Climate Change

The Evidence and Our Options

By Lonnie G. Thompson and Gioietta Kuo

There is no doubt that our planet is warming. Many climatologists have spoken out about the dangers of our continued path toward this warming, and there is now a very clear pattern in the scientific evidence documenting that the warming is due largely to human activity. It is already causing important changes in the climate. As many phenomena are accelerating, rapid and potentially catastrophic changes in the near future are possible. Furthermore, it should be realized that this pattern does not emerge simply from computer simulations, but from the weight and balance of the empirical evidence, as well.

In this paper, we shall concentrate on one set of data—ice-core records of climatic and environmental variations from the Polar Regions, and from low-latitude, high-elevation ice fields in 16 countries.[1] The ongoing, widespread melting of high-elevation glaciers and ice caps, particularly in the middle and low latitudes, provides some of the strongest evidence to date that large-scale, pervasive, and—in some cases—rapid changes in Earth's climate system are under way. This paper highlights observations of twentieth- and twenty-first-century glacier shrinkage in the Andes, the Himalayas, and on Mount Kilimanjaro.

Ice cores retrieved from shrinking glaciers around the world provide environmental data for periods ranging from hundreds of years to multiple thousands of years, and they suggest that the climatological conditions dominating those regions today differ from those under which these ice fields originally accumulated and have been sustained. The current warming is therefore unusual when viewed from the long-term perspective. In addition, we have the 160-year record of direct temperature measurements. Yet despite all this evidence, plus the well-documented continual increase in atmospheric greenhouse gas concentrations, societies have taken little action to address this global-scale problem. We conclude by pointing out the options still open to us: mitigation, adaptation, and—if these are only partially successful—then suffering.

The Evidence

Glaciers serve as early indicators of climate change. Here we report on 35 years of research of ice core data.

Lonnie G. Thompson, Distinguished Professor at Ohio State University, is one of the world's foremost authorities on paleoclimatology and glaciology. A Member of the National Academy of Sciences, Professor Thompson has published widely and has received numerous honors and other awards. He may be reached at thompson.3@osu.edu.

Gioietta Kuo, nuclear physicist, is from Cambridge, and is a Fellow of Oxford and Princeton with over 70 academic articles and about 100 other publications on the global environment in both English and Chinese. She may be reached at kuopet@comcast.net.

A. Northern Hemisphere Temperatures over the Last 1,000 Years

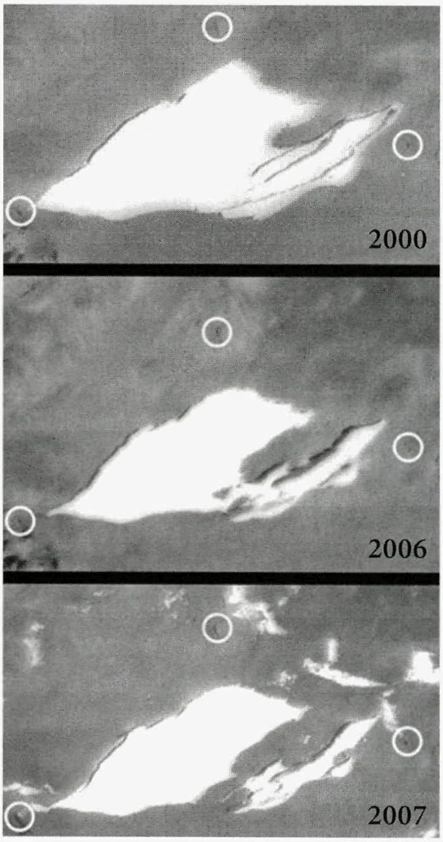
From a variety of high-resolution climate recorders, such as glacier lengths, tree rings, sediment cores and historical records, it has been found that for most of this period the average temperature has been relatively stable until the twentieth century. There has been warming since the industrial revolution, in particular in the last decade, so that now the global average is 0.7°C higher than where it stood in 1900. The temperature rise is most marked in the Arctic, the Antarctic, and in the interiors of large continents.

B. Retreat of Mountain Glaciers

Together, the world's mountain glaciers and the polar ice caps contain less than 4% of the world's ice cover. But they provide invaluable information about changes in climate. Because glaciers are smaller and thinner than the polar ice sheets, their ratio of surface to volume is greater. So they respond more quickly to temperature changes. In particular, warming trends are ampli-

Figure 1. Retreat of Glacier on Mount Kilimanjaro

Figure 2. Retreat of Furtwangler Glacier on Kibo Crater on Kilimanjaro



Source: Thompson et al. *PNAS.* 2009.

fied at higher altitudes where the glaciers are. All glaciers are retreating. They form an "early warning system" for climate change. Here are some notable examples.

By using a combination of terrestrial maps, satellite images, we have found that the glaciers on Mount Kilimanjaro have retreated in 1912, 1970, 2000, and 2006. From 1912 to 2006, 85% of ice has disappeared.

Furtwangler glacier on Kibo, the highest crater on Kilimanjaro, has decreased in size and thickness and has divided into two.

The Quelccaya ice cap, which is located in the southern Peru adjacent to the Amazon basin, is the largest tropical ice field on Earth. Here, ice has been melting to form lakes, and since 1978, 25% of this ice cap has disappeared.

Himalayan mountains contain more than 15,000 glaciers. Glaciologists at the Institute of Tibetan Plateau Research in Beijing have been monitoring 612 glaciers across the High Asian region since 1980. They have found that from 1980 to 1990, 90% of these glaciers were retreating and from 1990 to 2005, the proportion of retreating glaciers increased to 95%.

Almost 99% of the glaciers in Alaska, Glacial National Park, and the Alps are thinning.

C. Loss of Polar Ice

Satellite documentation of the area covered by sea ice in the Arctic Ocean is measured every September. Sea-ice cover decreased at a rate at a rate of approximately 8.6% per decade from 1979 to 2007. Then in 2007 alone, 24% of the ice disappeared. In 2006, the Northwest Passage was ice free for the first time in recorded history.

Polar ice sheets respond to temperature rise more slowly than mountain glaciers. But they are melting, too. The Greenland ice sheet has shown an increase in the size and number of lakes near the southern part of the ice sheet. There are many crevices which serve as pipes—*moulins*—which transport water quickly to the bottom of the ice sheet. These act as a lubricant to speed the flow of the ice into the sea.

Recently a large chunk broke off from the Petermann glacier and created an ice island. This event alone does not prove global climate change. But it is a fact that this is part of a long term trend of increasing rates of ice loss, coupled with documented temperature increases in this region at the rate of 2°C per decade, indicating that larger-scale global climate change is under way.

In the Antarctic, it has long ago been predicted that increase in CO_2 can result in the breakup of the ice sheets. Mean temperature on the Antarctic Peninsula has risen by 2.5°C in the last 50 years. Just as an ice cube does not raise the water level in a glass when it melts, so a melting ice sheet leave sea levels unchanged. However, ice sheets buttress the glaciers on land, and when these ice sheets collapse, it speeds the flow of glaciers into the ocean and causes sea level to rise quickly.

The loss of ice in the Arctic and Antarctic regions is especially troubling because these are the locations of the largest ice sheets in the world. Of the land ice on the planet, 96% is found in Greenland and Antarctica. Should they all melt, sea level would rise by an astounding 64 meters, in addition to the rise due to thermal expansion. Although research shows some variability in the rate of ice loss, it is clear that mountain glaciers and polar ice sheets are both melting fast, and there is no explanation other than global warming. Add to this the laboratory evidence and meteorological measurements, and the case for global warming simply cannot be denied.

Causes of Global Warming

So what causes global warming? Climatologists analyze climate in terms of climate forcing. A climate forcing is an imposed perturbation of the Earth's energy balance. If the sun shines brighter, that is a positive forcing that warms the Earth. Aerosols reflect sunlight, so they cause a negative forcing. Climatologists classify two types of forcing: natural forcing, which has existed for millions of years; and anthropogenic forcing, which includes more recent processes caused by human activity.

A. Natural Forcing

The most powerful natural forcing is the variation in Earth's orbit around the sun. These variations are primarily responsible for both the ice ages (glacial periods during which large regions at high and middle latitudes have been covered by thick ice sheets) and the warm interglacial periods such as the present Holocene epoch that began 10,000 years ago. Another is Earth's orbit round the sun, which gives us seasons. Still others include:

Volcanic aerosols, such as the ash spewed upward during the eruption of Mount Pinatubo, which forced millions of tons of sulfuric gases and ash particles high into the atmosphere, blocking sunlight. This lowered the Earth's temperature for a few years. It was a negative forcing.

The linked oceanic and atmospheric system known as El Niño (ENSO). It occurs every three to seven years in the tropical Pacific and brings warm, wet weather to some regions and cool, dry weather to other areas.

Periodic modulations in energy from the sun—such as the 11- to 12-year sunspot cycle. These changes in solar energy could affect atmospheric temperature across large regions for hundreds of years and may have caused the "medieval climate anomaly" that lasted from AD 1100 to AD 1300, as well as the "little ice age" of the sixteenth to nineteenth centuries. However, even though this warming affected certain regions, it did not affect the planet as a whole.

B. Anthropogenic Forcings

There is consensus among climatologists that the warming trend we have been experiencing for the past 100 years cannot be explained by any of the known types of natural forcing. Furthermore, it should be emphasized that the rate at which the Earth's temperature has been rising—culminating in this, the hottest decade on record, is abnormal. Sunspot cycles, for example, can increase the sun's output, raising temperature in our atmosphere. But we are seeing a temperature increase in the troposphere, the lower level of our atmosphere, and a simultaneous temperature decrease in the stratosphere, the upper level. This is the exact opposite of what we would expect if increased solar energy were responsible.

Similarly, global temperatures have increased more at night than during the day, again the opposite of what would occur if the sun were driving global warming. High latitudes have warmed more than low latitudes, and, because we get more radiation from the sun at low latitudes, we again would expect the opposite result if the sun were driving those changes. The conclusion is that changes in solar output cannot account for the current period of global warming. ENSO and other natural forcing also fail to explain the steady and rapid rise in the earth's temperature. In particular, this rise in the Earth's temperature is accelerating. This can only be due to anthropogenic human forces.

Animals and plants respiration convert oxygen into CO_2. There is normally a steady amount of greenhouse gas in the atmosphere. (See figures 3 and 4). As the orbital forcing brought the last ice age to an end and produced the warm Holocene period of the last 10,000 years, the oceans warmed, releasing CO_2 into atmosphere. This trapped infrared energy reflected from the Earth's surface and has warmed the planet slightly. All of this is a natural and self-regulating process, and is essential for life on the planet. But we humans can also change the level of atmospheric CO_2, and this is what we are doing! Change the level of greenhouse gases in the atmosphere, and the planet heats up or cools down.

When one drills down into an ice sheet, the deeper one drills, the further back one goes in time. Air bubbles are trapped in ice, and by analyzing the composition of these bubbles, one can obtain a history of such as the amount of greenhouse gases, the ratio of oxygen isotopes. One can derive the temperature and other environmental parameters of that time. Figure 3 shows the CO_2 in ppmv (parts per million by volume) from ice-core data for the last 400,000 years. Figure 4 shows the carbon dioxide (CO_2) and methane (CH_4) concentration for the last 800,000 years (over eight glacial cycles) from East Antarctic ice cores. Note the extremely high values for today.

From the onset of industrial revolution, when massive use of fossil fuel began, greenhouse gases started to rise sharply. The particularly sharp rise in the last 2 decades is quite unprecedented. The CO_2 concentration is now at 394 ppmv—a level not seen any time in the 800,000 years. Methane raises temperature even more than CO_2, and the amount of methane presently in the atmosphere is also at a level not seen in 800,000 years. Two-thirds of current methane emissions are byproducts of human activity, like oil and gas production, deforestation, and the raising of farm animals. Together, we emitted 8 billion tons of carbon in 2007 alone.

The evidence is overwhelming, that human activity is responsible for the rise of CO_2, methane, and other greenhouse gases, and that the increase is fueling the rise in global temperature. Furthermore, this phenomenon is accelerating. Between 1975 and 2005, CO_2 emissions increased 70% over the natural interglacial levels; and between 1999 and 2005 global emission accelerated at a rate of 3% per year. This climate change has already brought about great changes in the way we live.

Effects of Global Warming

About half of the rise in sea level is due to thermal expansion. In addition oceans are rising because ice is melting. So far, most of that water has come from mountain glaciers and ice caps. If the Greenland ice sheet were to melt completely, it would release enough water to raise the sea level by 7 meters. West Antarctica's melting would raise sea level by over 5 meters and East Antarctica by 50 meters. If the Earth were to lose just 8% of its ice, the consequences would be horrific. New York, London, Shanghai, and other low-lying cities would be submerged.

Low-lying countries like the Netherlands,

Figure 3. CO_2 Concentration from Ice Core Data over 400,000 Years

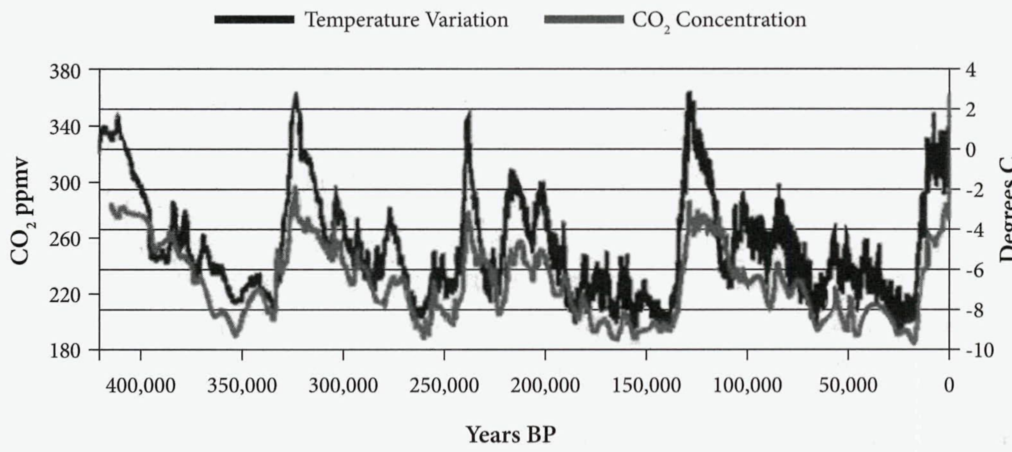
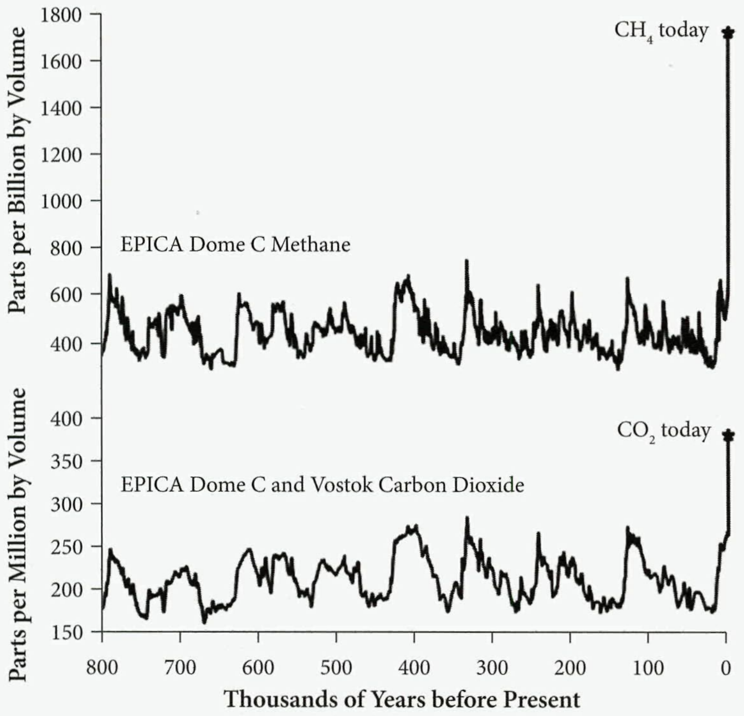


Figure 4. Concentration of CO_2 and CH_4 over the Last 800,000 Years from East Antarctic Ice Cores

The concentration of CO_2 and CH_4 in 2007 is shown as *.



thumb among crop ecologists: For every rise of 1°C above the norm, yields of wheat, rice and corn fall by 10%.

There is also an expansion of the Earth's warm areas. Warming at the equator drives a climate system called the Hadley Cell. Warm moist air rises from the equator and loses its moisture through rainfall as it moves north or south. Then dry air falls to the Earth at 30 degrees north and south latitudes, creating deserts and arid regions. Evidence suggests that over the last 20 years, this Hadley Cell has expanded north and south by about 2 degrees of latitude, which may broaden the desert zones. Therefore drought may become more persistent in the American Southwest, the Mediterranean, Australia, South America, and Africa.

The Maldives, and Indonesia are already finding their land inundated and there is a growing danger of climate refugees fleeing en masse to other countries. In addition, lack of fresh water is affecting drinking water and agriculture. For example, during the dry season, India, Nepal, Vietnam, and southern China all depend on rivers fed by Himalayan glaciers. The retreat of these glaciers directly threatens the water supply of millions of people.

Global warming has already resulted in climate changes that have consequences for global agriculture. The growing season for wheat and other grains had shifted to northern latitudes like Canada. A study published by the U.S. National Academy of Sciences[2] has confirmed a rule of

Accelerating Climate Change

Over the last century, the average rise in global temperature was 0.06°C per decade. Since the late 1970s, however, this rate has increased to 0.16°C per decade, and 11 of the warmest years on record have occurred in the last 13 years. The acceleration of global temperature is reflected in increases in the rate of ice melt. From 1963 to 1978, the rate of ice loss on Quelccaya in Peru was about 6 meters per year. From 1991 to 2006, it averaged 60 meters per year—ten times faster.

Ice retreat between 2003 and 2009 in the Himalayas slowed slightly, but loss in the mountains in the northwest increased markedly over the last few years. So the average rate of ice melt in the region was twice the rate of four decades before.

In the last decade, many of the glaciers that drain Greenland and Antarctica have increased their discharge into the oceans from 20% to 100%. Increasing rates of ice melt should mean an increasing rate of sea-level rise. Over most of the twentieth century, sea levels rose about 2 millimeters per year. Since 1990, the rate has been about 3 millimeters per year. So what is important is not just that the Earth's temperature is rising and ice is melting, but that the rate of this change is accelerating. This means that our future climate may not be a steady gradual change, but an abrupt and devastating global shock.

Tipping Points

Our climate system is highly complex and nonlinear. This means that a small change in one of its parameters could trigger a large change through various feedback systems. What is worrying is not so much that global warming is occurring, but that it is *accelerating*. This has caused many climatologists to warn that we may come to a tipping point when we are faced with an abrupt and devastating change in our climate system, one so violent and sudden that we will not recover from it.

There exist many interacting positive feedback loops. One is the ice albedo effect: As ice melts, it exposes darker areas beneath that reflect less solar energy. This leads to still more absorption of heat, causing further ice melt. Higher temperature also means that tundra permafrost melts, releasing CO_2 and methane from rotted organic material, which in turn leads to even higher global temperatures.

Sudden cold spells have happened in the past. The most recent one occurred around 5,200 years ago and left its mark in many paleoclimate records around the world. The most famous evidence of this abrupt weather change comes from Otzi, the Tyrolean ice man whose remarkably well-preserved body was discovered in the Alps in 1991 after it was exposed by a melting glacier. Evidence suggests that Otzi was shot in the back with an arrow, escaped his enemies, then hid behind a boulder and bled to death. We know that within days of Otzi's dying there must have been a climate event large enough to entomb him in snow; otherwise, his body would have decayed or been eaten by scavengers. Around the world there is evidence of this cold event as plants have been exposed by melting glaciers in Quelccaya and Kilimaanjaro. The Soreq cave in Israel recorded an abrupt cooling in the Middle East around 5200 years ago—the most extreme climatic event in the last 13,000 years.

In 2009 an interesting article appeared in *Scientific American.*[3] It was titled "Did Climate Change Doom the Neanderthals?" One theory holds that Neanderthals were an archaic variant of our own species—Homo sapiens—that evolved into, or was assimilated by, the anatomically modern European population. But another theory proposes that Neanderthals were a separate species, H. Neanderthalensis, which the modern humans swiftly exterminated after entering their territory.

Recently discovered data, known as "isotope stage 3" and spanning from 65,000 to 25,000 years ago, establish that Neanderthals lived through both warm and ice ages. At the beginning of this period, Neanderthals were the only people in Europe. However, "oxygen isotope stage 3" shows that the climate became increasingly unstable just prior to the last glacial maximum, swinging severely and abruptly. With this flux came profound ecological changes, such as forests turning to grassland, etc. Some evolutionary ecologists today believe that this swing in climate over the life time of Neanderthals could have pushed them into extinction.

Even if we stop emitting all greenhouse gases tomorrow, global warming will remain with us, and temperatures will continue to rise for another 20 or 30 years. Once methane is injected into the troposphere, it remains there for about 10 years. CO_2 stays 70 to 120 years, as oceans have long thermal inertia. As to what the future will bring, computer modeling such as the IPCC offers temperature and other predictions like sea level rise and arctic ice cover all the way to 2100. In our opinion, one must look at the assumptions that are inputs to these models. The reports on IPCC results often neglect the human-related time variations for future inputs that are, in principle, impossible to determine. To describe the time dependence of many parameters, one must assume certain emission characteristics for all variables that change the energy balance of the planet, such as CO_2, methane, nitrous oxide, ozone, etc. The best that climate codes can do is to prescribe certain most likely values for these quantities as a function of time.

This has been done by a great many scientists, economists, and modern historians. For example, one of the six scenarios used by the IPCC goes as follows:

> Scenario B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter. As in the A1 storyline, but with rapid changes in economic structures towards a service and information economy, the B1 storyline foresees reductions in material intensity and the introduction of clean and resource efficient technologies. It emphasizes global solutions to attain economic, social, and environmental sustainability including improved equity, but without additional climate initiatives.

It is difficult to believe that something as vague as this can correctly describe our future. In fact, the six different IPCC scenarios give widely different results for the end of this century. In our view we can make predictions for the next 20 years, but no further.

Our Options

Briefly, one might say that our options are mitigation, adaptation, and—if these are only partially successful—then suffering. We have offered a mass of evidence showing that climate change is happening and that it is accelerating. Despite some awareness that we should burn less fossil fuels and use alternative energy like wind, solar, biofuels, geothermal, and nuclear, efforts to initiate such changes are still minor and, as a percentage of total electricity production, fossil fuels still occupy over 60%, and their usage shows no sign of abating. At this juncture, rather than further damage our already fragile ecosystems to satisfy demands for more energy, one should seriously consider changes in our lifestyle aimed at reducing the demand for energy. Here are some important areas where changes may be made to reduce CO_2 emissions.[4]

Electricity generation. As a percentage of total global electricity generation, wind accounts for 1.9%, biofuel 1.8%, hydro 15%, geothermal 0.3% and nuclear 13%. Only nuclear power and geothermal energy can replace coal as steady base-load source, capable of generating 24 hours a day. For that reason their use is indispensable. The new IV generation "pebble bed" nuclear reactors are extremely safe in design. China is in the process of expanding its use of nuclear energy based on these new reactors.

Around 24% of CO_2 emissions come from global transport, and the percentage is still rising even though we know oil is peaking. We should change to efficient urban mass transport systems, develop more efficient electric and hybrid cars, and cut back on air transport as kerosene is on the wane. Using maglev trains is another viable alternative.

Conservation and efficiency should be increased in the housing sector. Replace incandescent bulbs by Compact Fluorescent light (CFL) and LEDs. Much electricity can be saved by more efficient design of buildings. This involves a stringent design methodology, making use of solar orientation, superinsulation, advanced window technology, airtight windows and doorways, ventilation, and space heating and cooling.

Around 2 gigatons of carbon are released into the atmosphere by deforestation. Taking carbon emission all together, the burning and degrading of fossil fuel contributes 7 gigatons. It is therefore very important to reduce deforestation, especially because our precious tropical rainforests form a cooling band that is the lung of our planet. Deforestation is now being recognized as a major cause of climate change.

By 2050, 80% of world's population will be living in urban areas. Agriculture will turn to indoor farming to save water and growing land, that means greenhouses and vertical faming. But massive amounts of energy will be required, and they had best come from non-fossil-fuel sources.

Recycling of waste water for both agriculture and drinking water will become necessary. Here, too, use of fossil fuels should be phased out.

Our world is overpopulated at 7 billion, and the United Nations forecasts 9 billion people worldwide by 2050. The addition of one person increases demand for water, food, education, employment, housing, healthcare and—most of all—energy resources. We have shown here that the melting of glaciers and ice caps is leading to scarcities of water and food, the two most vital ingredients for our survival. We should reduce fossil-fuel use and turn to renewables and nuclear energy to reduce global warming. Thus far, our society has not been successful in this development endeavor. Can we reduce the relentless rise of the world's population?

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