimates find a warming of 2-2.5 C to constitute "Dangerous Anthropogenic Interference" with the climate, a term meaning a high likelihood of severely disruptive or even catastrophic climate changes which most of the world (including the US) has pledged to avoid. The Earth has warmed ~0.8 C already, and another ~0.6 C will take place as the planet adjusts to its current energy imbalance with space. Thus we have only another 0.6-1.1 C to go. It will be almost impossible to avoid this much additional warming without prompt, large-scale action worldwide.

What can we do? Again, it comes down mostly to energy. A whopping 80% of today's energy comes from fossil fuel burning, releasing huge quantities of CO_2 (the most important GHG forcing) into the atmosphere. While future projections of the world's population and economy are much less certain than even climate projections, most plausible futures show a large increase in energy usage, with double to triple current usage in 50-75 years. There are two clear options. First, energy can be generated from renewable sources that do not generate GHGs. Second, energy can be used more efficiently. Given the scale of the problem, it seems clear that both are imperative (along with efforts to halt and reverse deforestation, especially in the tropics, which also contributes substantially to atmospheric CO_2 increases).

Physics can contribute greatly to both strategies. Further improvement in renewable energy from wind, solar, and nuclear power should be near or at the top of national priorities. Instead, US energy research and development spending is today only 40% of what it was in 1980. A ban on construction of coal-fired power plants that do not design in the capacity to add carbon sequestration in the future is required for a serious effort to limit CO_2 emissions. While there are substantial economic costs to limiting coal burning and increasing use of renewable energy, at least in the short-term, there are significant potential economic gains as well and the technology is ready. In the EU, the expansion of wind energy since the 1990s has eliminated the need for nearly 50 new coal-fired plants, and renewable energy there is now a $20 billion industry. Physicists are also at the forefront of developing more efficient ways to use electricity, such as solid-state lighting. Electricity generation is currently only ~37% efficient, with nearly 2/3 lost in generation, transmission and distribution, leaving ample room for improvement. Distributed generation with capture and use of waste heat is a simple way to more than double the efficiency of electricity generation.

While science and engineering are crucial to solving our energy and climate problems, there are important roles for policy makers as well. California's history of independent regulations, an ironic positive legacy of horrendous air quality in the Los Angeles basin, provides telling examples. Primarily through mandating more efficient use of energy, California has held its per capita energy use roughly constant since the early 1970s (http://www.energy.ca.gov/efficiency/). During that same period, per capita energy use has gone up ~50% nationwide. California's advanced efficiency standards started in the 1970s for major appliances such as furnaces, air conditioners and refrigerators. They have been so successful that energy use by these appliances has dropped 25, 40 and 75%, respectively. In contrast, the federal government only imposed standards in the early 1990s, when most of the efficiency gains had already been realized. Standards have also been gradually increased for buildings and utilities to use and generate energy efficiently. Contrary to the dire warnings sometimes heard from industry, the effect of standards has not been to destroy manufacturers by driving up the price of their product. Today's refrigerators that use one-quarter the energy of their 1970s predecessors and also cost roughly 60% less. Precedent shows that technology always seems to keep up with the regulations. Though industrial groups are currently suing California over its recent attempt to regulate emissions from automobiles more strictly, it's hard to accept that current regulations are adequate. Can some of the country's most talented scientists and engineers really not come up with a way to make more fuel efficient cars than we did in the 1970s (when current fuel efficiency standards were largely set)?

The benefits of having avoided the national increase of 50% in per capita energy use are tremendous. California emits 18 million tons less carbon per year, has greatly reduced emissions of smog precursors and particulate, both harmful to human health, and consumers save ~$12 billion in energy bills each year. This is money into the American economy instead of into foreign economies that seem almost inevitably to use their oil and gas income to maintain authoritarian regimes and often also to fund schools where fundamentalists are trained to hate the United States. Clearly using energy more efficiently is in America's best economic and national security interests in addition to environmental ones. Energy, economic and environmental success stories also exist in the developing world. For example, Brazil's sugarcane ethanol program for vehicles, begun in the 1970s in an effort to stop spending roughly half its earnings from exports on oil imports, has been enormously successful. Following decades of work, ethanol now sells for less than traditional gasoline without any subsidies and has saved Brazil over $50 billion in oil imports, far more than the program cost. At the same time it has created domestic jobs and substantially reduced the country's vulnerability to Middle Eastern oil crises. Efforts to wean the US from imported oil have, in contrast, been largely rhetorical.

Continued use of fossil fuels is inevitable for the immediate future, and potential solutions such as carbon sequestration and nuclear power require further study or remain controversial. There are no compelling reasons, however, that the US cannot rapidly become dramatically more energy efficient. Energy efficiency is not just a win-win situation, it's at least a "win to the fourth," improving air quality and human health, reducing climate disruptions, improving national security and boosting the American economy. Similarly, capture of methane released to the atmosphere from landfills, pipelines, mining and other sources reduces global warming and air pollution (methane is a precursor to ozone, a component of smog) and provides a valuable economic commodity (natural gas) that makes the long-term economics positive. Factoring in the costs of adverse health impacts of fine particles, reductions in black carbon soot also often lead to a net economic gain. Thus even without including the economic cost of climate change via a carbon tax or cap-and-trade system for CO_2, many global warming mitigation strategies make economic sense already for ancillary reasons. These are not put into practice due to systemic problems. For example, soot emitters do not pay the health costs, so lack an incentive to control emissions. Builders do not pay the occupant's energy bills, so are not motivated to strive for efficiency. Similarly, distributed power generation with use of waste heat saves energy, but utilities understandably aim to increase sales, not reduce them. Leadership is required to overcome these systemic problems and benefit society as a whole. Much is contentious in the US regarding solutions to global warming, but increasing energy efficiency and other "win-win" strategies should not be.

Drew Shindell is a senior climate scientist at NASA's Goddard Institute for Space Studies in New York. He is also a lecturer in the Department of Earth and Environmental Sciences at Columbia University.

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