The Science of Global Climate Change[1]

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Introduction

Three weeks ago I was vacationing in Florida and I went to visit the Kennedy Space Center. The Center has a new exhibit hall that recalls the excitement of the Apollo missions to land on the Moon in the late 1960s. One of the most famous photographs from the first flight to orbit the Moon is called "Earthrise," which shows the Earth rising above the horizon of the Moon. In the December 25, 1968 issue of *The New York Times*, Yale's renowned literary alumnus Archibald MacLeish captured the sense of awe that the picture conveyed to all who saw it, when he said[3]: "To see the Earth as it truly is, small and blue and beautiful in that eternal silence where it floats, is to see ourselves as riders on the Earth together, brothers on that bright loveliness in the eternal cold—brothers who know now they are truly brothers." It was this perspective that led to the conceiving of the Earth as the blue planet, the blue orb in the vastness of space.

What we have learned in the 35 years since, however, is that the statement is no longer appropriate in an important way, and I don't just mean that we now know better than to use the word "brothers" three times in a statement when we are talking about all of humanity. The problem that I am referring to is the implication that we are all simply "riders" on the Earth together. We know now that human activities are actually taking over control of the Earth, changing it in important ways—we are no longer just along for the ride.

Had an astronomer been looking at the Earth from some remote planet for the few hundred years leading up to MacLeish's observation, he (or she) might well have agreed with MacLeish. However, had the astronomer been continuing to observe up to the present, very unusual changes would have become evident. The astronomer would have been able to spot the depletion of the ozone layer that has occurred and wondered about the really sharp ozone depletion in the springtime Antarctic stratosphere that has been occurring since the time of MacLeish's statement—had he lived until this depletion was discovered in the mid-1980s, we might have had a more poetic name than "Antarctic Ozone Hole."

Even more surprising to this distant astronomer would have been the sharp increase in the carbon dioxide (CO_2) concentration that was occurring. If this astronomer had been observing for tens of millions of years, the astronomer's record would show a CO_2 concentration undergoing a more

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[2] To contact the author, email mmaccracken@comcast.net.
[3] According to David Barber in the Modern American Poetry website, in MacLeish's book *Riders on the Earth: Essays and Recollections* (1978), the statement is slightly different: "To see the earth as we now see it, small and blue and beautiful in that eternal silence where it floats, is to see ourselves as riders on the earth together, brothers on that bright loveliness in the unending night—brothers who see now they are truly brothers."

or less steady decline from a value of well over 1000-1500 parts per million (that is molecules of CO_2 per million molecules of air) to values of between about 200 and 300 ppm over the last few million years. We can say this because scientists such as Prof. Berner here at Yale have found records of such changes, for example, in geological formations[4]. This distant astronomer might have surmised that geological, and maybe even biological, processes could be tying up that additional carbon over these many millions of years, but would have been quite curious about the process that would be causing roughly a 30% jump in the atmospheric CO_2 concentration over the past 150 years. The conclusion would have to be that something very unusual was changing the natural course of events, taking over as the driver of this planet's history.

The human-induced climate change that the increasing CO_2 concentration is inducing ("global warming" for short) is thus a very fundamental issue—there is no natural process that we know of that could have caused the changes in atmospheric composition that have been observed.

1. Human Activities Are Changing Atmospheric Composition

The first of six key points about the climate change that I want to talk about this afternoon is the record of atmospheric composition over the last 1000 years, and the particularly sharp increase that has been occurring over the past 150 years. Figure 1 (courtesy of the US National Assessment) shows a record of the CO_2 concentration for the past 1000 years, based on ice core records and atmospheric observations. The increase since the start of the Industrial Revolution is very unusual compared to the relatively constant value of preceding centuries.

Two types of human activities are mainly responsible for the changes in the CO_2 concentration. The first has been a change in how we use land, including the clearing of forests, the plowing of the land, and the growing of crops. These activities actually started several thousand years ago as nomadic tribes settled down and started to grow crops—and there are some recent attempts to examine the importance of these early activities to modifying the climate over this longer period. However, as shown in Figure 2[5], the main contribution from land-cover related activities began in the 19th century, driven by the significant expansion of agriculture and the exponential growth in population (figure courtesy of the US National Assessment). Now, something like 50% of the Earth's land surface has been affected in a significant way by human activities, and human activities are responsible for the ongoing release to the atmosphere of 1-2 billion tonnes of carbon (GtC) each year, mainly in the form of carbon dioxide[6].

The second, and most important, cause of the change in the CO_2 concentration is the combustion of coal, oil, and natural gas. These fuels are together referred to as fossil fuels because they are

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[4] There are a range of techniques to do this, including: determinations of isotopic ratios in minerals and fossil plants; the type and amount of geological deposit; the type and physiology of fossil plants; the concentration in air trapped in bubbles in ice cores (record goes back about 420,000 years); and so on.

[5] The land use contribution is shown in maroon in Figure 2, being the increment above the fossil fuel emissions.

[6] Many official compilations of emissions present the amounts as the mass of carbon dioxide rather than of carbon. This has the effect of counting as emissions the mass of the oxygen molecules that are already in the atmosphere, so is a bit misleading. However, it does make the numbers bigger. To make the conversion, multiply the amount of carbon released by the relative molecular weights, so 44/12, or about 3.7, to get the mass of carbon dioxide released.

Figure 1: Record of the CO_2 concentration (in parts per million by volume) over the past 1000 years, reconstructed from ice cores up to 1957 and then from observations. Figure courtesy of the US National Assessment.

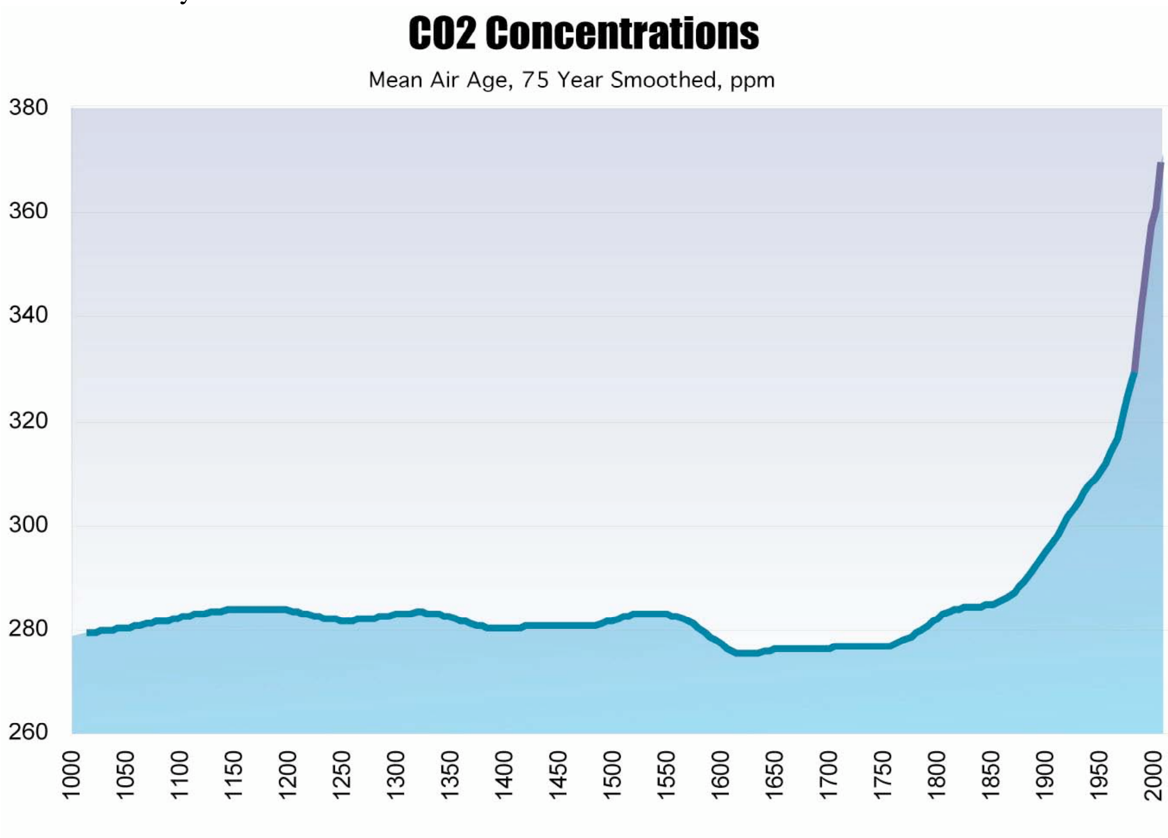
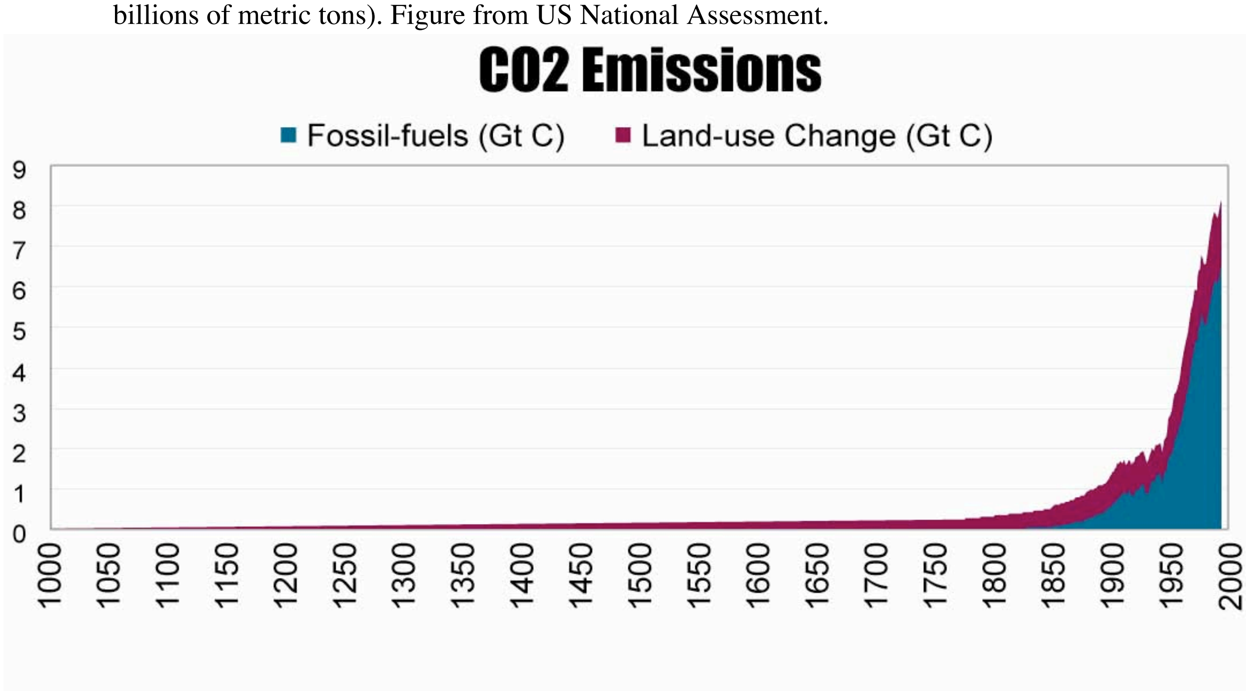


Figure 2: Reconstruction of past emissions of CO_2, in gigatonnes of carbon (GtC, billions of metric tons). Figure from US National Assessment.



derived from the fossilized remains of plants and animals. Basically, we are injecting back into the atmosphere carbon that was stored away by natural processes over periods of tens to hundreds of millions of years—all in the time span of a couple of centuries. Thanks to the research efforts of scientists such as Prof. Turekian, the fluxes and exchanges of various materials between the atmosphere, the oceans, the land and the subsurface are pretty well understood, and there is no doubt that it is human activities that are changing atmospheric composition.

Compilations of all the fossil fuels combusted each year indicate that all the world's people are injecting 6-7 billion tonnes of carbon into the atmosphere—roughly one tonne each year for every man, woman, and child on the planet. So, how much is this? Well, a ton of carbon as gasoline will get you roughly 10,000 miles[7]. Added together, the 8 billion tonnes of carbon that are emitted each year due to fossil fuel combustion and land use change are about equivalent to the net amount of carbon that the Northern Hemisphere's growing vegetation pulls out of the atmosphere each year from spring through summer—that is, the net amount of carbon taken up by new leaves, grasses, and trees each year. If the terrestrial biosphere could retain all of this extra carbon, we would not have a global warming problem—though we might well have to start traveling through all the kudzu-like vines that would result. It turns out, ignoring the baseline respiratory and decay processes, that about 3/4 of the incremental amount of carbon taken up each year is released back into the atmosphere in the fall and winter by decay processes. Even though another quarter of the annual anthropogenic contribution to carbon is taken up each year by the oceans, the half remaining is enough to increase the atmosphere's CO_2 concentration by about 0.5% per year. This is a lot of carbon—it is much more than we could easily capture by planting a few more trees along the Interstate highway system, as was proposed as a remedy some years ago.

2. Changing Atmospheric Composition Can Warm the Earth

The second key finding from scientific research, and this one is over 100 years old, is that changing atmospheric composition will warm the planet by enhancing the Earth's natural greenhouse effect. Common wisdom is that it is the Sun that keeps us warm, and it is true that it is the Sun that is the fundamental source of energy for our planet. However, it is really the atmosphere that keeps us warm—without the atmosphere it is estimated that the Earth would be some 33°C (or 60°F) colder than it is. If you were to take an instrument that could measure the amount of heat (i.e., infrared) radiation coming down from the sky and were to make measurements around the world, you would find that, totaled over the day and averaged over the surface of the Earth, *twice* as much energy is coming down to the surface in the form of heat energy (technically, infrared radiation—the kind that a hot stove gives off) as is coming down from the light of the Sun. As illustrated in Figure 3 from the US National Assessment report, what is happening is that the Sun warms the surface a bit; then, as a result, the surface, like any warm body, emits infrared radiation. As this radiation tries to escape from the planet, about 90% of it is absorbed by water vapor, CO_2, and other greenhouse gases in the atmosphere. These gases

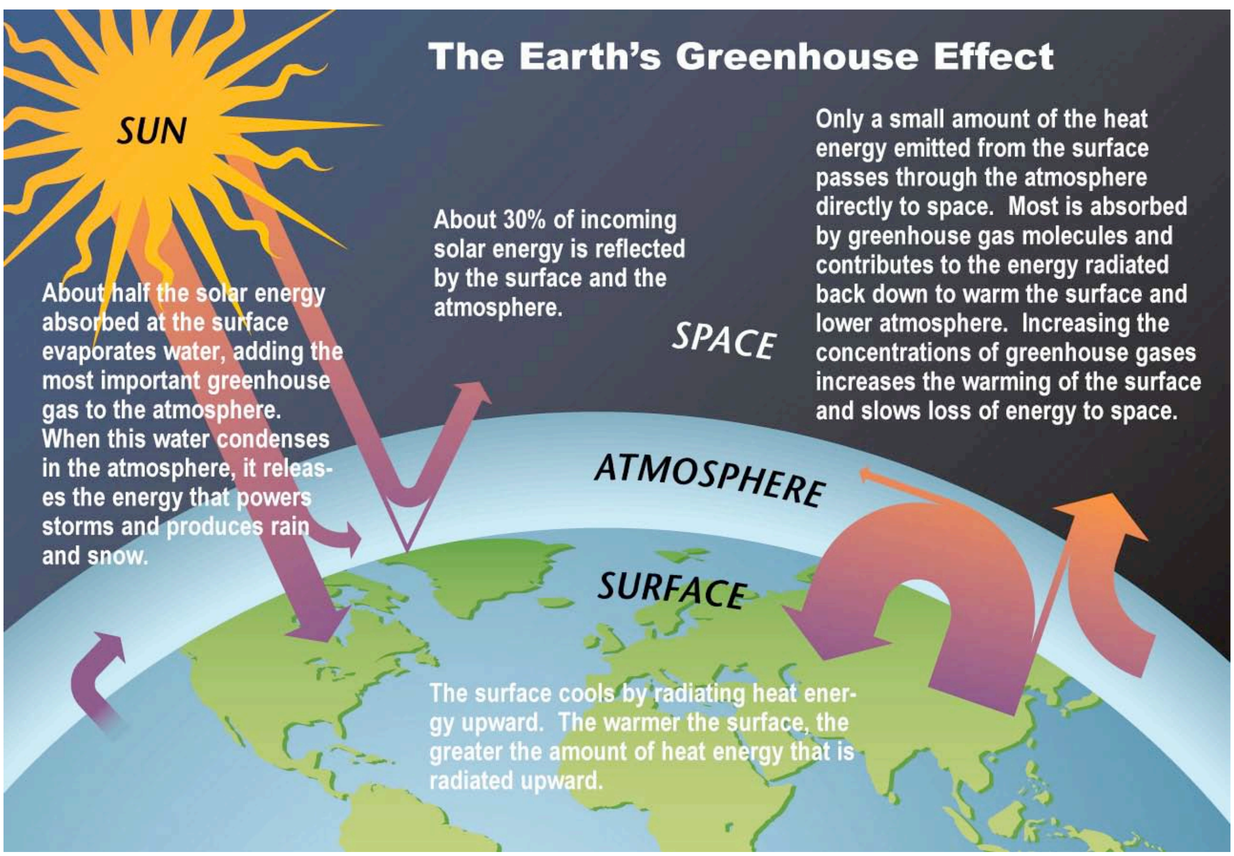
[7] A gallon of gasoline (e.g., octane) weighs about 6 pounds and is about 80% carbon. Thus a ton of carbon is equivalent to roughly 400 gallons of gas, which at 25 miles per gallon would give a range of 10,000 miles.

give up some of this energy to the surrounding oxygen and nitrogen molecules, warming the air, but they also radiate some of this energy away—both upwards and downwards. The downward radiation warms the surface, causing more upward radiation. This process goes on multiple times and gets pretty complicated because certain molecules absorb and emit energy only in certain wavelengths, but the net result is that roughly 80% of the energy that the surface is emitting comes back, creating the natural *greenhouse effect* that keeps the world from freezing.

What the greenhouse effect does for the Earth is roughly equivalent to what a Discover credit card will do for its user. However, while the Discover credit card only provides a 1% refund, the natural greenhouse effect provides roughly an 80% return—this high rate of return is what lets the Earth enjoy a pretty hot nightlife, so to speak. That this effect exists is evident in our everyday lives—or rather our every-night lives; if you go out on a cloudy or humid night, you will feel much warmer than if you go out on a clear or very dry night—when water vapor (or droplets) are present, the greenhouse effect can readily be felt.

Actually, of course, a lot more is going on. For example, much of the energy that is radiated back to the surface is used to enhance the hydrologic cycle—that is, to increase the amount of evaporation of water from the surface, and therefore increase the amount of rain and snow coming down.

Figure 3: Schematic diagram of the Earth's energy balance. The width of the arrows is proportional to the amount of energy. Figure from US National Assessment.



By adding gases such as CO_2 and other similarly acting gases and particles to the atmosphere, what we are doing is equivalent to increasing the Discover card's refund rate. By returning a higher fraction of the energy emitted from the surface, additional energy is provided to increase surface temperatures. Figure 3 illustrates the type and relative importance of the various factors.

Analyzing how the climate has changed in the past, how planetary climates work, and carrying out laboratory and modeling studies, all our scientific understanding together indicates that the Earth's climate has a sensitivity such that a doubling of the CO_2 concentration will, over several decades, cause a global warming of about 3°C (or about 5°F), plus or minus roughly 50%. The late Yale professor Barry Saltzman did a good deal of modeling to explore how the amount of warming depended on the baseline amount of CO_2 and the change in its concentration and whether the findings were consistent with scientific understanding of changes in past climates. This estimate of the climate sensitivity has been quite widely agreed to for about 25 years, although there are a few scientists who argue it could be lower, and others who argue it could be a bit higher.

All this concern over a few degree change may seem a bit overblown, given the large changes in temperature from day to day, season to season, and place to place, but it is a significant amount; it is estimated, for example, that the global average warming from the peak of the last ice age some 20,000 years ago to the present was about 5°C (8°F), so doubling the CO_2 concentration is equivalent to about half of that warming. We already have had more than a 30% increase in the CO_2 concentration and are inevitably headed for much higher levels.

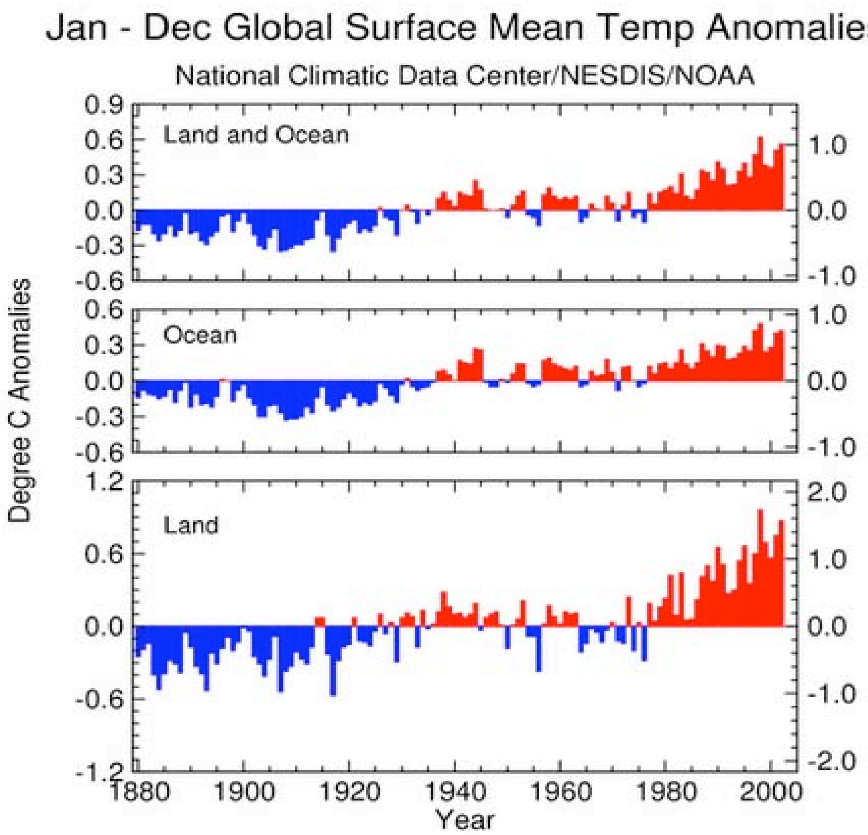
3. Human-induced Climate Change is Evident in the Climate Record

In that this CO_2 increase has been going on for 150 years or so, we should be expecting to see the climate changing in response. There are an increasing variety of observations indicating that the climate is changing. For example, Figure 4 shows the changes in the annual mean global average temperature from its 20th century baseline. As is evident from the trends in both land and ocean temperatures, the past few decades have been markedly warmer than 100 years ago.

With the CO_2 concentration being pushed up more rapidly since World War II, there has been an acceleration in the warming influence of CO_2 and, indeed, the changes in climate are becoming more evident. The world warmed about 0.6ºC (about 1ºF) over the 20th century, with much of the warming occurring during the past few decades. Observations also indicate that the oceans are warming and many glaciers around the world are melting. Both of these processes tend to cause sea level to rise, and indeed, this is being observed. There are also many other indicators that the climate is changing; perhaps most troubling is that shifts in the ranges of various plants and animals are being seen, and the large majority of these changes are consistent with what would be expected as a result of changes in the climate, even more so than other human-induced changes in the landscape.

However, determining if these changes are due to human activities is complicated by the fact that other factors are also causing the climate to fluctuate. These other factors include fluctuations in solar radiation, injection of aerosols into the stratosphere by major volcanic eruptions, injection

Figure 4: Globally averaged departures of annual average surface air temperature from their long-term mean. Figure courtesy of NOAA National Climatic Data Center.



of sulfate and soot aerosols into the atmosphere from combustion of coal, and just the chaotic interaction of the atmosphere with the oceans, as occurs, for example, with an El Niño.

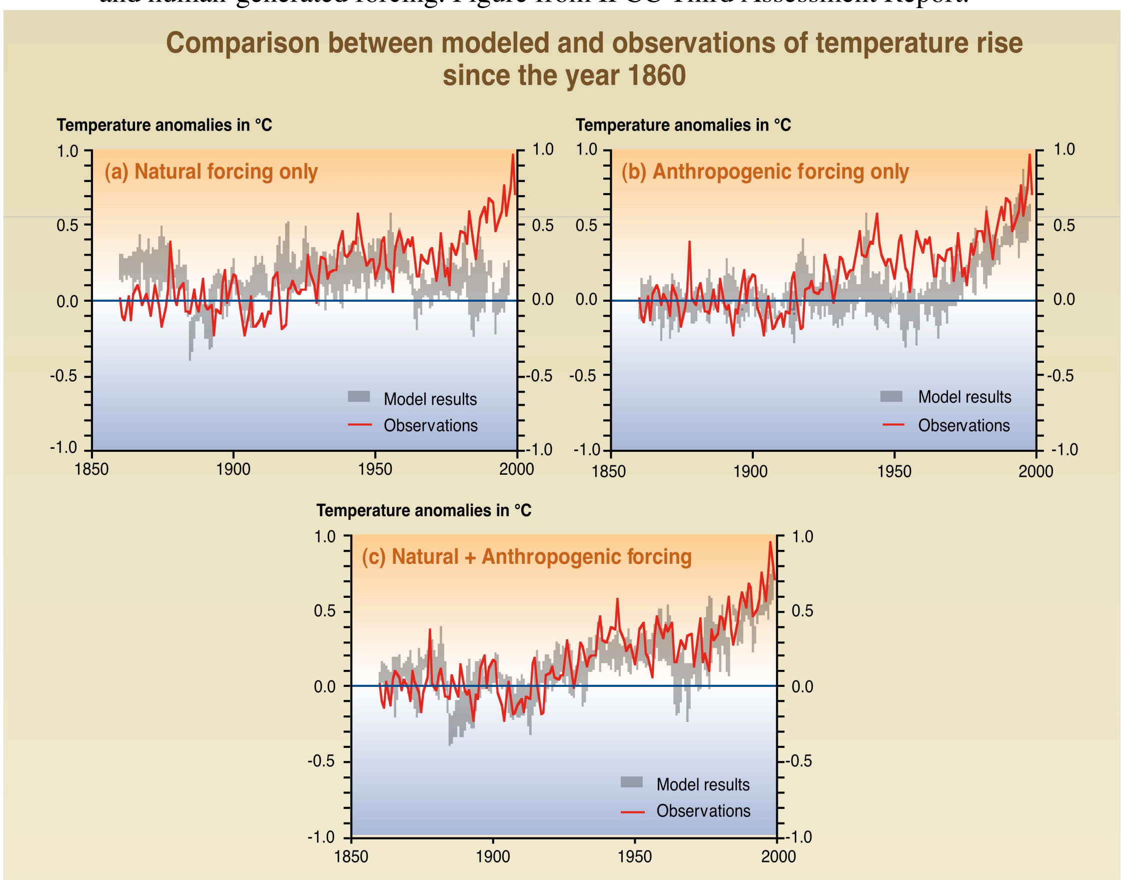
Attribution of all or part of these changes to changes in atmospheric composition requires quantitatively accounting for the contributions of all of the possible contributing factors as well as establishing the consistency of the observed changes with what would be expected based on our theoretical understanding—as a result, with such an attribution, the case is really more circumstantial than direct.

The limited records that we do have of the effects of volcanic eruptions and changes in solar radiation suggest they are likely to have played a role in past fluctuations in the climate. However, these factors have not changed in a way consistent with recent warming over the past several decades, so the recent warming does not appear to be due to natural causes. On the other hand, warming appears to be evident before the greenhouse gases started rising rapidly, so it may well be natural influences that caused the warming in the early 20th century[8]. As indicated in

[8] While the prevailing view is that the early 20th Century warming was mainly natural in origin, this is mainly a circumstantial conclusion. Interestingly, some indications are starting to emerge that at least some of that warming may have been induced by the combined influence of the increases in greenhouse gases and in aerosols.

Figure 5, the best explanation of recent changes in temperature (and also of the observed changes in other variables) is that they are due to the combined effects of increasing the concentration of CO_2 and other greenhouse gases and increasing the atmospheric loading of the particulate matter that also results from combustion of fossil fuels. Not all indicators are in full accord, however, and because the case is largely circumstantial, there are, and need to be, ongoing efforts to try to prove otherwise. However, the preponderance of observations and analyses indicate we are undergoing changes in the climate due to human activities.

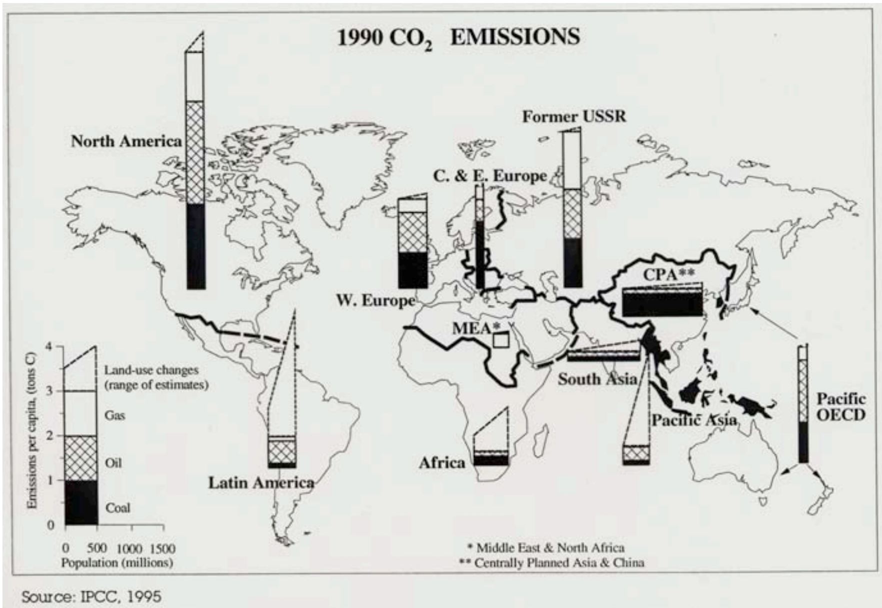
Figure 5: Comparison of model simulations of the globally averaged change in annual mean surface air temperature with observations of the same quantity assuming (a) only natural forcing by changes in solar and volcanic effects; (b) only human-generated forcing by greenhouse gases and aerosols; and (c) the combined effects of both natural and human-generated forcing. Figure from IPCC Third Assessment Report.



4. Climate Change Will Accelerate During the 21st Century

So, what lies ahead? At present, each year's fossil fuel use by the 6-plus billion people on the planet is leading to the emission of 6-plus billion tonnes of carbon to the atmosphere; this is an average of one tonne of carbon per person per year. The distribution of the emissions is, however, quite varied, as shown in the diagram below. In the underdeveloped countries, the emissions are of order half a tonne per person; in China, the level is approaching 1 tonne per

Figure 6: The height of the bar indicates the per capita rate of use; the width of the bar is proportional to population. Therefore, the area of the bar indicates total usage by country. The bars are shaded to indicate usage of coal, oil, and natural gas, and emissions due to changes in the biosphere (e.g., deforestation).



person; in Europe it is about 3 tonnes per person; and in the US and a few other countries, it is over 5 tonnes per person. When the climate change statement by the US Catholic Bishops[9] spoke about issues of equity, they were referring, in part, to this unequal use of fossil fuels and, therefore, about the unequal contribution of different peoples to the problem.

For the future, the world population looks likely to increase to at least 8 billion and possibly reach over 10 billion by the end of the century. As shown in Figure 7, most of the future growth in population is expected to occur in the developing world. While the birth rates are dropping in many of these countries, the populations of these countries will grow significantly as average lifetime is extended and the populations come into equilibrium.

In meeting the energy needs of all these people, emissions of CO_2 can be expected to rise dramatically, with countries like China and India expected to make extensive use of their low-cost coal reserves to provide the energy needed to enhance overall living standards (problems of air pollution and acid rain, however, do need to be overcome). In addition, with the coming depletion of oil later this century, the need for liquid fuels may need to be met by deriving such fuels from coal. Because this conversion process requires a good deal of energy, such an energy path would lead to emission of much more carbon per useful unit of fossil energy.

The Intergovernmental Panel on Climate Change (IPCC), representing the collective efforts of over 160 countries, has developed some scenarios for future emissions. Considering current

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[9] http://www.usccb.org/sdwp/international/globalclimate.htm

Figure 7: A mid range population projection for the 21st century. Figure courtesy of the Office of Science and Technology Policy.

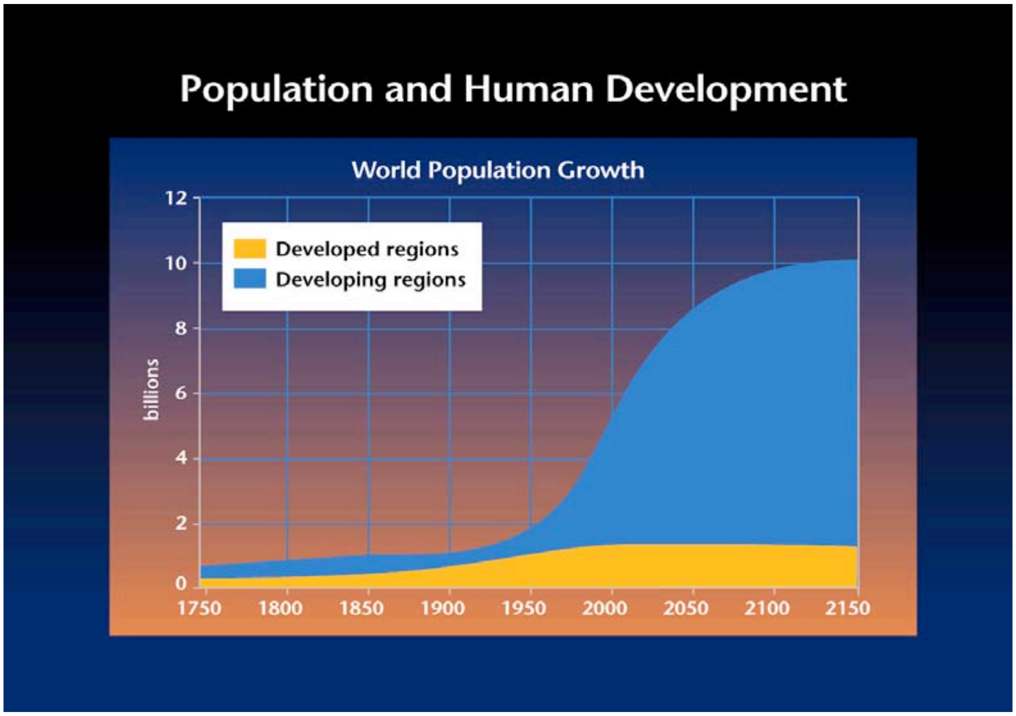
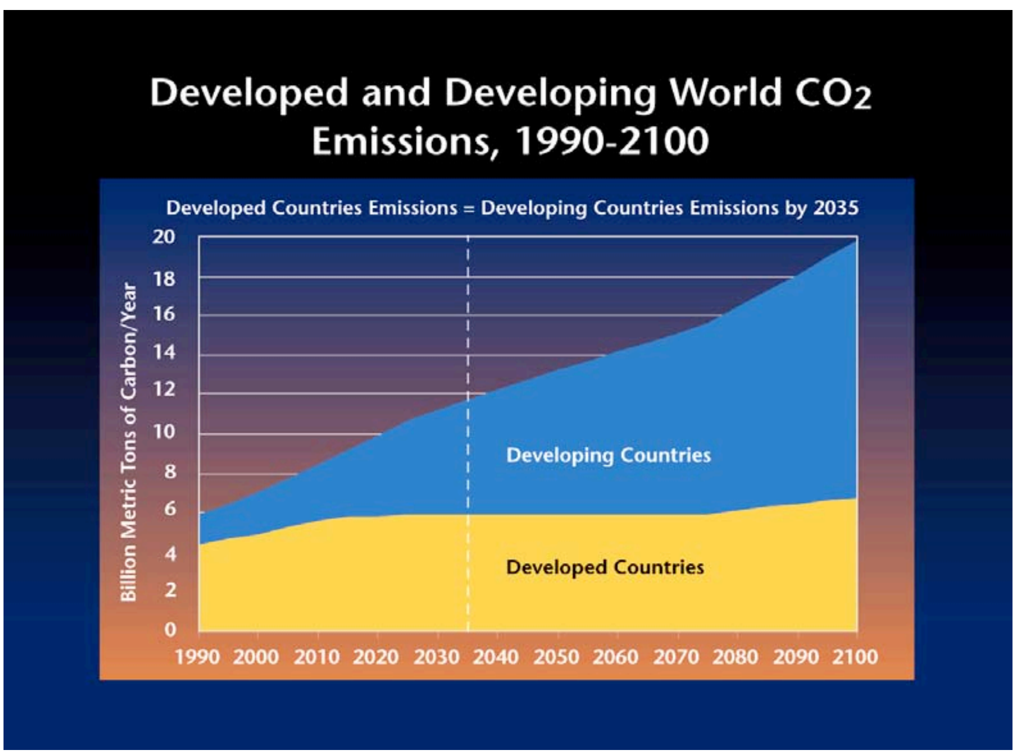


Figure 8: Mid-range projection of CO_2 emissions, based on a scenario from the IPCC Second Assessment Report.



trends and future possibilities, it is not at all difficult to come up with emissions scenarios that lead to emissions a few times as high as today's by the end of the century. Figure 8 shows one such scenario, which would roughly triple today's annual rate of emission of CO_2. Of the IPCC's full set of scenarios, its most ambitious energy scenario envisions virtually all additional energy above today's level coming from alternative energy sources; in its most pessimistic, in a climate sense, most of the additional energy would come from coal. The emissions scenario shown in the figure is roughly a mid-range case. Note that most of the emissions increase is projected to occur from countries currently considered to be developing.

Accepting the IPCC scenarios as representing a plausible range of what could happen with respect to emissions, by 2100 the CO_2 concentration would be expected to rise from its current level of just over 30% above the preindustrial level to somewhere between 100% to 300% or more above its preindustrial level; that is, the CO_2 concentration would be roughly 2 to 4 times its preindustrial concentration. The Earth has not experienced such high a CO_2 concentration in tens of millions of years, and unless the emissions were to be cut to about 75% below current levels, which seems very unlikely given the higher population and higher standard of living, the CO_2 concentration in the atmosphere will still be rising into the 22nd century.

So, what will this mean for the climate? Unfortunately, we can't construct physical models of the Earth in the laboratory to test things out, and there is no simple algebraic way to represent the Earth's climate. While paleoclimatic analogs provide some hint of what could happen, our data are pretty limited and the change in atmospheric composition is occurring much, much more rapidly than has ever been the case in the past. As a result, we are forced to rely on virtual models of the Earth system that are constructed in supercomputers using the fundamental equations and principles of physics, chemistry, and ecology to simulate the world's atmosphere, oceans, and land. As illustrated schematically in Figure 9, these computerized global climate models include all of the important processes governing the climate system. The level of confidence that can be placed in the models is then determined by testing, revising, and retesting the models to improve their ability to simulate how the climate of the Earth has worked in the past and is working today.

In general, the models represent the large-scale, time-averaged behavior of the Earth system reasonably well; for example, the models generally reproduce the seasons, the monsoons and the geographic distribution of the climate. When one looks very closely, however, the models do not simulate the details as well, particularly in regions of sharp terrain. In addition, the models do not yet simulate the natural chaotic behavior of the system as well as is needed for projecting changes in the frequency and intensity of extreme events. As Stanford scientist Steve Schneider has commented, the models represent a usable, but somewhat hazy, crystal ball.

Ideally, one would wait until all the various weaknesses in models had been addressed before applying them, but given that the Earth system is arguably the most complex system science is investigating, we will likely never have a perfect model. Thus, the decision comes down to whether or not to use the models to try to carefully derive at least some insights about how the future is likely to evolve. There can be legitimate discussion, in my view, about how careful we have to be in using these tools, but totally rejecting model results, as some of the noisier critics argue, seems to me to be failing to make use of the unique human capability for contemplating what coming decades may bring.

Presuming that future emissions of carbon are within the bounds of IPCC's fossil fuel emissions scenarios, the models project that there will be an increase in the global average temperature of about 2 to 5ºC (about 3 to 10ºF) during the 21st century as compared to an increase of about 0.6ºC (about 1ºF) over the 20th century—so several times as much. The range is about equally a result of the uncertainties in how emissions will change and of uncertainties in how the climate will respond. Figure 10 shows the IPCC's projections of future change for a range of emissions scenarios (each indicated by a different color line), with B1 having the least emissions and A1F1 having the highest emissions.

All of the various models developed by groups around the world, each making their own attempt to best match the behavior of the real world, project that the warming will be greater over land areas than over the oceans and greater in mid to high latitudes than in lower latitudes. The US

Figure 9: Schematic diagram of processes represented in global climate models. Figure from US National Assessment

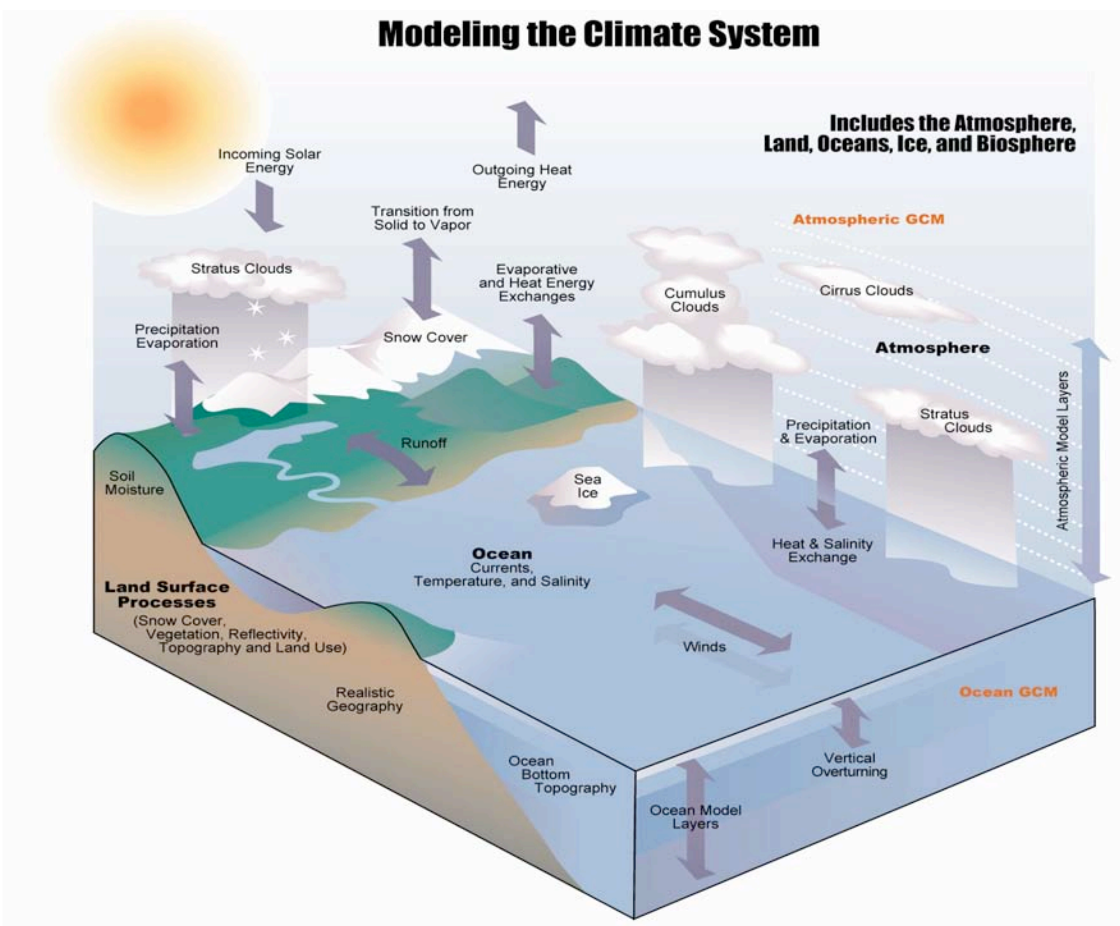
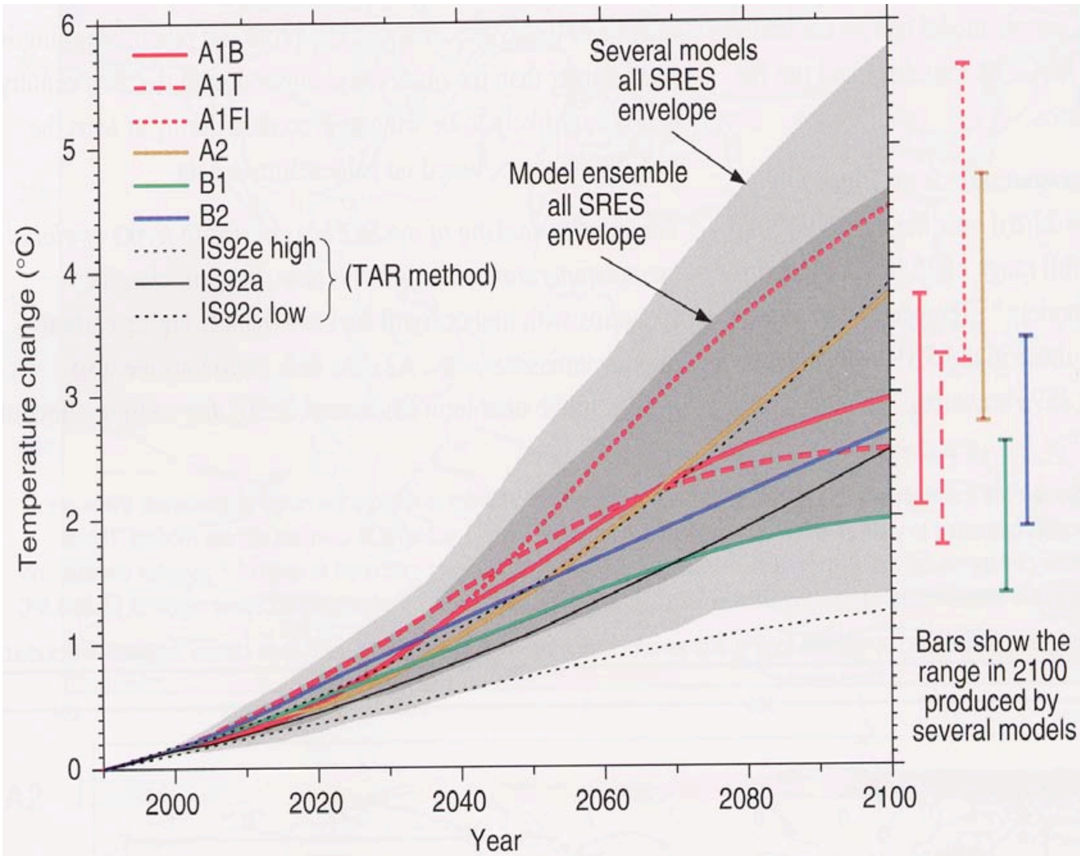


Figure 10: Model projections of the increase in global average surface air temperature from 1990 to 2100 for various emissions scenarios. Figure from IPCC Third Assessment Report.



meets both criteria—and such a change would be more or less like changing the climate of the northern tier of states to the climate of the central tier, and of the central tier to the southern tier. And if you live in the southern tier now, well, plan to spend summers inside, as the heat index will increase substantially. So, New England's climate would become like that of the Washington DC area; the Washington DC area like Atlanta, and so forth.

Associated with the warming, there will be other changes. Periods subject to frost will shorten, and summers will have more unusually hot days. Temperatures will not cool down so much at night. Rainstorms are likely to come with more intensity, with periods of heavy rain increasing in intensity the most. With evaporation occurring more rapidly, drying will occur faster, and so moisture stress will occur more rapidly. Basically, wet periods will be wetter, and drought periods drier. Mountain glaciers will be melting back more rapidly and sea level will be rising more rapidly as the warming causes the ocean waters to expand. Much less certainly, there is the possibility that some sort of abrupt change might occur, a change that might lock in some unusual atmospheric or oceanic circulation for a period of time. As Dr. Wallace Broecker, a chemical oceanographer at the Lamont-Doherty Earth Observatory, has commented, we are poking a capricious beast (e.g., a sleeping bear) with a very sharp stick—the effect may be gradual, or it may not. Continuing on the present path, the world faces unprecedented climatic change and quite possibly some surprises along the way.

5. Climate Change Will Affect the Environment, Natural Resources, Communities and People

So, why should we care that the climate is changing? While some studies about various types of impacts are underway, including, for example, some here at the School of Forestry and Environmental Studies, such investigations of potential impacts are only in their early stages (and they are not receiving much support from government research agencies). To provide a sense of the understanding that we do have, hundreds of scientists from around the country, working with local experts, governmental representatives, and the public, participated in the US National Assessment of the potential consequences of climate variability and change, which took place from 1997 to 2000. Through a series of workshops and assessments, the most important issues were identified for the various regions of the country and for key sectors of the economy. A very interesting set of reports emerged that is available over the Web at www.usgcrp.gov. A federal advisory committee, also composed of experts, then summarized and integrated the findings. Their report, which is available from Cambridge University Press for a quite modest price, was released in late-2000[10].

In this report, the National Assessment Synthesis Team summarized their key findings for the US as follows:

1. Assuming continued growth in world greenhouse gas emissions, temperatures in the US are projected to rise 5-9ºF (3-5ºC) on average in the next 100 years, although a wider range of outcomes is possible.
2. Climate change and the potential impacts of climate change will vary widely across the nation [Table 1, included at the end of this text, summarizes some of the regionally important outcomes].
3. Many ecosystems are highly vulnerable to the projected rate and magnitude of climate change. A few, such as alpine meadows in the Rocky Mountains and some barrier islands, are likely to disappear entirely in some areas. Others, such as forests of the Southeast, are likely to experience major species shifts or break up into a mosaic of grasslands, woodlands, and forests. The goods and services lost through the disappearance or fragmentation of certain ecosystems are likely to be costly or impossible to replace.
4. Water is an issue in every region, but the nature of the vulnerabilities varies. Drought is an important concern in every region. Floods and water quality are concerns in many regions. Snowpack changes are especially important in the West, Pacific Northwest, and Alaska.

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[10] National Assessment Synthesis Team, 2000, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change: Overview Report*, U. S. Global Change Research Program, Cambridge University Press, Cambridge UK, 154 pp., and *Foundation Report*, 612 pp. Viewable on-line at http://www.usgcrp.gov/usgcrp/nacc/default.htm

5. At the national level, the agriculture sector is likely to be able to adapt to climate change. Overall, US crop productivity is very likely to increase over the next few decades, but the gains will not be uniform across the nation. Falling prices and competitive pressures are very likely to stress some farmers, while benefiting consumers.
6. Forest productivity is likely to increase over the next several decades in some areas as trees respond to higher carbon dioxide levels. Over the longer term, changes in larger-scale processes such as fire, insects, droughts, and disease will possibly decrease forest productivity. In addition, climate change is likely to cause long-term shifts in forest species, such as sugar maples moving north out of the US.
7. Climate change and the resulting rise in sea level are likely to exacerbate threats to buildings, roads, powerlines, and other infrastructure in climatically sensitive places. For example, infrastructure damage is related to permafrost melting in Alaska, and to sea-level rise and storm surge in low-lying coastal areas.
8. A range of negative health impacts is possible from climate change, but adaptation is likely to help protect much of the US population. Maintaining our nation's public health and community infrastructure, from water treatment systems to emergency shelters, will be important for minimizing the impacts of water-borne diseases, heat stress, air pollution, extreme weather events, and diseases transmitted by insects, ticks, and rodents.
9. Climate change will very likely magnify the cumulative impacts of other stresses, such as air and water pollution and habitat destruction due to human development patterns. For some systems, such as coral reefs, the combined effects of climate change and other stresses are very likely to exceed a critical threshold, bringing large, possibly irreversible impacts.
10. Significant uncertainties remain in the science underlying regional climate changes and their impacts. Further research would improve understanding and our ability to project societal and ecosystem impacts, and provide the public with additional useful information about options for adaptation. However, it is likely that some aspects and impacts of climate change will be totally unanticipated as complex systems respond to ongoing climate change in unforeseeable ways.

The National Assessment effort did not attempt to come to a bottom line, the way that some economists have tried to do, including some here at Yale. Our sense was that the impacts are of such a variety and so intimately tied to how we think of ourselves and our regions that, aside from the many uncertainties, trying to weigh them in a net economic sense would not be meaningful. Questions arise about how one would weigh impacts on people of different wealth; how to account for some people experiencing significant impacts while other might experience small or even positive impacts; how to weigh impacts that will affect future generations compared to the present generation? There are approaches that can be used, but our sense was that having some national entity attempt to convert all of the various impacts to the single metric of a dollar was simply not how to explain the situation for the public and decision makers.

And the impacts I have been discussing are just for the US. For the rest of the world, the situation is likely even more challenging. This is especially the case for the developing world and countries with less diversified economies and fewer resources to devote to moderating and adapting to adverse consequences. In some areas, such as island nations, sea level rise and sea ice retreat will be most important, causing serious inundation during storms and exacerbating erosion problems; for other countries, the shifting boundaries of moist and dry regions will seriously impact agricultural production; in other areas, it will simply be the increase in temperature, making life miserable, particularly in urban areas where air conditioning is not yet extensive; and in some areas the most important consequences will arise from the spread of disease vectors and worsened problems of air and water quality.

While there have been attempts to sum up impacts nationally and globally, it is not at all clear how to properly and fairly compare different impacts. For example, are the effects of hotter, more humid days on the millions of people in New York more or less important than the potential flooding of the Marshall Islands and dislocation of thousands of people 50 to 100 years hence? In considering such consequences, the Bishops statement on climate change suggests that a simple economic analysis is not the basis on which to have the discussion. Rather, as will be discussed more in the accompanying talk by Fr. Drew Christiansen, issues of equity and fairness need to be considered, perhaps even be at the forefront of the public discussion about what to do.

6. Making the Problem Go Away is Difficult

The final point that I want to address is what the potential is, in a scientific sense rather than a political sense, for making this problem, somehow, go away. First, even if we could somehow magically go to zero emissions starting tomorrow, this would not mean that there would be no further changes in the climate. Because of the emissions that have already occurred, the world is likely to experience as much warming in the 21st century as in the 20th century, partly from the continuing effects of the greenhouse gases and partly as a result of halting the emissions of the sulfur dioxide that creates the light-colored, sun-reflecting haze over and downwind of industrial areas. This further climatic change, however, would not be the most devastating consequence. Because fossil fuels provide roughly 80% of the world's energy, the world cannot immediately give up this source of energy without causing global economic collapse—a point made often by the major oil and coal companies.

In that doubling the preindustrial concentration of CO_2 is likely to cause a global warming of roughly a few degrees, which would be likely, for example, to cause the death of most of the world's coral ecosystems and to initiate melting and the deterioration of major parts of Greenland and West Antarctic ice sheets, staying below that concentration level is considered by many to be desirable. Accomplishing this, however, would require that average per capita emissions of carbon worldwide remain at about the current level of one tonne per person, averaged over the 21st century. While there can be growth in energy generation and use per capita above this level by deriving energy from sources other than fossil fuels, coal is at present the least expensive fuel in many developing countries, so getting energy from other sources would require diverting money needed for basic survival needs such as water purification to generation of non-fossil energy. And to accommodate the growth in carbon emissions for those in the developing world while limiting the growth in the atmospheric concentration of CO_2 would require cutbacks in the average emission of carbon by those in the developed world. In that the population of the developing world is several times as large as that of the developed world, our cutbacks on a per capita basis would need to be several times as large as the gains of those in the developing world—each of us would need to cut back enough to allow for the gain by several others in the developing world.

Given present trends and the apparent unwillingness of major emitters to cut back their usage, the world seems to be on a path to considerably higher emissions than at present—perhaps 3 to 4 times as much as at present unless there are much more rapid breakthroughs in energy generation than has been the case. Such a course would push the world toward CO_2 levels closer to those during the Cretaceous period of over 65 million years ago, with near tropical vegetation at high latitudes and sea level eventually as much as 200 feet higher due to the melting of polar icecaps. While life itself would not be threatened and dinosaurs wouldn't likely return (at least naturally), the world would be a very different place.

It was this prospect of very significant global warming that led the nations of the world in 1992 to negotiate the UN Framework Convention on Climate Change, which set as its objective stabilizing the concentration of CO_2 (and some other gases)—that is, halting the rise. The US Senate nearly unanimously approved this Convention in 1992; the Bishops' statement supports the need for such efforts by calling for the stewardship of our environmental heritage.

With the Framework Convention agreed to, the Kyoto Protocol process is supposed to be the first stage in its implementation. Accomplishing the actual stabilization of the atmospheric concentration of CO_2, now or in the future, however, would require that the entire world population emit no more carbon than the US does today—and the US represents only about 5% of the world population. In such a case, if everyone had the same right to emissions, we in the US would need to cut our per capita emissions by about 95%. The Kyoto Protocol would have required those in the US to take a major step in this direction, requiring about a 30% per capita cutback in emissions over 20 years.

Although President Bush, in pulling the US out of the Kyoto Protocol process, did not express the reasons in this way, instead rather disingenuously blaming developing countries for not participating by cutting their relatively low emissions and complaining how this cutback would slightly reduce projected economic growth in the US from its near world-leading position, it was this large cutback in per capita carbon emissions that made the Kyoto agreement so challenging for the US[11]. When you listen to the political speeches what you hear about is total emissions by country or total emissions by the developed and developing worlds. So, it is said, for example, that emissions by China will soon increase so that their emissions are larger than those of the US. What is not added in these explanations is that the population of China is roughly 4 times the population of the US, so their per capita emissions are only 25% of those in the US. I have avoided framing the issue in terms of total emissions because, again as the Bishops' statement expressed, issues of equity need to be considered along with total emissions, standard of living, and other factors. Science may be science, but how it is expressed and what is said can involve

[11] When it was first negotiated, the way in which the effect of the cutback on the US was going to be eased was through an increase in carbon sequestration and through purchase of carbon emissions permits from other countries that could less expensively reduce emissions through improvements in efficiency. In the later negotiation process, however, these approaches were either eliminated or tightly restricted, forcing the very large cutbacks to be made virtually entirely within the US.

many other considerations when the outcome is closely tied to services on which the public has come to rely.

On this issue of the US withdrawing from the Kyoto Protocol process, the cutback proposed for the US would have been a major step. We could have been helped significantly along the way by technological improvements, especially if we had continued the pace of technological improvement that resulted from the programs put in place by President Carter following the major oil embargoes. Unfortunately, that rate of improvement eroded away due to governmental inaction, and it will take some effort to get restarted.

An additional challenge is the continuing growth of the US population, which was not allowed for in the Kyoto accord. With the need to meet the energy needs of the increased number of Americans, not to mention our ever-increasing preferences for SUVs and other low efficiency vehicles, the demand for energy is increasing significantly even while per capita usage is only slowly changing. Much of our population growth today is due to immigration, and stemming it would run into a range of other considerations, traditions and outside pressures. For these reasons, the US is thus in quite a predicament, and doing little to get out of it.

The situation in Europe is, however, quite different. Because the European population is not growing much, and is projected to start declining in some countries, technological improvements can potentially meet European requirements under the Kyoto Protocol. As a result, the European nations are moving forward in its implementation, and in some cases projecting overall societal benefits from doing so. In my opinion, the failure of the US Administration to adequately explain the differences in the situations facing the US and Europe has been an important factor in contributing to the misunderstandings about the Kyoto process in the US and around the world. In addition, the failure of the US to propose a serious alternative to the commitment it had negotiated has seriously exacerbated the situation, and needs to be remedied.

It is important to remember, however, that the Kyoto Protocol, even if implemented, will not achieve stabilization of the CO_2 concentration in the atmosphere—in pursuit of that objective, to which we and the world are legally committed by the UN Framework Convention on Climate Change, the Protocol is only a first step if the heritage we leave to our grandchildren is not going to be a rapidly warming world.

Thank you.[12]

Additional Information on climate change and climate change impacts is available over the Web at, for example, http://www.climate.org and http://www.usgcrp.gov/usgcrp/links/assessments.htm

[12] The views expressed are those of the author, drawing on the findings of major national and international scientific assessment reports that have undergone extensive expert review.

Table 1: Examples of important consequences of climate change affecting particular areas of the United States

Regions and Subregions	Examples of Key Consequences Affecting:		
	The Environment	Society and the Economy	People's Lives
Northeast New England and upstate NY Metropolitan NY Mid-Atlantic	Northward shifts in the ranges of plant and animal species (e.g., of colorful maples) Coastal wetlands inundated by sea-level rise	Reduced opportunities for winter recreation such as skiing; increased opportunities for warm-season recreation such as hiking and camping Coastal infrastructure will need to be buttressed	Rising summertime heat index will make cities less comfortable and require more use of air-conditioning Reduced snow cover
Southeast Central and Southern Appalachians Gulf Coast Southeast	Increased loss of barrier islands and wetlands, affecting coastal ecosystems Changing forest character, with possibly greater fire and pest threat	Increased productivity of hardwood forests, with northward shift of timber harvesting Increased intensity of coastal storms threaten coastal communities	Increased flooding along coastlines, with increased threat from storms Longer period of high heat index, forcing more indoor living
Midwest Eastern Midwest Great Lakes	Higher lake and river temperatures cause trend in fish populations away from trout toward bass and catfish	Increasing agricultural productivity in many regions, ensuring overall food supplies but possibly lowering commodity prices	Lowered lake and river levels, impacting recreation opportunities Higher summertime heat index reduces urban quality of life
Great Plains Northern Central Southern Southwest/Rio Grande Basin	Rising wintertime temperatures allow increasing presence of invasive plant species, affecting wetlands and other natural areas Disruption of migration routes and resources	Increasing agricultural productivity in north, more stressed in the south Summertime water shortages become more frequent	Altered and intensified patterns of climatic extremes, especially in summer Intensified springtime flood and summertime drought cycles

West California Rocky Mountains/Great Basin Southwest/Colorado River Basin	Changes in natural ecosystems as a result of higher temperatures and possibly intensified winter rains Enhanced coastal erosion	Rising wintertime snowline leads to earlier runoff, stressing some reservoir systems Increased crop yields, but with need for greater controls of weeds and pests	Shifts toward more warm season recreation activities (e.g., hiking instead of skiing) Greater fire potential created by more winter rains and dry summers
Pacific Northwest	Added stress to salmon populations due to warmer waters and changing runoff patterns	Earlier winter runoff will limit water availability during warm season Rising forest productivity	Reduced wintertime snow pack will reduce opportunities for skiing, increase opportunities for hiking Enhanced coastal erosion
Alaska	Forest disruption due to warming and increased pest outbreaks Reduced sea ice and general warming disrupts polar bears, marine mammals, and other wildlife	Damage to infrastructure due to permafrost melting Disruption of plant and animal resources supporting subsistence livelihoods	Retreating sea ice and earlier snowmelt alter traditional life patterns Opportunities for warm season activities increase
Coastal and Islands Pacific Islands South Atlantic Coast and Caribbean	Increased stress on natural biodiversity as pressures from invasive species increase Deterioration of corals reefs	Increased pressure on water resources needed for industry, tourism and communities due to climatic fluctuations, storms, and saltwater intrusion into aquifers	Intensification of flood and landslide-inducing precipitation during tropical storms More extreme year-to-year fluctuations in the climate
Native People and Homelands	Shifts in ecosystems will disrupt access to medicinal plants and cultural resources	The shifting climate will affect tourism, water rights, and income from use of natural resources	Disruption of the religious and cultural interconnections of Native people and the environment