The Increasing Pace of Climate Change

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ABSTRACT

Combustion of coal, oil, and natural gas and, to a lesser extent, deforestation, land-cover change, and emissions of halocarbons and other greenhouse gases, are rapidly increasing the atmospheric concentrations of climate-warming gases. The resulting warming of about 0.1 to 0.2°C per decade that has taken place over the last several decades is very likely the primary cause of the loss of snow cover and Arctic sea ice, the more frequent occurrence of very heavy precipitation, rising sea level, and shifts in the natural ranges of plants and animals. Global average temperature is already ~0.8ºC above its preindustrial level. As expected, warming has been greater in mid and high latitudes compared to low latitudes, over land compared to oceans, and at night compared to day.

The present atmospheric levels of long-lived greenhouse gases are pushing toward further warming of ~1.0-1.5ºC. This further warming is being held back by the time it takes for the oceans to warm and by the cooling influence of short-lived sulfate aerosols. As a result, at least as much further warming as has occurred to date would be expected even if global greenhouse gas emissions could be immediately cut to zero. At their present rate, ongoing emissions and the past commitment to warming are projected to lead to further warming at a rate of ~0.2-0.3ºC per decade over the next several decades, especially if emission controls are not put in place. Such warming and the associated changes are likely to cause severe impacts to key societal and environmental support systems. Present estimates are that reducing emissions sharply by 2050 and to near zero by 2100 will be required to limit the increase in global average surface temperature to no more than 2 to 2.5°C above its 1750 value of about 15ºC, and that this will be necessary to avoid the most catastrophic, but certainly not all, consequences of climate change.

INTRODUCTION

It was only 40 years ago that the Apollo 8 mission orbited the Moon and the astronauts observed the first "Earthrise," a view that inspired poet laureate Archibald MacLeish to characterize the Earth as a blue orb in space with "ourselves as riders on the Earth together" [1]. Majestic as the imagery, the reality is that humans are no longer *riders* on the planet; we are now the drivers, directly determining atmospheric composition and surface cover, and thereby responsible for climate change and sea level. As Nobelist Paul Crutzen has suggested [2], we have shifted the geological era from the relative constancy of the natural Holocene (i.e., the last 10,000 years during which civilization developed) to the changing conditions of the new Anthropocene, the era of human dominance of the Earth system.

That human activities are having a global-scale influence is most evident in satellite views of the nighttime Earth. Excess light now illuminates virtually all the developed areas of the planet, locating the cities, industrial areas, tourist centers, and transportation corridors. With roughly two billion people having to rely on fires and lanterns instead of electricity, what is visible only hints at the full extent of the human influence on the planet. Over 80 percent of the world's energy (and a higher fraction if rural biomass sources are excluded) comes from the combustion of coal, petroleum, and natural gas. Combustion of these fuels, derived from the fossilized remains of plants and animals accumulated over hundreds of millions of years, is providing tremendous benefits to the roughly 6.5 billion people on Earth, ensuring food, medicine, shelter, and a longer and easier life. Fossil fuels have become the dominant source of energy because they are relatively abundant, accessible, transportable, storable, and concentrated. In addition, a global infrastructure is in place that provides their energy for use day or night, rain or shine. Fossil fuels are thus indispensable to the support of today's standard of living for peoples around the world.

However, the global use of fossil fuels and a number of other societal activities introduce a range of health and environmental problems. Some problems, like air and water pollution, result from inherently wasteful and inefficient activities and can readily be controlled using improved technologies. The emissions of other substances, such as mercury and sulfur dioxide (SO_2) from coal combustion, result from trace contaminants and can generally be controlled at relatively low cost—once a commitment is made to improve environmental quality rather than just foster economic growth. Emission of carbon dioxide (CO_2), however, is different in two important ways: (1) it is a primary constituent of fossil-fuel exhaust streams; and (2) a significant fraction of the increment to the global atmospheric CO_2 concentration persists for many centuries, acidifying the ocean for millennia, and leading to significant, disruptive, long-term, and even irreversible consequences for the environment and society.

To collect and assess international scientific understanding about climate change, the Intergovernmental Panel on Climate Change (IPCC) has, since 1990, been conducting assessments of the effects of human activities on climate, resultant impacts on the environment and society, and on options for slowing and stopping climate change. The series of four IPCC assessments over the past 20 years, the most recent in 2007 [3-6], has spurred significant gains in understanding and, because of their wide-ranging and rigorous review process, earned international credibility, including endorsements by the academies of science of many countries and many professional societies. The basic scientific aspects are well established, and the risk of significant impacts is clear. While many details remain to be worked out about the pace and regional manifestations of the coming changes in climate, there is an increasing likelihood that the changes induced by later this century could well have catastrophic impacts, and this conclusion is prompting intensifying pressure to sharply reduce greenhouse gas emissions as rapidly as possible.

The most important findings for governments and decision makers facing the challenge of climate change can be summarized in six straightforward findings:

- Emissions from human activities, particularly from combustion of coal, oil, and natural gas using technologies that do not capture and permanently sequester the CO_2, are raising the atmospheric concentrations of long-lived climate-warming gases.
- Enhancing the natural greenhouse effect in this manner will lead to global warming that will, in turn, lead to associated changes in climate and a rise in sea level that will persist for many centuries.
- Changes in the climate and sea level are already evident, and these changes are consistent with theoretical understanding and model simulations of the human-induced changes in atmospheric composition.

- Future warming and sea level rise are projected to be substantial, especially if emissions continue to rise.
- The environment and society will both be impacted in significant ways by changes in the climate, CO_2 concentration, and sea level rise.
- Slowing and stopping climate change, and avoiding the most severe consequences, will require substantial reductions in greenhouse gas emissions over coming decades.

While uncertainties do exist, the first two findings are very well established, the second two are becoming increasingly well established; and the last two lay out the prospects for the future and the challenge that society faces in dealing with the issue. Supporting explanations for these findings are presented briefly in the following sections, and more details are available in a recent review article [7] and in the IPCC assessments [3-6].

FINDING 1: GREENHOUSE GAS CONCENTRATIONS ARE RISING

In 2007, the CO_2 concentration measured at the Mauna Loa Observatory in Hawaii, a site representative of the global average value, was ~383 ppmv (parts per million by volume). This concentration is ~21 percent higher than the value of ~315 ppmv observed when the station was established in 1957 and ~37 percent above the pre-industrial value of ~280 ppmv. The concentrations of methane, nitrous oxide, chlorofluorocarbons, and other halocarbons are also rising [8].

These increases in concentration are being driven by a range of human activities. Net emissions of CO_2 from land use, decay, and deforestation are estimated to have been contributing ~1.5±0.5 PgC/yr for the last 50 years (1 PgC/yr equals 10^{15} gC/yr equals 1 gigatonne of C per year or GtC/yr). Combustion of coal, oil, and natural gas, which transfers geologically stored carbon into the atmosphere, was about equivalent to the land use contribution in 1950, but has grown dramatically since then. Annual fossil-fuel emissions totaled ~7 PgC/yr in 2000, and have risen to ~8.4 PgC/yr in 2006 [9]. This amount is roughly equivalent to the seasonal uptake of C each year as the northern hemisphere living biosphere goes from spring to fall. The annual increase in the atmospheric burden is about half of this amount as a result of uptake by the ocean and additional long-term storage by the biosphere.

With respect to emissions estimates, note that the scientific literature expresses emissions as the mass of C emitted (as CO_2) because of interest in following the C atom through the atmosphere, ocean, and biosphere, where it gets chemically bound in different forms. The national and international regulatory and negotiation processes, however, keep track of the mass of CO_2 emitted (so the mass of material that must be dealt with), so their calculations include the weight of the two oxygen atoms, making the regulatory mass emitted a factor of 3.67 larger than the scientific expression of the mass. To simultaneously consider the effects of the other gases, the mass emissions of other gases are multiplied by the global warming potential of that gas, which is chosen to make their climatic influences equal over a 100-year interval. Summing overall greenhouse gases yields the CO_2-equivalent emissions (or concentrations), and the emissions are typically given in units of millions of metric tons of CO_2-equivalent (or MMTCE).

The recent acceleration in CO_2 emissions is occurring primarily to meet the rapid growth in the global demand for energy, particularly in China, India, and elsewhere in eastern Asia. Burning coal is presently the least expensive energy option, so the number of coal-fired electric plants is increasing sharply. Given the development going on in this region of the world, most projections suggest continuing rapid increases in global emissions of CO_2 unless strong policy actions are taken.

While media attention in the US, prompted by the administration, has focused on China recently overtaking the US in total emissions, those in developing countries point out that there remains a significant disparity in per capita emissions. Globally, present per capita emissions are about 1.3 tC/yr, with China near that value, India and many developing countries below (or even well below) that value, Europe at about 3 tC/person/yr, and the US and Canada about twice the European value. Indeed, with rare exception, the most developed countries all have per capita emissions that are 2-5 times the global average, suggesting that such a per capita level is needed to sustain a modern society. The developed nations also generate several times as much value per unit of CO_2 emissions (i.e., in terms of dollars of GDP per metric ton of CO_2 emitted). The administration's proposed standard for moving forward has focused on improving this measure of emissions (basically, with the US having, or nearly having, the highest total emissions and highest per capita emissions for a large country, focusing on the economic efficiency measure was about the only way to make the US situation look other than horrific in terms of climate change influence). Unless the developing countries become as economically efficient as the US and Europe (which will be difficult given the greater share of their economies devoted to heavy industry), their per capita emissions will likely need to surpass those in developed nations to achieve an equivalent standard of living. As a result of these considerations, most no-policy emissions scenarios project that future global emissions of C from fossil fuels will be several times as large as at present unless there are very rapid advances in reducing the cost of generating energy from solar, wind, and biomass resources [10].

For 2005, EPA [11] found that ~84 percent of the CO_2-equivalent emissions resulted from CO_2 emissions (1.66 PgC/yr, or 21 percent of the global total), 7.4 percent from CH_4, 6.5 percent from N_2O, and 2.2 percent from halocarbons and perfluorocarbons. The relative roles of CO_2, ~94 percent of which is from fossil-fuel combustion, and halocarbons are rising, while the relative roles of CH_4 and N_2O are slowly declining. Of the U.S. CO_2 emissions, 33 percent result from transportation (more than 60 percent from use of personal vehicles), 27 percent are from industry (split between direct use of fossil fuels and use of electricity derived from them), 21 percent are from residential use (70 percent from use of electricity), and 18 percent are from commercial sources (78 percent due to electricity). The electric generation sector uses 93 percent of the coal in the U.S., and, because combustion of coal leads to higher CO_2 emissions per unit energy than other fuels, 41 percent of the CO_2 emissions result from generation of electricity.

With the US not moving at a national level to push emissions down, various states are beginning to do so. Considering each state as a nation gives a sense of how intertwined and complex these relationships between total and per capita emissions can become. Based on emissions data and populations of several years ago, and it is unlikely much has changed since, the state with the highest total emissions from combustion of coal, oil, and gas was Texas, emissions from which were about twice those of California, even though California's population is about two-thirds larger. On a per capita basis (with the US average per capita emissions being a bit below 6 tC/person/yr), Wyoming was the highest, with over 30 tC/person/yr, and North Dakota was second with about 20 tC/person/yr. At the other extreme, Oregon, Vermont, New York, and California had the lowest per capita emissions, each with about 3 tC/person/yr (or about half the US average).

The primary reason for these differences was not choice, but circumstance; Texas and Wyoming are both states heavily involved in energy intensive activities such as extraction, processing, and/or combustion of coal and oil to benefit those in other states—by contrast, Oregon, Vermont, New York, and California, while actively encouraging efficiency, each rely on heavy industrial products and electricity made elsewhere, and/or have abundant hydroelectric and other non-carbon-based energy that is available due to their particular geography. An alternative approach would look at the carbon footprint of the lifestyles in each region, including both the national and international components, but this can get very complicated, and is why the notion of a carbon tax that would impose the effect of the footprint on prices is pushed as a policy step instead of trying to do an actual accounting.

FINDING 2: INTENSIFYING THE GREENHOUSE EFFECT WILL LEAD TO WARMING

The Earth's climate is different than that of the moon largely because of the trapping of infrared radiation by the atmosphere, which is a consequence of its composition, and because of the thermal inertia provided by the oceans. Rather than all of the incoming solar radiation being absorbed at the surface, with the absorbed fraction warming the surface up until balanced by emission of infrared (IR) radiation, the atmosphere intervenes: clouds, and to a lesser extent the surface and atmospheric gases, reflect about 30 percent of the incoming solar radiation back into space. Clouds and atmospheric greenhouse gases (those gases having three or more atoms) absorb and emit back toward the surface all but 5-10 percent of the upward-directed IR radiation, thereby impeding the natural cooling of the planet. As a result, the Earth's surface temperature is ~33ºC higher than would be the case if the greenhouse gases (GHGs) in the atmosphere were having no effect on the IR radiation.

Mars and Venus provide excellent tests of our understanding of how the GHGs cause this to occur. The surface temperature of Venus is much higher than the Earth, but not because Venus is closer to the sun. On a per unit area basis, the very bright clouds that make Venus so visible in the night sky limit absorption of solar radiation to less than for Earth. Instead, the very high atmospheric concentrations of GHGs in the atmosphere of Venus allow some solar energy to pass through, but then recycle the IR radiation over and over, thereby pumping up surface and atmospheric temperatures until planetary emissions match absorbed solar radiation. Although the Martian atmosphere is mainly CO_2, it is farther from the sun; lacking water vapor, its surface temperature is only slightly elevated by its GHGs. Once adjustments are made for the very different compositions and pressures of these planetary atmospheres, the same radiation models used to simulate solar and IR radiation fluxes in the Earth's atmosphere explain the conditions observed on the Earth's sister planets. Without a doubt, increasing the concentrations of GHGs will lead to warming, climate change, and sea level rise.

Understanding of the greenhouse effect can also be checked against Earth's climatic history. Using all sorts of geological, geochemical, isotopic, and biological indicators, significant success has been achieved in reconstructing past climatic conditions and in understanding the reasons that the changes occurred, including changes in the amount of incoming solar radiation and the Earth's orbital parameters, the locations of the continents and surface geography, and atmospheric composition [3, Chapter 6]. What is clear from the record is that over the Earth's 4.6 billion year history, its climate was not random, but was controlled and altered by the changing roles of various forcing factors.

Ice age cycling over the last few million years provides one example of how the climate's sensitivity to changes in available energy can be estimated. Data extracted from Antarctic ice cores provide the best combination of detail and length of record. Now extending back ~800,000 years [12], the record shows well-correlated variations in temperature and in CO_2 and CH_4 concentrations. The overall timing is also well-correlated with the combined effects of the cycling of three of the Earth's orbital elements, the major features of which involve: (1) the ellipticity of the Earth's orbit, which varies between near circularity and slight ellipticity with a frequency of ~100,000 years; (2) the tilt of the Earth's axis, which varies between about 22 and 25 degrees with a period of ~41,000 years; and (3) precession, which measures the time of year of closest approach to the sun and has a period of ~26,000 years. When the major and minor terms of these cycles, which are a result of the time-varying gravitational pull of the sun and planets, are properly combined, the periodicities that emerge, particularly for the amount of solar radiation reaching high latitudes, match quite well with the periodicities determined from the ice cores over the full length of the record. Reassuringly, the present orbital parameters are closest to those of the 40,000 year interglacial that occurred about 420,000 years ago. In the absence of human influences, this analog suggests that we are not near to the start of another ice age, a concern that was raised based on pure statistical considerations back in the 1970s and can now be discounted.

Working with a two-dimensional (latitude-vertical) climate model [one that has been completely overhauled since I built the first such model for my dissertation in the 1960s], Berger and his colleagues in Belgium have made simulations of the climate changes that would be caused by the changing influences over hundreds of thousands of years. Although not completely prognostic (i.e., not completely predicted from basic physics), their results indicate significant progress in quantifying the contributions of various factors to glacial-interglacial cycling [13]. The results suggest that, considering all of the process involved, the record is most consistent with a climate sensitivity (i.e., change in global average temperature) of ~3°C for a doubling of the atmospheric CO_2 concentration—and, interestingly, his model does not generate glacial cycling with a CO_2 concentration above ~400 ppmv. This paleo-derived climate sensitivity is within the range (2 to 4.5ºC) and identical to the most likely value (~3ºC) that emerges from climate model simulations based solely on knowledge of atmospheric and oceanic physics and assuming the 19th century climate as initial conditions [3, Chapter 8].

FINDING 3: RECENT CLIMATE CHANGE IS UNEQUIVOCAL AND ITS CAUSE IS PRIMARILY HUMAN ACTIVITIES

That the climate is changing is evident from the increasing upturn in global average surface temperature since the start of the Industrial Revolution. Overall warming totals ~0.8ºC, with most of the increase occurring since 1970. Increases in ocean temperatures and sea level (because ocean warming causes thermal expansion); reductions in sea ice, mountain glaciers, snow cover, and increasingly in ice sheet mass; and poleward and upward shifts in the ranges of temperature sensitive species all provide reinforcing evidence that change is underway.

To evaluate the relative contributions of natural factors (changes in solar radiation and volcanic activity) and human-induced factors (increase in greenhouse gas concentrations, changes in aerosol loadings, depletion of stratospheric ozone), global atmosphere-ocean models are used to determine the individual and combined influences of each factor—basically generating its "fingerprint." That the stratosphere is cooling while the troposphere and surface are warming does not match the every-level-warming fingerprint of increasing solar radiation, ruling it out as the primary cause of the recent warming. Similarly, volcanic activity causes a surface cooling, so it cannot be the cause—and because we are getting warming when no volcanic aerosols are present means a lessening of volcanic activity cannot be the primary cause. Only an increase in the concentration of GHGs matches the dominant vertical pattern and timing of the warming of the observed changes, with an increase in sulfate aerosols also likely to be playing a role in creating the hemispheric asymmetry and delaying most of the warming until after 1970.

When driven by the historic record of natural and anthropogenic climate forcings, the newest model results, as shown in Figure 1, show good agreement with the observed changes in temperature since the start of the 20th century on not only a global basis, but also on a continental-scale basis. Because the warming influence of GHG increases was offset by the cooling influence of sulfate aerosols, changes in surface temperature during the early 20th century appear to have been mainly due to natural factors. For the past several decades, however, natural factors have likely played a very small role (indeed, observations of solar radiation indicate that it has been slowly decreasing), and the observed warming can only be explained by the rising concentrations of GHGs. The dominance of the GHG forcing is expected to continue because the lifetimes of the perturbations in the atmospheric concentrations of the long-lived GHGs are decades to centuries or longer (depending on species), meaning that their influence on IR radiation will build up over time and extend well into the future. In contrast, the cooling influence of aerosols rapidly plateaus because of their short atmospheric lifetime.

FINDING 4: INCREASING EMISSIONS WILL LEAD TO MUCH MORE WARMING

IPCC's 2007 assessment presents projections of changes in climate from an international set of comprehensive atmosphere-ocean-land-cryosphere models for six scenarios of how international society and its sources of energy (and therefore of GHG emissions) might evolve in the absence of specific policy actions to limit GHG emissions. For the

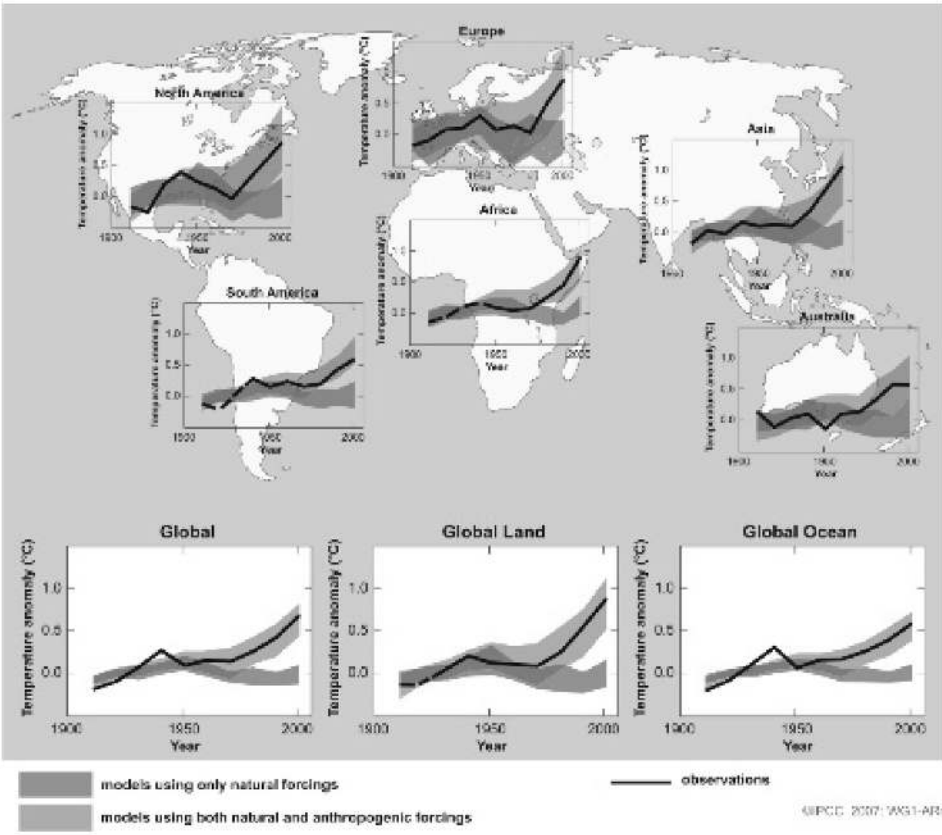

Figure 1. Comparison of observed continental- and global-scale changes in near surface air temperature (solid line) with the envelope of possible climatic states constructed from ensemble simulations by multiple climate models using just natural forcings (lower, darker band) and natural and anthropogenic forcings (upper, lighter band). The observed data are decadal averages plotted at the center of each decade from 1906 to 2005, and all changes are normalized to the period 1901 to 1950, during which the anthropogenic influences of increasing greenhouse gases and sulfate aerosols tended to counterbalance each other [3, Chapter 9]. Copyright 2007 Cambridge University Press.

21st century, the models project an overall global warming of ~2 - 4ºC, raising temperatures to ~2.5 - 4.5ºC above their pre-industrial level.

While this may seem a modest increase in temperature compared to seasonal variations or the change experienced in relocating from New York to Arizona, it is a shift imposed not just on society, but also on the environment, and not just on an individual, but also on everyone and everything. For the next few decades, the projected temperature increase of 0.2 - 0.3ºC per decade shows little dependence on emissions scenario, in part because the mix of energy technologies will change only slowly, and in part because much of the warming over the next couple of decades will be a result of past emissions. Beyond 2050, the emissions resulting from our energy choices—starting now—will make an increasing difference. High emissions scenarios, in which coal (without sequestration) remains an increasing source of electricity, lead to very large increases in global average temperature by 2100 with further increase beyond. If this scenario comes to pass, climatic conditions will ultimately likely to return to near those of the Cretaceous (>65,000,000 years ago), when there was no polar ice, high latitudes had near tropical summers, and sea level was a few hundred feet above present. Even the most optimistic no-policy emissions scenarios, which envision early and widespread reliance on cost-effective renewable technologies, are projected to lead to global warming of several degrees, which, based on what happened during the Eemian interglacial about 125,000 years ago, would also mean sea level rise of 4-6 meters or more as a result of substantial melting of the Greenland and/or West Antarctic ice sheets. That both ice sheets are now losing mass suggests this path is quite possibly the lower bound of what lies ahead unless sharp cuts in emissions are quickly implemented.

Warming is not all that occurs. Storm tracks shift in response to the changes in temperature gradients and airflows, likely leaving some regions (like the southwestern US) drier. Precipitation tends to become more intense, continuing a trend that was evident over much of the 20^{th} century, leading to more drenching rains, especially as a result of more intense tropical storms. Away from the storm tracks, higher temperatures increase evaporation, increasing soil moisture stress and causing faster transition to drought conditions.

While much of the focus has been on the increase in temperature, most projections indicate that, in general, relative humidity remains roughly constant, which means that the absolute humidity is going to rise. This means that the heat index, or discomfort index, will also be rising, and substantially so in the typically humid areas of the country. In that much more energy is required to remove the moisture from the air than to lower air temperature, the energy demand for air conditioning is very likely to rise sharply unless buildings are constructed to limit daytime heating and infusion of moisture.

While the prospects of a steady rise in temperatures are already daunting, paleoclimatic evidence suggests that the climate system has thresholds that, if passed, could lead to changes in the climate that are abrupt or would significantly amplify the rate of change. For example, warming can lead to thawing of permafrost soils, greatly increasing the natural release of methane. In that methane has a global warming potential that is very large, any increase in methane concentration could greatly amplify near-term warming. For much of the last decade, the atmospheric methane concentration has been roughly constant, suggesting some success in limiting human-caused emissions, but the global concentration has recently started to rise, and it appears to be a result of increasing methane coming from the warming tundra—if so, global warming will very likely be greater than even the significant amount already projected. There are also other possible thresholds that might be crossed. Recognition of this possibility is creating the intensifying international pressure for near-term reductions in emissions to begin.

FINDING 5: CLIMATE CHANGE WILL LEAD TO A WIDE RANGE OF ENVIRONMENTAL AND SOCIETAL IMPACTS

Even in the absence of climatic change, the rise in the CO_2 concentration will affect the biosphere. On land, the increase will tend to help plants grow better and use available soil moisture more efficiently. To the extent crops can out-compete the weeds and pests that also benefit, this has the potential to increase yields of some crops, especially in the most productive areas. In the oceans, however, the rising CO_2 concentration will decrease the pH. This effect is already evident in shallowing of the depth at which calcium carbonate dissolves. By mid-century, further ocean acidification will threaten the world's coral atolls and those species of the marine food web that make carbonate shells for protection. The potential seriousness of this issue is only beginning to be understood, but is already prompting some examination of whether CO_2 could be economically scrubbed from the atmosphere and whether there might be a way to increase the ocean's ability to buffer the increase in acidity (basically, antacid for the ocean).

Climate change itself will have a wide range of significant consequences (see Figure 2). Warming will force poleward and up-mountain relocation of many plant species, which will become decreasingly successful as an adaptation strategy as land runs out and existing species are crowded out--significant loss of global biodiversity is projected. For food and fiber production, climate change is likely to lead to increases in yield in mid-latitudes for small warming, but larger warming is projected to lead to very hot and dry periods during the growing season. Thermal and water stress on plants will be augmented by increasing pressure from pests and weeds; in some regions pests are already killing off key species and, along with the hotter and drier weather, the frequency and intensity of wildfires is likely to continue to increase.

Human health is likely to be most impacted by more frequent and intense heat waves, greater threats of insect and other vector-borne diseases, and injury and mental stress resulting from dealing with more extreme weather. Of most long-term concern are the disruptions of coastal habitats and the dislocation of people and infrastructure that are expected from increases in storm surge heights and inland reach. Such changes are likely consequences of both significant sea-level rise and increase storm intensity, with the impacts being most significant initially for barrier islands and low-lying river deltas and estuaries. By late in this century or early in the next, when sea level rise could be a meter or more, the effects are likely to spread further inland, especially in low elevation regions such as Florida and around Chesapeake Bay, which will also be exposed to higher storm surges from more intense tropical cyclones. Additional impacts are likely as a result of changes in the relative impacts in one region versus another, in areas where resources are not available for proactive adaptation, and to indigenous peoples, whose coupling with their environment makes them vulnerable, especially in the Arctic.

FINDING 6: STOPPING CLIMATE CHANGE WILL REQUIRE SHARP REDUCTIONS IN EMISSIONS

To limit the projected impacts, the nations of the world, including the U.S., adopted the UN Framework Convention on Climate Change (UNFCCC) in the early 1990s. Its objective is to stabilize "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system," doing so in a manner that would protect ecosystems and food production

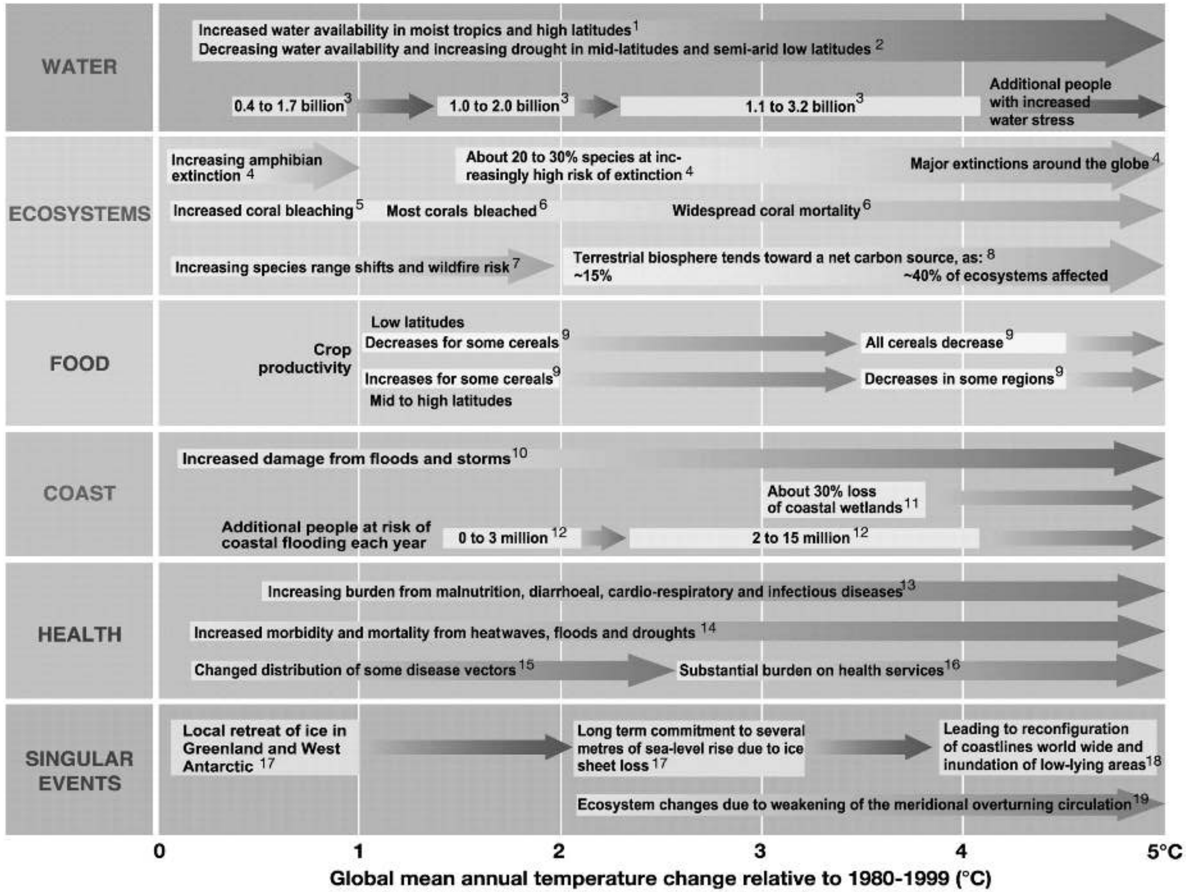

Figure 2. Examples of global impacts in key sectoral areas projected to result from changes in climate associated with the indicated increase in global average temperature and, where relevant, increases in sea level and atmospheric CO_2 concentration [4]. Copyright 2007 Cambridge University Press.

while enabling "economic development to proceed in a sustainable manner." Achieving stabilization will only be possible by sharply reducing emissions of GHGs, ensuring that emissions do not exceed, and are preferably below, the natural removal rates that result from physical, chemical, and biological processes.

Stabilizing CO_2 concentration, which is the primary cause of global warming, at or near its present level would require cutting global emissions by at least 80 percent. Because such a sharp reduction would take time, the CO_2 concentration would continue to rise well above its present level. Even the most optimistic of IPCC's no-policy emissions scenarios, which essentially envision level emissions averaged over the 21^{st} century, result in the CO_2 concentration rising to over 500 ppmv (and effectively even higher due to the warming contributions of increases in the concentrations of other GHGs), and less optimistic scenarios lead to CO_2 concentrations from 700 to well over 1000 ppmv.

Returning atmospheric composition to its present state, or to a state with even lower greenhouse gas concentrations to halt the melting of the Greenland and Antarctic ice sheets, will require going to near-zero emissions for CO_2 and other long-lived greenhouse gases (e.g., nitrous oxides, halocarbon). For there to be a 50 percent likelihood of limiting global warming to 2°C above preindustrial conditions [REF], which is the level that the European Union suggests would start to bring on "dangerous" climate change, requires that much of the global reduction in emissions be accomplished by 2050 and the rest by 2100.

Given the dominant contribution of the US to global emissions, especially on a per capita basis, it is quite clear that the US needs to move aggressively to demonstrate to the world that a modern society can prosper with low greenhouse gas emissions—and to start on this path in the very near term. A number of bills in Congress call for such an effort—roughly an 80 percent reduction in CO_2 emissions by 2050. Globally, the developed world needs to join in this effort and developing nations need to, in the near term, greatly increase the efficiency of their use of carbonaceous fuels and then, over the long term, join with the developed nations in reducing CO_2 emissions as technologies become available. In addition, all nations need to move aggressively to limit methane, soot, and air pollutant emissions, and to stop deforestation. There is a path to limiting climate change—the challenge is to gain its acceptance and implement it quickly.

CONCLUSION

Former President Bill Clinton offered a rationale in a September 2007 speech to the Carbon Disclosure Project suggesting that the challenge of transforming the national energy system is just what the US needs: "Unless you're going to make it illegal for people to move their money around or illegal to buy something from some other country, you cannot maintain a growing economy with rising median wages over any significant length of time unless there is a source of good new jobs every five to eight years… this historic challenge we're facing from climate change is this decade's source of good new jobs for rich countries, and foolishly, the United States passed it up" [14].

If we fail to act, we will leave a rapidly changing climate to our children and grandchildren (and their grandchildren), requiring them to devote substantial resources to adapting to the ever-changing environment. As Benjamin Franklin said: "It has been my opinion that he who receives an Estate from his ancestors is under some kind of obligation to transmit the same to their posterity." More recently, a local church bulletin board offered a starker view: "Life offers many choices; eternity only two." We can either work cooperatively to avoid catastrophe, or we will experience it.

References

1. MacLeish, A., 1968: Riders on Earth together, brothers in eternal cold, *The New York Times*, December 25.
2. Crutzen, P.J., and E. Stoermer, 2000: The Anthropocene, *Global Change International Geosphere Biosphere Programme*, Newsletter 41, May 2000, c/o The Royal Swedish Academy of Sciences, Stockholm, Sweden.
3. Intergovernmental Panel on Climate Change (IPCC), 2007: *Climate Change 2007*: The Physical Science Basis, S. Solomon et al., eds., Cambridge University Press, 996 pp. [All IPCC publications are downloadable from http://www.ipcc.ch].
4. Intergovernmental Panel on Climate Change (IPCC), 2007: *Climate Change 2007*: Impacts, Adaptation and Vulnerability, M. Parry et al., eds., Cambridge University Press, 976 pp.
5. Intergovernmental Panel on Climate Change (IPCC), 2007: *Climate Change 2007*: Mitigation of Climate Change, B. Metz et al., eds., Cambridge University Press, 851 pp.
6. Intergovernmental Panel on Climate Change (IPCC), 2007: *Climate Change 2007*: Synthesis Report, R. Pachauri, et al., eds., World Meteorological Organizations and United Nations Environment Programme, Geneva, Switzerland.
7. MacCracken, M.C., 2008: Prospects for Future Climate Change and the Resources for Early Action, *Journal of the Air and Waste Management Association*, 58, 735-786.
8. Levinson, D. H., and J. H. Lawrimore (eds.), 2008: State of the Climate 2007, Special Supplement, *Bulletin of the American Meteorological Society*, 89, S1-S179.

9. Canadell, J.G., C. Le Quéré, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T. J. Conway, N.P. Gillett, R.A. Houghton, and G. Marland, 2007: Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks, *Proceedings of the National Academy of Sciences* 104, 18866-18870.
10. Intergovernmental Panel on Climate Change (IPCC), 2000: *Special Report on Emissions Scenarios* (SRES), N. Nakićenović, et al., eds., Cambridge University Press, 599 pp.
11. http://www.epa.gov/climatechange/emissions/usinven toryreport.html
12. Jouzel, J., et al., 2007: Orbital and millennial Antarctic climate variability over the past 800,000 years, *Science* 317, 793-796.
13. Berger, A., 2001: The role of CO_2, sea-level and vegetation during the Milankovitch forced glacial-interglacial cycles, pp. 119-146 in *Geosphere-Biosphere Interactions and Climate*, L. Bengtsson, and C.U. Hammer, Cambridge University Press, Cambridge, UK.
14. http://www.cdproject.net/videos/CDP5_New_York/bill_clinton/showvideo.asp.

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