Confronting the Climate–Energy Challenge

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Combustion of coal, oil, and gas has raised the amount of carbon dioxide in the atmosphere to levels higher than they have been for millions of years. A brief review of the history of Earth's climate puts the next hundred years in its natural context, suggesting that most predictions based on climate models may be underestimating the problem. Reducing risks of future climate change requires changes in existing energy systems. These changes will be in three areas: increasing energy efficiency, increasing the stock of non-fossil energy generation, and adopting technologies for capturing and storing carbon dioxide from fossil fuels.

KEYWORDS: climate change, paleoclimate, energy, carbon sequestration

INTRODUCTION

Energy is an essential element of modern society, with more than 80 percent coming from the combustion of fossil fuels. But the continued use of fossil fuel as the major source of world energy has ominous implications for the environment. Current consumption of fossil fuel releases more than 25 billion tonnes of carbon dioxide into the atmosphere each year. If current trends continue, atmospheric carbon dioxide (CO_2) will triple by the end of the century, bringing Earth's atmosphere to a composition not seen for more than 40 million years. Given the long lifetime of energy infrastructure, it is difficult to design even the most aggressive mitigation strategy to keep CO_2 from doubling, especially with large deposits of inexpensive coal in those countries that consume the most energy.

Motivated by concerns about climate change, human health, economic prosperity, and national security, nations are beginning to choose new ways of obtaining energy that minimize harmful consequences. Nuclear, solar, wind, geothermal, and biomass energy, along with efforts to enhance energy efficiency, are all receiving greater attention from industries, governments, and individuals around the world. But fundamental questions remain about these technologies and their applications. Many are still expensive relative to fossil fuels and may also have harmful impacts when expanded to larger scales. More-efficient and less-expensive technologies may emerge but will require decades of basic research in science and engineering. A transition to new energy systems also raises a broad set of questions about national security and economic development.
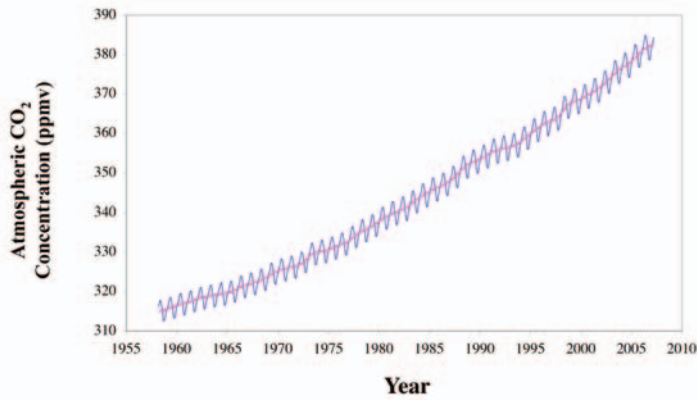
In this paper, I discuss the components of a broad strategy to address the energy–climate challenge. First, I outline a core argument for why climate change is likely to generate broad demand for change in our energy systems and why that demand is likely to increase over the next few decades. Second, I discuss the various energy technologies that are likely to contribute to national and international strategies to address climate change by minimizing carbon dioxide emissions. Finally, I discuss whether the implementation of such strategies is likely to be sufficient to avoid catastrophic consequences and what additional options may exist.

THE GREAT CLIMATE EXPERIMENT

The life work of Charles David Keeling produced the famous Keeling curve (FIG. 1), a record of carbon dioxide measured in the atmosphere at Mauna Loa, Hawai'i, far away from local sources of pollution. Keeling started monitoring in the late 1950s when atmospheric CO_2 was only 315 parts per million (ppm), and it was over 380 ppm when he died in 2005. This rise is due primarily to the burning of fossil fuels: coal, oil, and gas (Keeling and Garcia 2002). Deforestation and other changes in land use have also contributed. The rise in atmospheric CO_2 has not been as fast as the growth in CO_2 emissions. Approximately 60% of the CO_2 emitted to the air stays in the atmosphere, while 20% is taken up by the ocean and 20% by terrestrial ecosystems; this partitioning was demonstrated by measuring the subtle decline in atmospheric oxygen by Keeling's son, Ralph (Keeling and Garcia 2002). This distribution has been remarkably constant over the last two decades. However, the capacity of the ocean and the terrestrial biosphere to partially compensate for our carbon emissions may change as future climate change slows down ocean circulation and as accumulation of organic carbon in soils with subsequent CO_2 emissions begins to balance the enhanced uptake in areas of reforestation.

The Keeling curve is a spectacular record of human impact on the atmosphere, although viewed by itself it understates the scale of our challenge. A more appropriate way to view Keeling's measurements is in the context of a longer record of atmospheric CO_2 measured in ice cores from Antarctica. With the recent drilling of the EPICA core, measurements of ancient atmospheric composition obtained from bubbles in the ice have now been extended back 650,000 years before present (Siegenthaler et al. 2005). Over this time interval, CO_2 reached minimum levels of approximately 180 ppm during the glacial maxima, and peaked below

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FIGURE 1 Atmospheric CO_2 concentrations (ppmv) derived from in situ air measurements at Mauna Loa Observatory, Hawai'i (Keeling et al. 2001)

300 ppm during the interglacials, never rising above 300 ppm (FIG. 2). Direct measurement of more ancient CO_2 levels is not possible unless more ancient ice is identified. However, through a variety of geochemical measurements, including carbon isotopes of organic molecules (Pagani et al. 1999) and boron isotopes that are used to reconstruct seawater pH (Pearson and Palmer 1999), atmospheric CO_2 concentration can be indirectly estimated over much longer timescales. These data suggest that atmospheric CO_2 has not been much higher than 300 ppm for 30 million years or longer. In this context, the scale of our global experiment becomes clear: we are perturbing the atmosphere beyond any state seen through the entire history of the human species. Therefore, we must look to the past to understand the likely implications.

BEYOND NATURAL VARIABILITY

The geologic record demonstrates not only that CO_2 is higher than it has been for millions of years, but also that the recent warming observed over the last 140 years of instrumental record is beyond the range of natural climate variability. Paleoclimate reconstructions of the last several millennia come from many sources, including tree rings, corals, lake sediments, ocean sediments, and speleothems. These records exhibit a substantial amount of regional climate variability over the last 1000 years, although the

Northern Hemisphere average temperature based on reconstructions from multiple proxies remained relatively constant until the last 140 years (Crowley 2000). For example, there are still debates on whether the Little Ice Age, which had a dramatic effect on European farming in the 17th and 18th centuries, was associated with a change in global average temperature (Crowley 2000), but there is no doubt that the Little Ice Age was much greater in western Europe than in other regions. A goal of paleoclimatology has been to understand how local climate changes observed in the various archives relate to larger patterns of climate that can be attributed to specific external forcings (such as CO_2) or to specific dynamical processes (such as El Niño and the North Atlantic Oscillation).

There is one archive of information on past climate that has provided the most compelling evidence for an anthropogenic effect on Earth's climate because the information comes from a part of the Earth system that is very stable: the equator. Tropospheric temperatures near the equator are remarkably constant over seasonal and interannual timescales, especially at higher altitudes where the effects of the boundary layer are small. Starting in the 1970s, L. Thompson and colleagues pioneered the use of solar-powered drilling equipment to obtain ice cores from tropical glaciers at high altitudes in Africa, the Himalayas, and the Andes, recovering records that in some locations extended back to the Last Glacial Maximum (LGM), 20,000 years ago. Through multiple visits to these remote locations, they have documented that tropical glaciers all over the world are receding faster and faster, and in many locations may disappear in the next few decades (FIG. 3) (Thompson et al. 2006). The ice cores, along with plant remains exposed as the glaciers recede, prove that the rate of melting observed today has not happened for thousands of years and cannot be explained by any cycle of natural variability.

CLIMATE SENSITIVITY: A VIEW FROM THE PAST

There is no serious debate that carbon dioxide will cause Earth's surface to warm; what is uncertain is how much warming will occur. To observe the influence of CO_2 on climate, we need only consider our neighboring planet Venus, which has a surface temperature of 465°C because its atmosphere is nearly 100 times denser than Earth's and is composed almost entirely of CO_2. If Earth were dry like
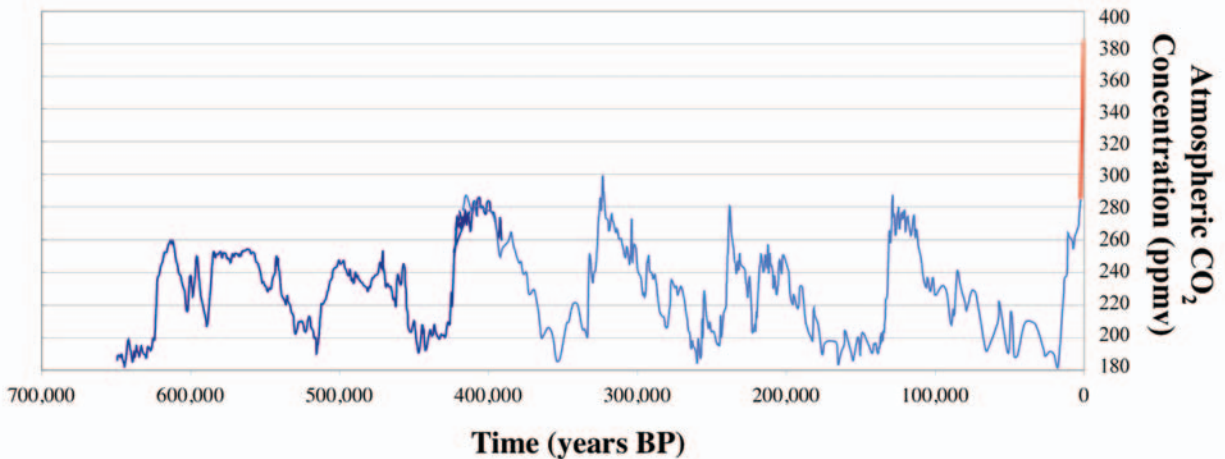

FIGURE 2 Atmospheric CO_2 concentrations inferred from inclusions in ice cores from Vostok (Petit et al. 1999; dark blue line), EPICA (Siegenthaler et al. 2005; light blue line) and obtained from instrumental measurements (Keeling et al. 2001; red line)

Venus, predicting how human activities would affect the climate would be straightforward. Water on Earth affects the climate system in a number of different ways, which makes prediction more complicated. First, water vapor itself is the most important greenhouse gas, acting as an amplifier of other forcings, such as CO_2. Water can also change the planetary albedo—a measure of how much light from the sun is reflected back to space—through the formation or melting of ice or with certain types of clouds. Much of the uncertainty in predicting climate change over the next few centuries is due to uncertainty about the role of water vapor, specifically how big the amplification will be in response to a perturbation from the rise in CO_2.

The standard measure of how much amplification occurs in response to a rise in atmospheric CO_2 concentrations is climate sensitivity, defined as the change in global average temperature for a doubling of atmospheric CO_2. Most general circulation models used to predict future climate change use a climate sensitivity of between 1.5 and 4°C, based on calibration of these models to the observed temperature change over the last century. However, the last century may not be a good predictor of climate sensitivity in the future as CO_2 rises to levels far beyond the calibration range. This is where the geologic record of past climate change is especially useful. From both cold climates of the Pleistocene and warm climates of the Cretaceous and Eocene, the paleoclimate record can tell us something about how sensitive Earth may be to changes in atmospheric CO_2.

The timing of the periodic ice ages over the last two million years was set by changes in the distribution of incoming sunshine caused by variations in Earth's orbit around the Sun. But orbital variations by themselves are not capable of driving global temperature changes of 5°C between glacial maxima and interglacials like the one we live in today. The orbital variations are amplified by changes in planetary albedo due to changes in land and sea ice and by changes in CO_2, as discussed above. The orbital variations are probably connected to climate through the growth of land ice, following the suggestions by Milankovitch (Imbrie 1982). Over these time intervals, temperature and CO_2 are coupled: the temperature change affects the CO_2, both directly through solubility in seawater and indirectly through circulation changes and perhaps aridity and enhanced dust deposition (Sigman and Boyle 2000), while the CO_2 affects the temperature through the greenhouse effect.

One way to estimate the relative contributions of ice albedo and CO_2 is by looking at the temperature change between glacial and interglacial worlds in the tropical waters of the western Pacific, far from the polar ice sheets. The western equatorial Pacific is a warm and stable area of the world ocean; in this region, the sea surface temperature varies very little over seasonal and interannual timescales, and is not sensitive to changes in the polar regions or to changes in the deep circulation. Recent work has shown that the sea surface temperature in the western equatorial Pacific was approximately 3°C colder during the LGM (Lea et al. 2000). This cooling may be explained predominantly by radiative effects associated with changes in atmospheric CO_2, which suggests that at least 2°C of the 5°C total change from glacial to interglacial climates can be attributed to CO_2. As discussed above, atmospheric CO_2 has fluctuated over the late Pleistocene between 180 ppm and 280 ppm, which corresponds roughly to a 50% increase from glacial maximum to interglacial, or half a doubling. This means that a 2°C change from CO_2 implies a climate sensitivity of almost 4°C, which is at the high end of modern estimates.
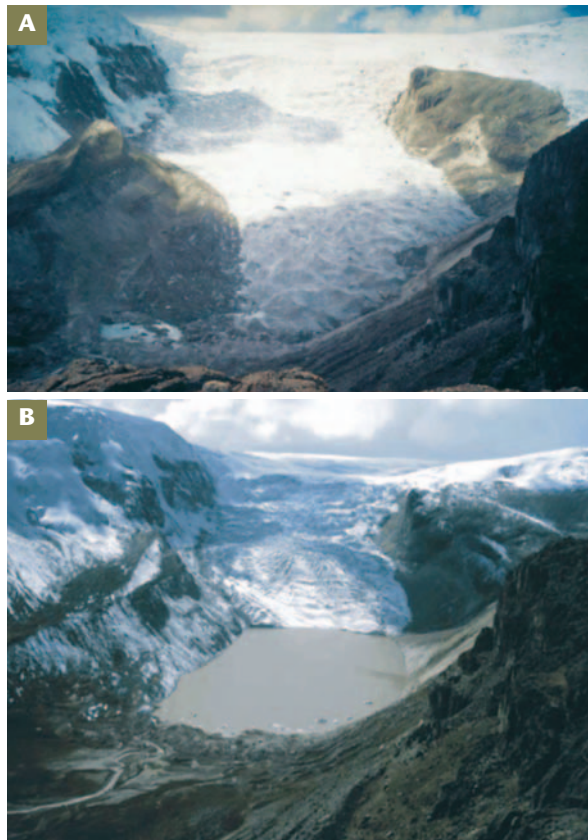
FIGURE 3 Changes in the Qori Kalis Glacier, Quelccaya Ice Cap, Peru, between 1978 (**A**) and 2002 (**B**). Loonie Thompson and colleagues have demonstrated similar glacial retreat in tropical locations around the world (Thompson et al. 2006). PHOTO CREDIT LONNIE THOMPSON

Warm episodes of Earth history reveal even more cautionary lessons. The Eocene, which extended between 55 and 35 million years ago, was the last time when there is clear evidence for global warmth, and we suspect that CO_2 was well above modern levels (Pearson and Palmer 1999). The reconstructions of Eocene climate, including isotopic, chemical, and paleobiological data, reveal a general picture of a very warm world, with polar temperatures elevated by as much as 6 to 10°C, but tropical temperatures only slightly higher than modern, if at all (Zachos et al. 2001). In addition to the reduced meridional temperature gradient, there is evidence from the fossil locations of warm-climate plants such as palm trees that winters in the continental interiors were much milder than today (Wing and Greenwood 1993).

We do not know precisely how high atmospheric CO_2 was during the Eocene, so it is difficult to use the Eocene as a direct measure of climate sensitivity. However, the extreme warmth at high latitudes, and in particular the wintertime warmth in continental interiors, cannot be simulated by climate models by elevating greenhouse gas concentrations unless special cloud feedbacks are included that are not present in the models used to predict future climate change (Sloan and Pollard 1998). This suggests that there are feedbacks missing from our models that may cause us to underestimate future climate change, particularly at high latitudes. One interesting hypothesis is that the warm continental interiors were due to optically thick polar stratospheric clouds that formed in the Eocene during times of higher CO_2 (Sloan et al. 1992; Kirk-Davidoff et al. 2002). If correct, such a mechanism should become evident in the next century as CO_2 rises above 500 ppm. Whatever the

explanation, the inability of climate models to simulate Eocene warmth serves as a warning that future climate change may be larger than climate models predict.

An important difference between the Eocene and climate change we might expect over the next few centuries is that the warm climate in the Eocene persisted for millions of years, with higher CO_2 concentrations brought about most likely from higher rates of volcanic outgassing (e.g. Berner et al. 1983). This means that the entire climate system as well as most ecosystems in the Eocene had time to adjust to the higher radiative forcing and reach a quasi-equilibrium state, with no ice caps at high latitudes and very warm deep-ocean temperatures. In contrast, our experiment this century is happening quickly enough that there may not be enough time (thankfully) to melt all the ice caps or to warm the entire deep ocean.

A better analogue of future climate may be a time in the geologic past when a perturbation in greenhouse gas concentration occurred over a shorter timescale. Just such an event happened at the very beginning of the Eocene, 55 million years ago. During the Paleocene–Eocene Thermal Maximum, global temperature warmed by 6°C in less than 10,000 years (Zachos et al. 2001), coincident with a change in the carbon isotope composition of seawater that was likely the result of the oxidation of a large amount (i.e. >5000 Gt) of organic carbon (Higgins and Schrag 2006). Because the event occurred over a time interval longer than the mixing time of the oceans, the atmosphere and oceans had time to equilibrate. By modeling the carbon cycle during this event, it was shown that the CO_2 concentration in the atmosphere must have tripled or possibly quadrupled, implying a climate sensitivity of 3 to 4°C per doubling, consistent with evidence from the Pleistocene (Higgins and Schrag 2006). However, this may be a low estimate relative to what we may see over the next few centuries because there were no ice sheets or sea ice before this event, so there was no amplification like the one that may be important in our future.

A final lesson from the study of past climates is that climate changes are not always slow and steady but can occur in decades or even years. As interpreted from Greenland ice cores, the abrupt changes of more than 20°C in regional temperature during the last glacial period (e.g. Severinghaus et al. 1998), with smaller effects throughout the Northern Hemisphere, are spectacular examples of how quickly regional climate can change. The mechanisms responsible for such changes during the ice age probably required greater extent of land glaciers and sea ice, and so these same mechanisms are unlikely to be experienced in exactly the same way over the next century. However, a number of possible "tipping points" can result in abrupt and irreversible change in the climate system. One is the response of glaciers on Greenland and Antarctica to enhanced polar warming over the next century. We do not know enough about glacial melting to be able to predict whether these ice sheets will decay smoothly or whether there is the possibility for threshold behavior resulting in a very rapid collapse. Another potential tipping point is the roughly 500 Gt of carbon stored in permafrost in the tundra regions, particularly in Siberia because it was not glaciated during the Pleistocene, allowing labile organic carbon to accumulate in frozen soils. As those soils warm, carbon in organic matter is fermented by microbes and released as methane or respired by microbes and released as CO_2 (Schiermeier 2001). Either way, such a release of greenhouse gases could be a disaster if it happened quickly as it would overwhelm any emission-reduction program we might implement.

In general, Earth appears to be more sensitive to changes in atmospheric CO_2 than the models we use to predict the future because climate sensitivity in a strict sense appears to be higher in nature than in our models and because the models cannot provide probabilistic estimates for abrupt climate change. It would be a grave mistake to take these lessons from ancient climates as a reason to disregard predictions from climate models. These models are not perfect, but they do represent our best understanding of the climate system based on a century of observations, and they remain an essential tool for exploring future scenarios. At the same time, it is not surprising that the models are not perfect as our atmosphere is heading to a state unlike any seen for millions of years. In confronting climate change, it is important to realize that our predictions may be conservative.

TOWARDS A SOLUTION

Given the dramatic changes we are observing today and the dire view from Earth history, what can we do? The first challenge we must confront in working towards a solution to future climate change is that any "solution" will be incomplete. Some amount, perhaps even a substantial amount, of climate change is unavoidable. Reducing CO_2 emissions so that they are below the level of CO_2 uptake by the oceans and biosphere will not happen in a decade or two, but only through prolonged actions over 50 years and perhaps longer. Even if more immediate actions were possible, the current atmosphere with more than 380 ppm CO_2 may be too warm to allow the ice sheets on Greenland or West Antarctica to survive; exactly how much melting will occur if emissions were stabilized at current levels remains uncertain. In addition, the oceans will continue to warm for decades even if emissions were halted. Ecological changes due to climate change that has already occurred will continue to unfold for decades. Another problem is that the CO_2 resides in the atmosphere and surface ocean for centuries and is only slowly taken up by the deep ocean. If we were to reduce our emissions to zero immediately, it would take more than 200 years for terrestrial and oceanic uptake of carbon to restore the atmosphere to its pre-industrial condition. Thus, there is great momentum in the climate system, in the heat capacity of the oceans, in ice sheets, and in the residence time of carbon dioxide in the atmosphere, and this fact makes a certain amount of climate change inevitable. Future impacts will include sea level rise, changes in rainfall patterns, early melting of mountain snowpack and glaciers (which serve as a water supply for billions of people), changes in storms and tropical cyclones, and ecological changes that affect ecosystems crucial to human society. Adaptation efforts are essential to help people adjust to these changes.

Some people have argued, based on economics, that we dispense with mitigation and focus all our efforts on adaptation, trying to avert the impacts of climate change or at least make them less costly (Lomborg 2004). The flaw in this argument is that adaptation becomes more and more difficult—ultimately impossible—if mitigation is not pursued. Consider the impact of sea level change, only one of many serious impacts of future climate change. One might propose that it is reasonable to do nothing about CO_2 emissions in response to future sea level rise and instead focus our efforts on building dykes and levees to protect low-lying areas and on moving cities to higher ground. This might be a fine strategy if sea level rise stopped after 2100. But after the first meter of sea level rise due to melting of the Greenland ice sheet, there will be the second, and the third—ultimately 7.2 meters if the Greenland ice sheet melts entirely (FIG. 4). And then there is the 6 meters of sea level equivalent stored in West Antarctica, and the 50 meters or

so in East Antarctica. The consequences of ignoring climate change and allowing atmospheric CO_2 to reach 1000 ppm or higher—quite possible if no mitigation steps are taken—are simply too great to allow adaptation in any meaningful sense.

Thus, dealing with climate change means both adaptation and mitigation. Adaptation requires significant attention and resources, but this discussion will focus on mitigation and more specifically, its scientific and technological challenges. Climate change mitigation requires an enormous shift in energy systems, which are themselves issues of national security and economic prosperity. This means that solving the climate–energy challenge is not just solving the problem of high CO_2 emissions; it also means creating low-carbon sources of energy that are secure and inexpensive. It is a challenge far too great to describe in detail in this paper. Instead, I will attempt in the final section to outline some of the scientific and technological approaches that are likely to be a part of any solution. It is important to remember, however, that scientific and technological considerations may be trumped by considerations of national security and economic well-being.

ENERGY SYSTEMS OF THE FUTURE

One source of confusion in discussions on how to reduce CO_2 emissions is that our energy system is really more than one system. We use energy for transportation, for electricity to power our lights and electronics, to heat or cool our homes, for manufacturing, and for agriculture. Our energy choices within each of these sectors come with different technological constraints that require different types of solutions if reductions in CO_2 emissions are to be achieved. For example, the internal combustion engine (along with the gas turbine in airplanes) currently dominates the transportation sector and is fueled almost exclusively by petroleum, responsible for approximately 40% of global CO_2 emissions (TABLE 1). The electricity industry has a much broader set of energy sources, including coal, natural gas, nuclear, hydroelectric, wind, solar, biomass, and geothermal, although coal, natural gas, and nuclear are currently dominant. Thus, the discussion of strategies for mitigating climate change must address not just sources of energy, but sources in relation to different societal needs.

Another consideration is differences in energy technologies among countries. Some countries, such as Saudi Arabia and Russia, are rich in hydrocarbon resources, and this guides their energy decisions. Other countries, such as Japan, have almost no domestic energy resources, and turn to technological solutions such as solar and nuclear power. The end use of energy also varies among countries. For example, both China and the U.S. have large coal reserves, but China consumes almost twice as much, in part due to its large manufacturing industry compared with the service economy of the U.S. (BP 2006). What this means is that there is no single strategy for how the world will address climate change but rather a portfolio of strategies. Rapidly developing countries will have different solutions from those of developed countries. Even countries with similar levels of economic development will employ different solutions because of geography, political and cultural attitudes, and political systems. This does not mean that individual solutions must be created for all countries. CO_2 emissions are not distributed evenly; a handful of countries contribute most of the emissions and will be responsible for bringing about most of the reductions. If the U.S., China, India, the European Union, Russia, Japan, Australia, Canada, and perhaps Indonesia and Brazil each take significant steps to
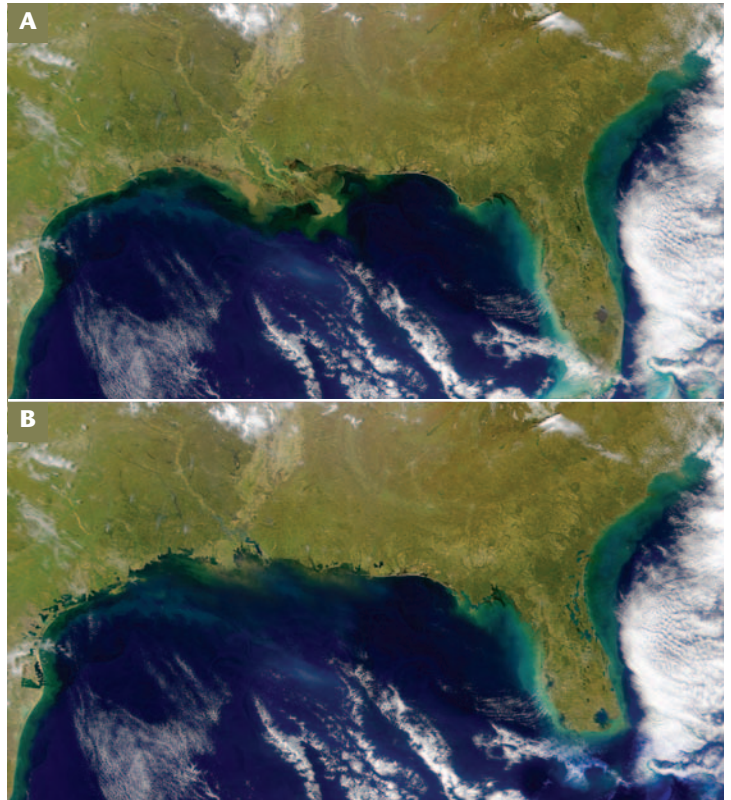
FIGURE 4 Artistic representation of the southeastern United States today (**A**), and (**B**) what it would look like if half of the Greenland ice sheet melted (3.5 m sea level rise). ART CREDIT: J.T. WILLIAMS AND D.P. SCHRAG

reduce emissions, it is likely that such efforts will be successful in reducing the impacts of climate change on the rest of the world.

Another constraint is the timescale over which it is possible to build new energy systems. Eliminating carbon emissions from electricity generation by using nuclear power, for example, would require building two large nuclear plants each week for the next 100 years. This rate of change is simply not possible given current constraints on steel production, construction capacity, and the education of operators, and because of many other practical considerations. Taken together with the diverse uses of energy and the different needs of different nations, this means that there is no silver bullet solution for the climate–energy challenge. A myriad of approaches is required. One can group these approaches into three broad categories, each of which will contribute an essential part to any serious climate mitigation effort.

Reduction of Energy Demand

The first category involves reducing CO_2 emissions by reducing energy consumption. This does not necessarily require reducing economic activity, i.e. consuming less; rather it means restructuring society, either by investing in low-energy adaptations such as efficient public transportation systems, or by adopting energy-efficient technologies in buildings, in automobiles, and throughout the economy. Huge discrepancies in energy efficiency exist today among developed countries. In general, countries with higher historical energy prices, such as most of western Europe, are more efficient than countries with inexpensive energy, including petroleum. However, the differences can also be explained by historical investments in cities and suburbs and in highways and public transportation systems, as well

as by a variety of other factors. But whatever the cause of the current differences among countries, there is great potential across the developed and the developing world to dramatically lower energy use through smarter and better energy systems.

Much of the efficiency gains can be accomplished with existing technologies, such as compact-fluorescent lighting or more efficient building designs; these are often referred to as the "low hanging fruit" as they are often economically advantageous because they are simple and inexpensive. In addition, there are technological improvements in end use that would contribute greatly to any emissions reduction effort by making large jumps in energy efficiency. For example, if better batteries for electric automobiles can be developed that are economical and reliable, and if the technology is broadly adopted, it will allow for the replacement of the low-efficiency internal combustion engine with the high-efficiency electric motor. Moreover, electric cars would break the monopoly that petroleum currently has as the source of energy for transportation, thus addressing security concerns involving the geopolitics of oil and allowing transportation fuel to come from carbon-free sources discussed below. Whether better batteries are technically possible remains a question.

Non-Fossil Energy Systems

The second category of solutions to the climate–energy challenge involves expansion of non-fossil energy systems, including wind, solar, biomass, geothermal, and nuclear power. Again, there is no silver bullet. Wind is currently the most economical of these energy systems for electricity generation. However, wind requires huge excess capacity because of problems with intermittency, and so it cannot become a source for baseload power unless storage technologies improve. Solar-generated electricity has similar problems with energy storage and is also expensive compared with wind or nuclear power. Nuclear power can be used for baseload power, unlike wind or solar, but issues of safety, storage and handling of nuclear waste, and security concerns about nuclear weapons proliferation will have to be addressed before widespread expansion is likely, at least in the U.S. and western Europe (aside from France). This category is one with great hopes for technological "breakthroughs"—such as fusion, inexpensive solar, and inexpensive fuel cells—that may revolutionize our energy systems. Thus, basic research and development must be a part of any climate mitigation strategy. However, no responsible strategy should rely exclusively on breakthrough technologies as they may not exist for decades, if ever.

Outside of the electric realm, biomass converted to biofuel may play a major role in reducing CO_2 emissions in the transportation sector, at least until powerful, inexpensive, and reliable battery technologies or some alternative transportation technologies are developed. For example, Brazil currently obtains most of its transportation fuel from fermentation of sugar cane into ethanol, and similar programs are being implemented around the world. A more efficient technology may be the conversion of biomass into synthetic diesel fuel via the Fischer-Tropsch process, which was used by the Germans in World War II to transform coal into liquid fuel. This process has the advantage of creating a more diverse range of fuel products, including jet fuel for air transport, and of being more efficient through use of all types of biomass, not just sugar (or cellulose for a cellulosic conversion process). Moreover, the Fischer-Tropsch process, which involves gasification of the biomass followed by conversion to liquid fuel via a cobalt or iron catalyst, requires

removal of CO_2 to avoid poisoning the catalyst, making adaptation easy for the capture and storage of CO_2, as discussed below.

Carbon Sequestration

The third category of solutions involves CO_2 capture from emissions sources and storage in geologic repositories, a process often referred to as carbon sequestration. This is an essential component of any climate mitigation portfolio because of the abundance of inexpensive coal in the largest economies of the world. Even with huge improvements in efficiency and increases in nuclear, solar, wind, and biomass power, the world is likely to depend heavily on coal, especially the five countries who hold 75% of world reserves: U.S., Russia, China, India, and Australia (TABLE 1). However, as a technological strategy, carbon capture and storage (CCS) need not apply only to coal; any point source of CO_2 can be sequestered, including biomass gasification, which could result in negative emissions.

The scientific questions about CCS deal with the reliability of storage of vast quantities of CO_2 in underground repositories—and the quantities are indeed vast. Reservoir capacity required over the next century is conservatively estimated at one trillion tonnes CO_2, and it may exceed twice this quantity. This amount far exceeds the capacity of old oil and gas fields, which will be among the first targets for sequestration projects because of additional revenues earned from enhanced oil recovery. However, there is more than enough capacity in deep saline aquifers to store centuries of emissions (Anderson and Newell 2004), and also in deep-sea sediments, which may provide leakproof storage in coastal sites (House et al. 2006). In general, the storage issues do not involve large technological innovations, but rather improved understanding of the behavior of CO_2 at high pressure in natural geologic formations that contain fractures and faults. Geologic storage does not have to last forever—only long enough to allow the natural carbon cycle to reduce the atmospheric CO_2 to near pre-industrial levels. This means that storage for 2000 years is long enough if deep-ocean mixing is not impeded significantly by stratification. It seems likely that many geological settings will provide adequate storage, but the data to demonstrate this over millennia do not yet exist. A more expansive program aimed at monitoring underground CO_2 injections in a wide variety of geologic settings is essential if CCS is to be adopted before the middle of the century (Schrag 2007).

The technological advances in CCS involve improving the efficiency of the capture of CO_2 from a coal-fired power plant. Capture can take place either by postcombustion adsorption, or through design of a power plant (either oxy-combustion or gasification) that produces a pure stream of CO_2 as an effluent. Either way, the capture of CO_2 is expensive, both financially and energetically. It has been suggested that capture and storage combined would use roughly 30% of the energy from the coal combustion in the first place (IPCC 2005) and may raise the cost of generating electricity from coal by 50% (Anderson and Newell 2004), with two thirds of this increase coming from capture. Even though these estimates are uncertain, given that carbon sequestration is not yet practiced at any coal plant, it is clear that technological innovation in the capture of CO_2 from a mixed gas stream is important.

Carbon sequestration also includes enhanced biological uptake such as through reforestation or fertilization of marine phytoplankton. These approaches could be considered a separate category as planting trees is quite different from injecting vast quantities of CO_2 underground. If pur-

	COAL		PETROLEUM		NATURAL GAS	
	RESERVES	PRODUCTION	RESERVES	PRODUCTION	RESERVES	PRODUCTION
U.S.	184.0	0.64	3.6	0.30	3.0	0.29
Russia	117.1	0.15	9.0	0.42	26.2	0.33
China	85.4	1.24	1.9	0.16	1.3	0.03
India	69.0	0.22	0.7	0.03	0.6	0.02
Australia	58.6	0.23	0.5	0.02	1.4	0.02
Middle East	0.3	0.00	90.2	1.11	39.4	0.16
Total World	**678.2**	**3.23**	**145.8**	**3.59**	**98.4**	**1.51**

Carbon content was calculated assuming 25.4 tonnes carbon per tera-joule (TJ) coal; 19.9 tonnes carbon per TJ petroleum; 14.4 tonnes carbon per TJ natural gas (CO_2 content 3.6 times as much). Differences between anthracite, bituminous, lignite, and sub-bituminous coal were not included. (DATA FROM BP 2006)

sued aggressively, such strategies might offset CO_2 emissions by as much as 7 Gt per year by the end of the century, out of total emissions of more than 80 Gt per year as forecasted in most business-as-usual scenarios. These approaches might be an important piece of a solution, but they will not replace the need for improved energy efficiency, non-fossil energy sources, and carbon sequestration.

WILL IT BE ENOUGH?

The nature of the climate experiment means that no one truly knows what a safe level of CO_2 really is, apart from the impossible goal of the pre-industrial level of 280 ppm. It is possible that nations will implement many of the approaches outlined above over the next few decades, which would stabilize atmospheric CO_2 below 600 ppm; it is difficult to imagine that a much lower stabilization level will be realized given the current state of the world energy systems. It is possible that this effort will be enough, that the world will warm another 2 or 3°C, that ice sheets will slowly melt, and that most of the severe consequences will be gradual, allowing adaptation by humans and natural ecosystems. On the other hand, it is also possible that even with concerted effort and cooperation among the large nations of the world, the climate system will respond too quickly for humans to adapt, that the Greenland and West Antarctic ice sheets will decay more quickly than expected, and that the impacts of a warmer world on humans and on natural ecosystems will be worse than we now predict.

It is very difficult to know which scenario is correct. Because of the potential for catastrophe, it seems prudent to ask what societies might do if the rate of climate change were to accelerate over the next few decades and if the consequences were to be much worse than anticipated. One approach that has long been discussed is the engineering of our climate system by adjusting the incoming solar radiation by means of reflectors in space or in the upper atmosphere (Keith 2000); indeed, there may be some ways to accomplish a reduction in solar radiation at very low cost relative to other strategies of mitigation (Schelling 1996). Recently, such ideas have gained more prominence (Crutzen 2006), not as a substitute for serious emissions reductions, but in the sober realization that efforts to reduce emissions may not be sufficient to avoid dangerous consequences. The power to engineer the climate comes with an awesome responsibility. How could we engineer such a system to be failsafe? Which countries would control this effort? Who would decide how much to use, or when? And what would happen if something went wrong, if we discovered some unforeseen consequences that required shutting the effort down once human societies and natural ecosystems depended on it?

These scientific, political, and ethical questions will be debated over the next few years and decades. However, it is likely that they will not be hypothetical for long; even with the most urgent efforts over the next decade to take action and begin mitigation efforts with vigor, we must accept that we are heading into a climate state that no human has ever seen. Surprises are inevitable; how we deal with them may be our greatest challenge.

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