Global Warming: A Science Overview

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Fossil fuels (i.e., coal, oil, and natural gas) provide about 85% of the world's energy, sustaining the world's standard-of-living and providing much of the power for transportation, generation of electricity, home heating, and food production. Compared to other sources of energy, fossil fuels are relatively inexpensive, transportable, safe, and abundant. At the same time, their use contributes to environmental problems such as air pollution and acid rain, which are being addressed through various control efforts, and to long-term climate change, which governments have begun to address through adoption of the UN Framework Convention on Climate Change negotiated in 1992.

Drawing primarily from international assessment reports (see references for reports by the Intergovernmental Panel on Climate Change (IPCC)), this paper summarizes six key elements of the science of climate change (often referred to simply as "global warming" although the projected changes involve changes in many variables in addition to a rise in global average temperature). These results are presented as context for considering the challenges of both limiting long-term warming and adapting to the warming that will occur as a result of past use of fossil fuels and the inevitable future use over coming decades.

Human Activities are Changing Atmospheric Composition by Increasing the Concentrations of Radiatively Active (Greenhouse) Gases and Particles

Observations from global measurement stations and reconstructions of the composition of the atmosphere in the past clearly indicate that human activities are increasing the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and of various halocarbons (HCFCs and, until very recently, CFCs). These gases are collectively referred to as greenhouse gases because of their warming influence on the climate.

While these gases occur naturally, records going back many thousands of years indicate that the present concentrations are well above natural levels. The history of emissions versus concentrations, analyses of carbon isotopes, and other scientific results all confirm that these changes are occurring as a result of human activities rather than because of natural processes. For example, the CO_2 concentration is currently about 370 parts per million by volume (ppmv), which is about 30% above its preindustrial value of about 280 ppmv (see Figure 1b). This increase has been due primarily to the combustion of fossil fuels and secondarily to the release of carbon occurring in the clearing

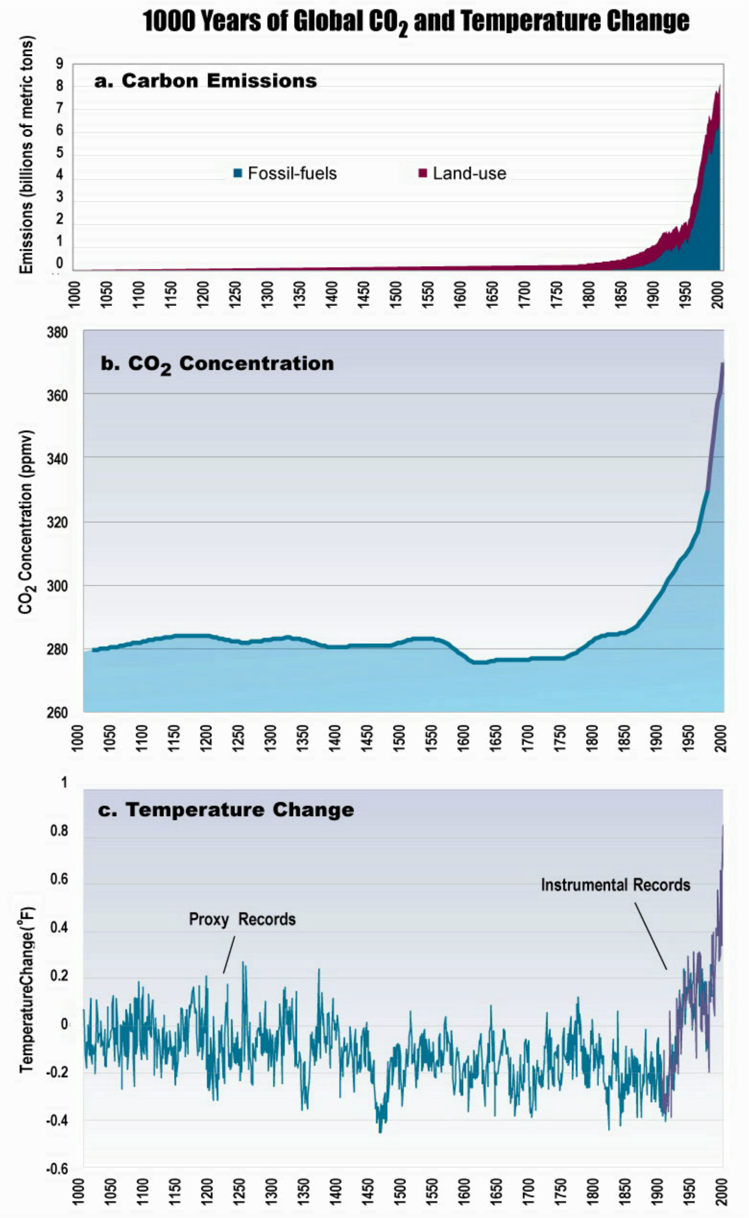


Figure 1. *Carbon emissions,* CO_2 *concentrations, and temperature change over the past millennium. (a) Over the past 1000 years, but especially since 1850, the emissions of carbon dioxide (expressed in terms of carbon emitted) have grown from near zero to over 7 GtC/year (billions of tonnes of carbon per year); of this total, approximately 6 GtC/yr are from combustion of coal, oil, and natural gas and approximately 1 GtC/yr are from net changes in land use. (b) As a result of the* CO_2 *emissions, its concentration has increased from about 280 ppmv to about 370 ppmv over the past 1000 years, especially since 1850. (c) Reconstruction of the global-scale record of temperature departures from the 1961-90 average (primarily from proxy records from the Northern Hemisphere) suggests a relatively slow and steady cooling of about 0.2ºC (0.4ºF) that extended over most of the last 1000 years; beginning in the late 19th century and continuing through the 20th century, an unusually rapid warming of about 0.6ºC (1.0ºF) has taken place (from NAST, 2000, which contains primary references).*

of forested land and the plowing of soils for agriculture (see Figure 1a). The CH_4 concentration is up over 150%. Its increase is due primarily to emissions from rice agriculture, ruminant livestock, biomass burning, landfills, and fossil fuel development, transmission, and combustion. The concentrations of many halocarbons are entirely new to the atmosphere—many of these compounds are solely a result of human activities. The persistence (or lifetimes) of the excess contributions of these gases in the atmosphere range from decades (for CH_4) to centuries (for CO_2 and some halocarbons) to thousands of years (for some perfluorocarbons). Thus, with ongoing emissions, the excesses of their concentrations above natural levels are likely to persist for many centuries.

Human activities are also contributing to an increase in the atmospheric concentrations of small particles (called aerosols), primarily as a result of emissions of sulfur dioxide (SO_2), soot, and some various organic compounds. The emissions of these human-induced aerosols result primarily from use of fossil fuels (primarily from coal combustion and diesel and 2-stroke engines) and from biomass burning. Once in the atmosphere, these compounds can be transformed or combined in various ways. For example, SO_2 is transformed into sulfate aerosols that create the whitish haze common over and downwind of many industrialized areas. This haze tends to exert a cooling influence on the climate by reflecting away solar radiation. Soot aerosols can combine with organics and form mixed aerosols that can exert warming or cooling influences. Changes in land cover, especially where this leads to desertification, can also lead to increased lofting of particles into the atmosphere. Dust lofted in this way generally has a cooling influence on the climate while also decreasing visibility; dust can also be carried to intercontinental scales as a result of long-distance transport.

Of critical importance is that the typical lifetime of aerosols in the atmosphere is less than 10 days (for example, sulfate and nitrate compounds are often rained out, causing the acidification of precipitation known popularly as "acid rain"). Because of their relatively short lifetime in the atmosphere, emissions must be quite substantial for global concentrations to build up to the level that will have a long-term climatic influence that is as great as for the greenhouse gases with their longer atmospheric lifetimes. However, concentrations can become quite high in particular regions, and the pollution effects that result can cause regional disturbances of the climate. For example, aerosols lofted in southern Asia are suspected to be contributing to the diminishment of the monsoon.

Although natural processes can also affect the atmospheric concentrations of gases and aerosols, observations indicate that this has not been an important cause of changes over the past 10,000 years. Thus, it is well-established that human activities are the major cause of the dramatic changes in atmospheric composition since the start of the Industrial Revolution about 200 years ago.

Increasing the Concentrations of Greenhouse Gases will Warm the Planet and Change the Climate

From laboratory experiments, from study of the atmospheres of Mars and Venus, from observations and study of energy fluxes in the atmosphere and from space, and from reconstructions of past climatic changes and their likely causes, it is very clear that the atmospheric concentrations and distributions of radiatively active gases play a very important role in determining the surface temperature of the Earth and other planets. Figure 2 provides a schematic diagram of the energy fluxes that determine the Earth's temperature (and climate).

Of the solar radiation reaching the top of the atmosphere, about 30% is reflected back to space by the atmosphere (primarily by clouds) and the surface; about 20% is absorbed in the atmosphere (primarily by water vapor, clouds,

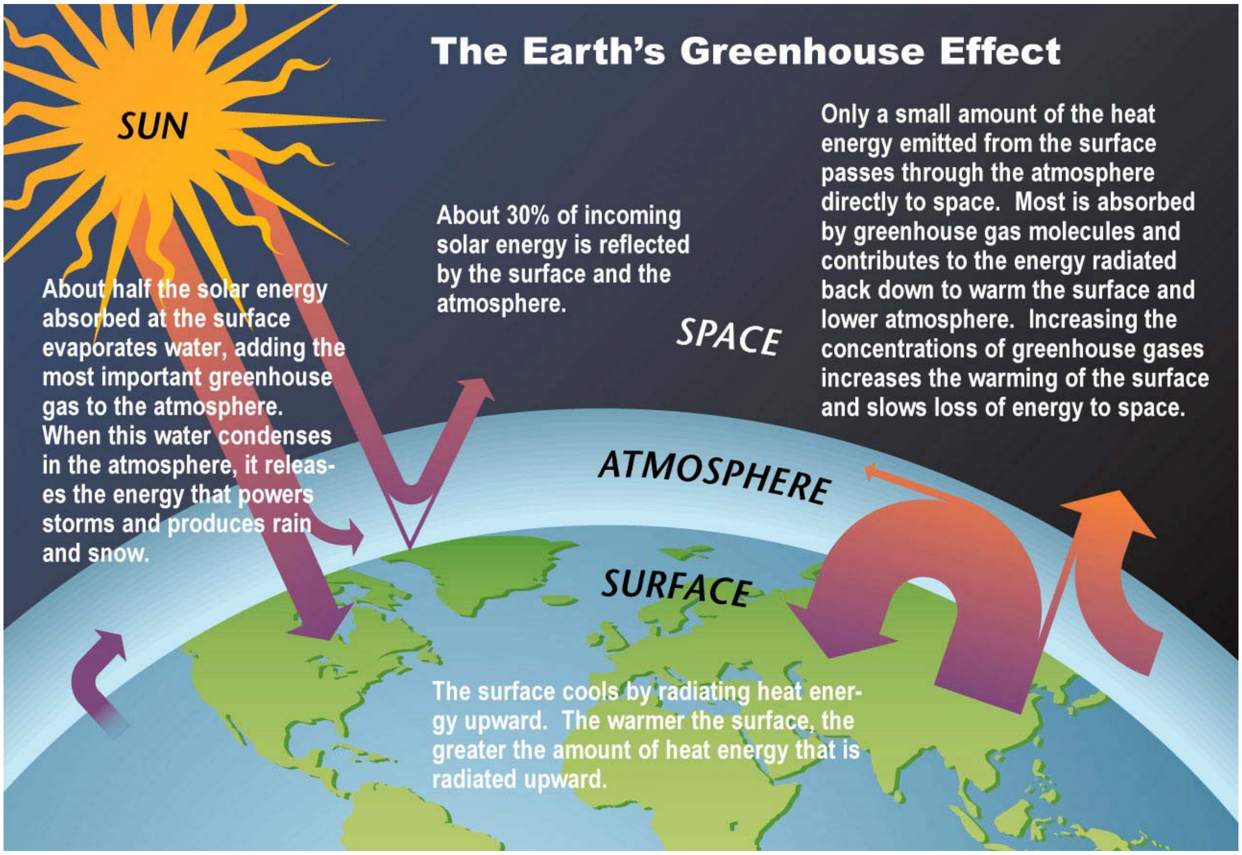


Figure 2. *Schematic diagram of the Earth's greenhouse effect, with arrows proportional in size to the fluxes of energy by the particular process (NAST, 2000). Of incoming solar radiation, about 30% is reflected back into space by clouds and the surface, about 20% is absorbed in the atmosphere, and about 50% is absorbed at the surface. Most of the infrared (heat) radiation emitted by the surface is absorbed in the atmosphere and the atmosphere in turn then emits about 90% of this amount back to the surface, adding to its heat gain from the Sun. The extra energy at the surface is used to evaporate water or heat the near surface atmosphere. In the atmosphere, the extra energy it receives from the Sun, from absorbed infrared radiation, from latent heating released during precipitation, and from sensible heating, is emitted to space to balance the net solar radiation absorbed by the surface and atmosphere.*

and aerosols), and about 50% is absorbed at the surface. For a system to come to a steady state temperature, the energy absorbed must be balanced by radiation that is emitted away as infrared (or heat) radiation. Were the Earth's atmosphere transparent and its surface a simple radiator of energy to space, the Earth's average surface temperature would equilibrate at close to 0^{o}F (-18ºC), given the current reflectivity of the Earth-atmosphere system. Such a temperature would be much too cold to sustain life as we know it.

However, the Earth's atmosphere is not transparent to infrared radiation, being able to recycle some of it in a way that creates a warming influence. This warming effect occurs because much of the infrared radiation emitted by the surface and by the greenhouse gases and low clouds in the atmosphere is absorbed by various radiatively active gases in the atmosphere. For example, less than 10% of the infrared radiation emitted by the surface gets through directly to space without being absorbed. A significant fraction of the absorbed energy is radiated back to the surface by the atmosphere's greenhouse gases and clouds, providing additional energy to warm the surface. This radiation in turn causes the surface to warm, which raises its temperature and causes more radiation to be emitted upward, where much of it is again absorbed, providing more energy to be radiated back to the surface. This emission-absorption-reemission process is popularly called the *greenhouse* effect, even though the processes involved are different than keep a greenhouse warm and humid. The effect of this natural greenhouse effect is to raise the average surface temperature of the Earth from about 0°F (-18°C) to almost 60°F (15°C).

An additional warming influence results because the atmospheric temperature decreases with altitude up to the tropopause (about 8-10 miles up) before temperatures start to rise again in the stratosphere, which is warmed by the solar absorption by ozone (O_3) molecules. As a result of this temperature structure, when the concentrations of greenhouse gases are increased and the atmosphere becomes more opaque to infrared radiation, the absorption and reemission of infrared radiation to the surface comes from lower and warmer layers in the atmosphere. Because the emission of infrared energy is proportional to the fourth power of temperature, this has the effect of increasing the downward emitted radiation, tending to enhance the natural greenhouse effect. Similarly, emission outward to space occurs from higher and colder layers when the concentrations of greenhouse gases are increased. As a result, the surface-atmosphere system has to warm even more to achieve a planetary energy balance with the incoming solar radiation.

The most important radiatively active (or greenhouse) gas is water vapor (to be radiatively active, molecules need to have at least 3 atoms so that various rotational and vibrational bands can be activated by the radiation). Not only does water vapor absorb infrared radiation emitted by the Earth's surface, but it also absorbs infrared radiation from the Sun. In addition, under appropriate conditions, water vapor can condense and form clouds that absorb and emit infrared radiation as well as absorbing and scattering solar radiation. In addition to water vapor, other greenhouse gases in the atmosphere that are present in significant concentrations include CO_2, CH_4, N_2O, and many chlorofluorocarbons, the concentrations of all of which are being directly affected by human activities, and O_3, the tropospheric and stratospheric concentrations of which are being indirectly affected through chemical reactions caused by the emissions of other gases. Because of their connection to human activities, these greenhouse gases are usually referred to as the anthropogenic greenhouse gases (strictly speaking, their concentrations are being anthropogenically modified).

Observations from space-based instruments clearly indicate that the rising concentrations of the anthropogenic greenhouse gases are tending to enhance the natural greenhouse effect. Even though the greenhouse effect of the anthropogenic greenhouse gases is exceeded by the positive greenhouse effect of atmospheric water vapor, their effect is not overwhelmed by it. Instead, the warming caused by the increases in concentrations of CO_2, CH_4 and other anthropogenic greenhouse gases is significantly amplified by a positive water-vapor feedback mechanism. This positive feedback occurs because more water vapor can be present in a warmer atmosphere, so that warming leads to an increase in atmospheric water vapor and a further warming. At the same time, however, changes in atmospheric water vapor and in atmospheric circulation can change the extent and distribution of clouds, and this can in turn affect the extent of the absorption and scattering of solar radiation and the absorption and reemission of infrared radiation through relatively complex and uncertain cloud feedback mechanisms.

Overall, there is no scientific disagreement that increases in the atmospheric concentrations of the anthropogenic greenhouse gases will tend to raise the Earth's average surface temperature—the key questions are by how much and how rapidly.

Increases in the Concentrations of Greenhouse Gases Since the Start of the Industrial Revolution are Already Changing the Climate, Causing Global Warming

The evidence is clear-cut that the concentrations of greenhouse gases have risen significantly since the start of the Industrial Revolution and that increasing the concentrations of greenhouse gases will induce a warming influence on the Earth's climate. A key test of scientific understanding is to determine if the time history and magnitude of climatic changes that are occurring match those expected to be occurring, based on theoretical and numerical analyses, as a result of past emissions and the resulting changes in atmospheric composition. Complications in this analysis arise because other influences on the Earth's radiation balance (referred to as *radiative forcings*) also can be affecting the climate. These radiative forcings include natural influences, such as changes in the output of solar radiation or in stratospheric particle loadings caused by volcanic eruptions, and human-induced changes, such as depletion of stratospheric ozone, enhancement of tropospheric ozone, changes in land cover, and changes in the amount of aerosols in the atmosphere.

To have the best chance of identifying the human influence, it is most useful to look at the longest records of the climatic state. Instrumental records of average temperature for large areas of the Earth go back to the mid-19th century. These records indicate a warming of over 1°F (about 0.6ºC) over this period. Extensive proxy records (i.e., records derived from tree rings, ice cores, coral growth, etc.) for the Northern Hemisphere going back about 1000 years also indicate very significant warming during the 20th century compared to the natural variations apparent over earlier centuries. As shown in Figure 1c, a sharp rise in the temperature began during the late 19th century and continued through the 20th century. This warming appears to be much more persistent than the earlier natural fluctuations that were likely caused by the inherent natural variability of the ocean-atmosphere system (i.e., internal variability) and the natural variations in solar radiation and the occasional eruption of volcanoes (i.e., external variability). That warming is occurring is also confirmed by rising temperatures measured in boreholes (i.e., dry wells), retreating mountain glaciers and sea ice, increasing concentrations of atmospheric water vapor, rising sea level due to melting of mountain glaciers and thermal expansion in response to recent warming (augmenting the natural rise due to the long-term melting of parts of Antarctica), and related changes in other variables.

The key question is whether these changes might be a natural fluctuation or whether human activity is playing a significant role. Among the reasons that the effect is being attributed largely to human activities is the coincidence in timing with the changes in greenhouse gas concentrations, the very large and unusual magnitude of the changes compared to past natural fluctuations, the warming of the lower atmosphere and cooling of the upper atmosphere (a sign of a change in greenhouse gas concentrations rather than in solar radiation), and the global pattern of warming. Some uncertainty is introduced because some of the warming occurred before the sharpest rise in greenhouse gas concentrations during the second half of the 20th century. Some analyses indicate that as much as 20-40% of the overall warming may be due to a coincidental increase in solar radiation, although other factors, such as changes in land cover or in soot emissions, may also have had an influence. In addition, some uncertainty has been introduced because the rise in tropospheric temperatures over the past two decades may have been a bit slower than the rise in surface temperature. Whether this difference is real or arises from, for example, calibration issues with the satellite instrumentation, natural variations in Earth-surface temperatures, the confounding influences of ozone depletion, volcanic eruptions, and atmosphere-ocean interactions, or other factors is not yet clear.

Taking all of the scientific results into consideration, the Intergovernmental Panel on Climate Change (IPCC, 1996a) concluded in its Second Assessment Report in 1995 that "The balance of evidence suggests a discernible human influence on the global climate." This conclusion, in essence, is equivalent to the criterion for a civil rather than a criminal conviction. In its Third Assessment Report (IPCC, 2001), the IPCC indicated even more clearly that the magnitude and timing of the warming during the 20th century, especially during the last 50 years, quite closely matches what would be expected from the combined influences of human and known natural influences.

Future Emissions of Greenhouse Gases and Aerosols Will Lead to Significant Further Climate Change, Including Much More Warming and Sea Level Rise than Occurred During the 20th Century

With the global population of 6 billion and current average fossil fuel usage, each person on Earth is responsible, on average, for emissions of about 1 metric ton (tonne) of carbon per year. Per capita use varies widely across the world, reaching nearly 6 tonnes per year in the US and about 3 tonnes per year in Western Europe, but amounting to only about 0.5 tonne per person per year in developing countries such as China and India. Projections for the year 2100 are that the global population may increase to 8 to 10 billion. As a result of the rising standard-of-living and the necessary energy required to sustain it, average per capita emissions across the globe may double as fossil fuel use grows significantly in the highly populated, but currently underdeveloped, emerging economies. If this happens, total annual emissions would more than triple from about 6 billion tonnes of carbon per year to about 20 billion tonnes of carbon per year. New estimates by the IPCC suggest emissions in 2100 could range from about 6 to over 30 billion tonnes of carbon per year (IPCC, 2000).

If global emissions of CO_2 gradually increase to about 20 billion tonnes of carbon per year by 2100, models of the Earth's carbon cycle that are verified against observations of past increases in concentration, project that the atmospheric CO_2 concentration would rise to just over 700 ppmv. This would be almost double its present concentration, and over 250% above its preindustrial value. Scenarios of future concentrations based on consideration of ranges in global population, energy technologies, economic development, and other factors project that the atmospheric CO_2 concentration could range from about 500 to over 900 ppmv in 2100, with concentrations rising even further in the next century. Depending on various control measures, this rise in the CO_2 concentration could also be accompanied by increases in the concentrations of CH_4 and N_2O, as well as of sulfate and soot aerosols, although it would take an unrealistically large (and unhealthy) amount of aerosols to limit radiative forcing to the extent that it is projected to rise as a result of the increases in the concentrations of the anthropogenic greenhouse gases.

Projections of the climatic effects of such changes in atmospheric composition are often based on use of computer-based climate models that are constructed based on the application of fundamental physical laws and results of extensive field investigations of how atmospheric processes work. To gain a level of confidence in the models, they are tested by comparing their simulations to the observed behavior of the climate from recent decades, recent centuries, and for geological periods in the past. Based on the model results and theoretical analyses, as well as on extrapolation of recent trends, the global average temperature is projected to rise by about 2.5 to 10ºF (about 1.4 to 5.8ºC) by 2100 (IPCC, 2001a). Such a warming would lead to temperatures that would far exceed those existing during the period in which society developed (see Figure 3). In addition to the warming influence of the rise in the CO_2 concentration, reduction in the

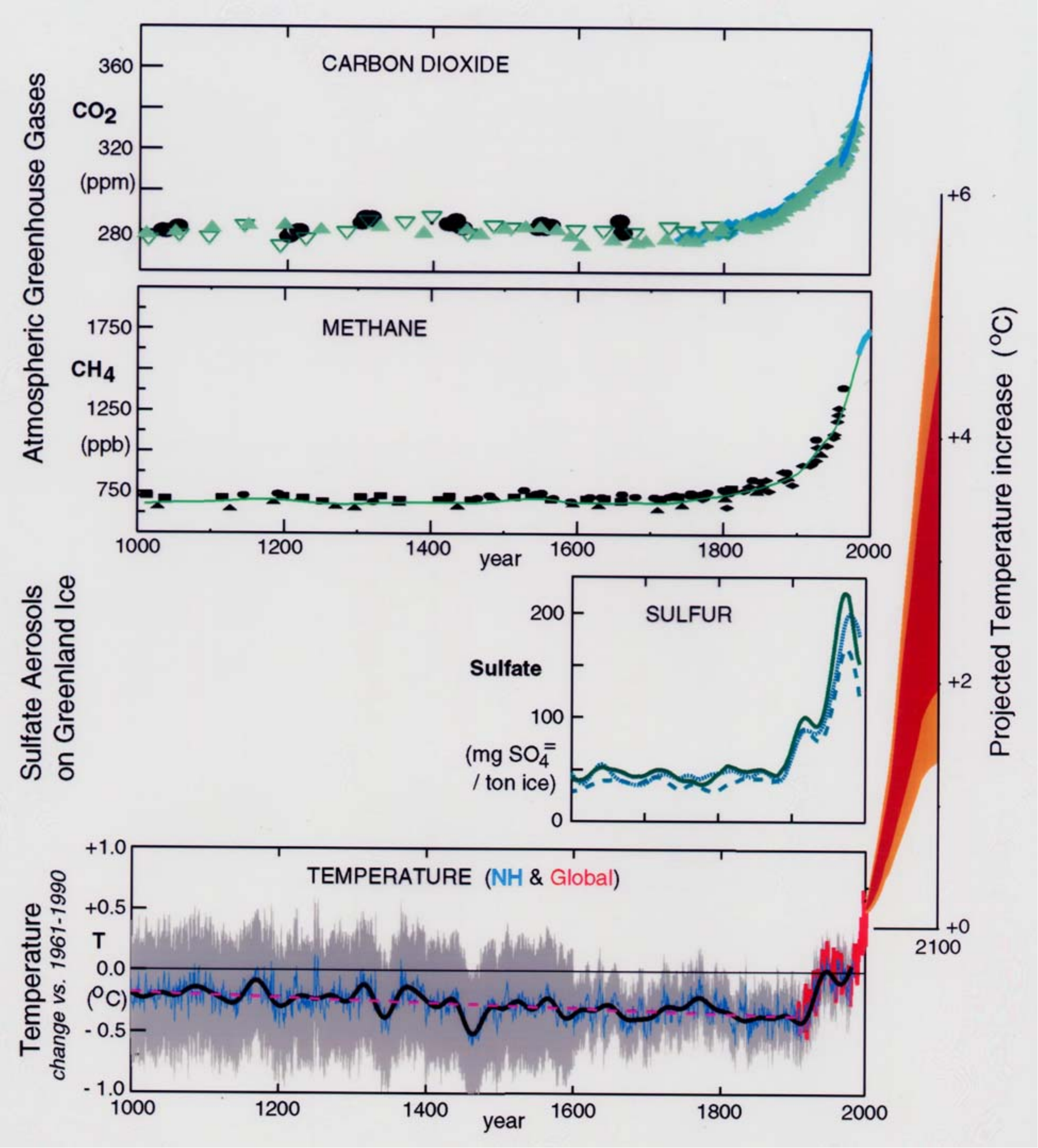


Figure 3. Projection of the increase in global average surface temperature during the 21st century in comparison to conditions that have existed during the past 1000 years. Concentrations of carbon dioxide, methane, and sulfate aerosols increased significantly during the industrial age. A sharp rise in temperature has been occurring since the late 19th century. Based on model simulations reinforced by theoretical and paleoclimatic analyses, global average temperatures are projected to rise 1.4 to 5.8 ºC by 2100 (from IPCC, 2001a).

emissions of SO_2 in order to reduce acid precipitation and enhance air quality and public health could contribute to the warming, although an associated reduction in soot aerosol emissions might counteract this effect.

Based on these longer-range projections, it is very likely that the warming over the next several decades will be greater than the warming over the whole 20th century, even were there to be sharp reductions in CO_2 emissions. Associated with this warming would be shifts in precipitation zones and an intensification of evaporation and precipitation cycles, creating conditions more conducive to extremes of floods, droughts, and storms. In addition, projections are that the rate of sea level rise would increase from 4 to 8 inches/century (0.1 to 0.2 m/century) over the 20th century to a rate of 4 to 36 inches/century (0.1 to 0.9 m/century) during the 21st century. As was the case for the sudden appearance of the Antarctic ozone hole, there are likely to be surprises as well, given the presence of potential thresholds and non-linearities. One of the possibilities is the potential disruption of the Gulf Stream and the global scale deep ocean circulation of which it is a part. The recurrence of a weakening such as apparently occurred as the world emerged from the last glacial about 11,000 years ago would be expected to cause a strong cooling centered over Europe (were this to happen during the 21st century, the cooling would likely only moderate somewhat the influence of global warming) and an acceleration in the rate of sea level rise (due to reduced sinking of cold water into the deep ocean).

The Environmental and Societal Consequences of Climate Change are Likely to be Diverse and Distributed, With Benefits for Some and Damages for Others

With fossil fuels providing important benefits to society, contemplating changes in the ways in which most of the world's energy is generated would seem appropriate only if the types of consequences with which societies will need to cope and adapt are also quite significant. Several types of consequences for the US have been identified (NAST, 2000; NAST, 2001; Department of State, 2002). A similar summarization of scientific findings has been made for the world by the Intergovernmental Panel on Climate Change (IPCC, 1996b, 1996c, 2001b). The following sections summarize broad categories of impacts, particularly in terms of impacts for the US, recognizing that those in the US may be able to more readily adapt to these changes than those in developing nations.

Human Health

Sharp increases in summertime heat index would be likely to increase mortality rates in the US were it not for the expected offset of these conditions by the more extensive availability of air-conditioning. The poleward spread of mosquitoes and other disease vectors has the potential to increase the incidence of infectious diseases, but is likely to be offset by more attention to public health and enhancing building and community design and maintenance standards. The increased intensity of extreme events may injure or kill more people (and disrupt communities) unless steps are taken to enhance risk-adverse planning and construction.

Food Supplies

Higher CO_2 concentrations are very likely to enhance the growth of many types of crops and to improve their water use efficiency. If this happens widely (i.e., if other constraints on agriculture do not arise), agricultural productivity would be expected to rise, increasing overall food availability, and reducing food costs for the public. For farmers in some areas, the lower commodity prices that would be likely to result would reduce farm income, and farmers in marginal areas, even though benefiting from some gain in productivity, are unlikely to remain competitive. This could cause economic problems in nearby rural communities unless other profitable crops are identified.

Water Supplies

Changes in the location and timing of storms will alter the timing and amount of precipitation and runoff and warmer conditions will change snow to rain, requiring changes in how water management systems are operated. This will be especially the case in the western US because there is likely to be less snow and more rain in winter coupled with more rapid and earlier melting of the snowpack. These changes are likely to require a lowering of reservoir levels in winter and spring to provide a greater flood safety margin, even though this would risk reducing water availability in summer when demand will be rising. Across much of the US, the intensity of convective rainfall (e.g., from thunderstorms) is projected to increase, creating the potential for enhanced flooding in watersheds that experience frequent rainfall. Conversely, increased summertime evaporation may also reduce groundwater recharge in the Great Plains, and cause lower levels in the Great Lakes and in rivers such as the Mississippi, reducing opportunities for shipping and recreation.

Fiber and Ecosystem Services from Forests and Grasslands

While winter precipitation may increase in some areas, temperatures are likely to significantly increase in most areas. The increase in evaporation rates is likely to reduce summertime soil moisture. Some, but not all, of these effects may be offset by the increased CO_2 concentration that will help many types of plants grow better (if other factors such as nutrients are not limiting). As seasonal temperatures and soil moisture change, ecosystems will be affected, causing changes in prevailing tree and grass types and then associated changes in wildlife. As regions accumulate carbon in vegetation and dry out during persistent warm episodes, fire risk is likely to increase in many regions. Some climate model projections suggest a much drier southeastern US, stressing the current forests or even leading to their transformation into savanna (see Figure 4). At the same time, the southwestern deserts may get wetter and sprout more vegetation (which may, however, increase fire risk in dry seasons). What is most important to understand is that the notion of ecosystem migration is a misconception—particular species will become dominant in different locations. However, this will likely mean the deterioration of existing ecosystems and the creation of new ones, albeit likely not with the complexity and resilience of current systems because there will not be sufficient time for adjustment and evolution to take place. If the climate changes at the rates projected, stresses on ecosystems over the next 100 years may be as great as over the last 10,000 years.

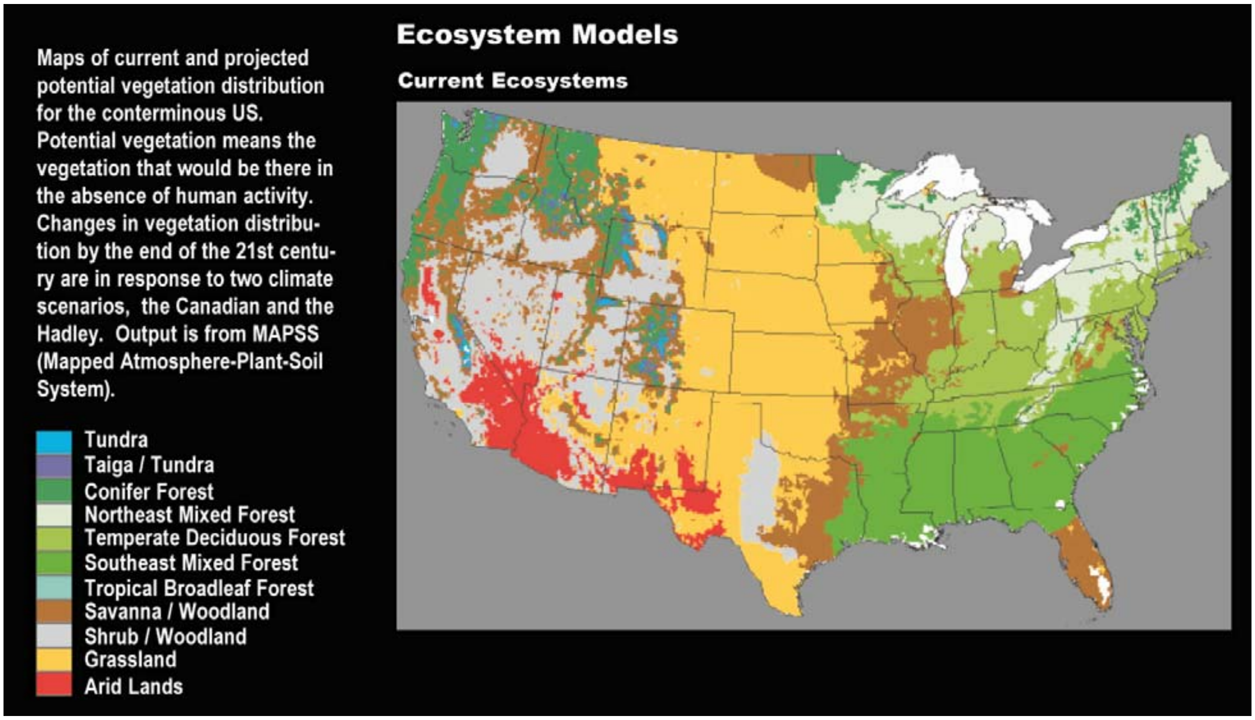
Coastal Endangerment

Mid-range projections suggest that the relatively slow rate of rise of sea level this century (about 4 to 8 inches, reduced or amplified by regional changes) may increase by a factor of 3 during the 21st century. For regions currently experiencing subsidence of their coastlines (e.g. Louisiana, the Chesapeake Bay, etc.), there could be a significant acceleration in inundation and loss of coastal lands, especially of natural areas such as wetlands and other breeding grounds where protective measures such as diking cannot be afforded. The rate of loss will be greatest during coastal storms when storm surges (and therefore damage) will reach further inland and further up rivers and estuaries. For developed areas, strengthening of coastal protection is needed, not just to protect against sea level rise, but also to reduce current vulnerability to coastal storms and hurricanes.

Transportation

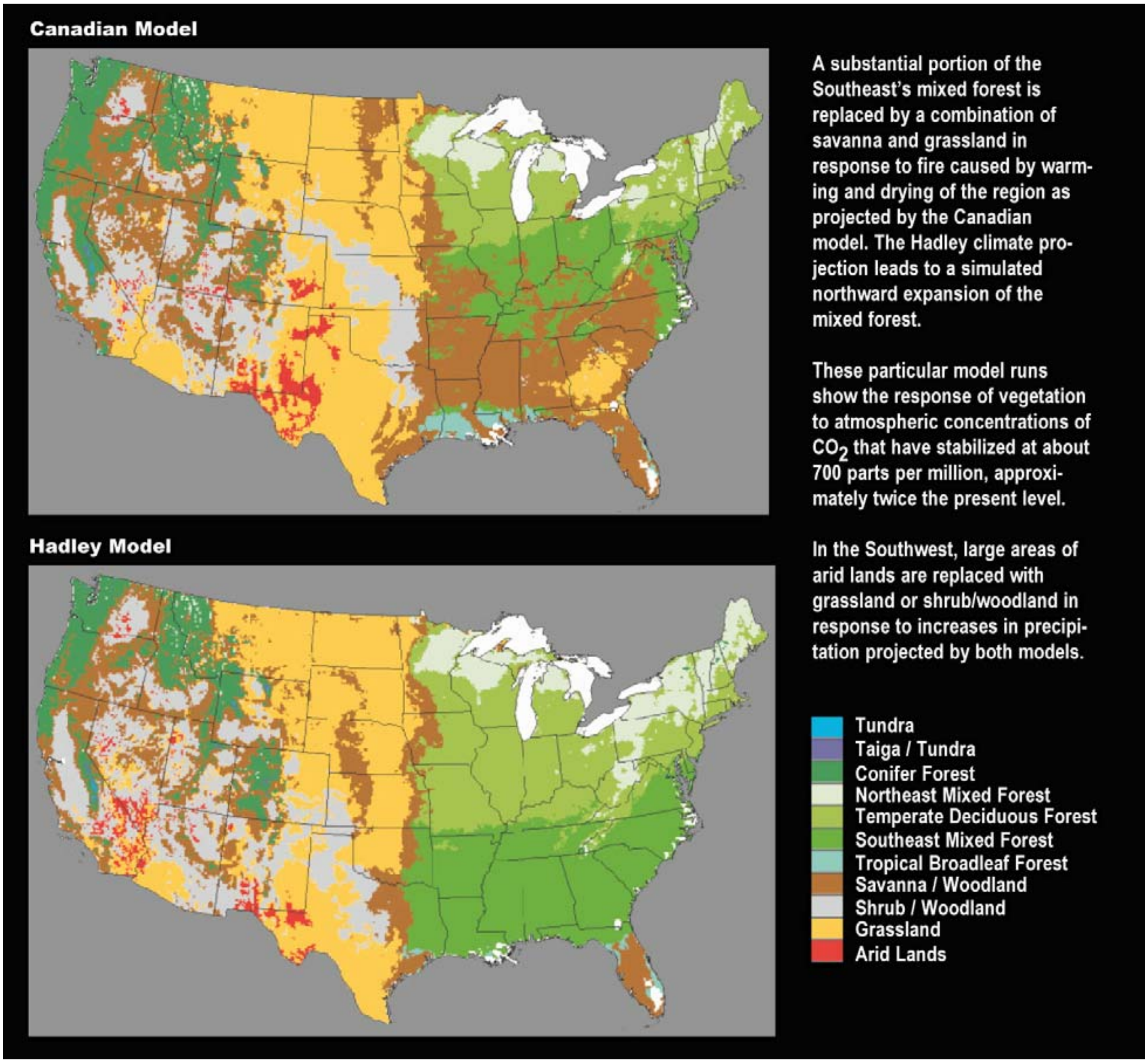
While the US transportation system is very reliable and quite robust, impacts from severe weather and floods currently cause disruptive economic impacts and inconvenience that sometimes become quite important for particular regions. While information is only starting to emerge about how climate change might lead to changes in weather extremes, a range of possible types of impacts seem possible, including some that are location dependent and some that are event specific. Location-dependent consequences might, for example, include: lower levels in the Great Lakes and the St. Lawrence River, and, particularly during the summer, in the Mississippi-Missouri-Ohio River systems. Lower levels could significantly inhibit shipping, even though reduction in the thickness and duration of lake ice in the Great Lakes during winter could lengthen the shipping season.

Along coastlines, reduction in ice cover could lead to more damage to coastal infrastructure, especially because waves would be expected to be larger and cause more erosion. In addition, sea level rise could endanger barrier islands and coastal infrastructure while shifting sediments and channels in ways that might affect coastal shipping and require more frequent dredging and remapping. In the Arctic, warming is already reducing the extent of sea ice, and further warming could lead to the opening of Arctic waters for shipping while also causing more rapid melting of permafrost that could destabilize roads, pipelines, and other infrastructure.



Maps of current and projected potential vegetation distribution for the conterminous US. Potential vegetation means the vegetation that would be there in the absence of human activity. Changes in vegetation distribution by the end of the 21st century are in response to two climate scenarios, the Canadian and the Hadley. Output is from MAPSS (Mapped Atmosphere-Plant-Soil System).

Figure 4a. *Computer-based ecosystem models that associate the most likely type of ecosystem with the prevailing and future climatic conditions have been used to estimate the potential for changes in the predominant vegetation as a result of climate change. (a) Map of the prevailing vegetation of the conterminous US using vegetation models calibrated for the climatic conditions of the late 20th century.*



A substantial portion of the Southeast's mixed forest is replaced by a combination of savanna and grassland in response to fire caused by warming and drying of the region as projected by the Canadian model. The Hadley climate projection leads to a simulated northward expansion of the mixed forest.

These particular model runs show the response of vegetation to atmospheric concentrations of CO_2 that have stabilized at about 700 parts per million, approximately twice the present level.

In the Southwest, large areas of arid lands are replaced with grassland or shrub/woodland in response to increases in precipitation projected by both models.

Figure 4b. *(b) Maps of projected vegetation for the conterminous US based on two projections of climatic conditions for the latter part of the 21st century. The Canadian model scenario projects that the prevailing climatic conditions are likely to be relatively hotter and drier than present conditions, especially in the southeastern US and during the warm months, whereas the Hadley (U.K.) model projects that climatic conditions will tend to be warmer and moister. In both models, increased precipitation in the southwestern US tends to reduce the extent of arid lands. In the southeastern US the Hadley scenario projects continued coverage by a mixed forest, whereas the Canadian model projects that savanna and woodland conditions are likely to become predominant.*

Event-specific consequences could include: more frequent occurrence of heavy and extreme rains (a trend already evident during the 20th century); reduced or shifted occurrence of winter snow cover that might reduce winter trucking and air traffic delays; altered frequency, location, or intensity of hurricanes accompanied by an increase in flooding rains; and warmer summertime temperatures that raise the heat index and may increase the need for air pollution controls. Early model projections suggest that the return period of severe flooding could also be significantly reduced (e.g., the baseline 100-year flood might occur as often, on average, as every 30 years by 2100). By reducing the density of the air, warmer temperatures will also cause reductions in combustion efficiency, which would both increase costs and require longer runways or a lower load for aircraft. Starting to consider climate variability and change now in the design of transportation systems could be a very cost-effective means of enhancing both short- and long-term resilience.

Air Quality

Warmer temperatures generally tend to accelerate the formation of photochemical smog. The rising temperature and rising absolute (although perhaps not relative) humidity are projected to raise the urban heat index significantly, contributing to factors that lead to breathing problems. Meeting air quality standards in the future is likely to require further reductions in pollutant emissions (although, of course, a move away from the combustion engine might make this change much easier). Increasing amounts of photochemical pollution could also have greater impacts on stressed ecosystems, although the increasing concentration of CO_2 may help to alleviate some types of impacts as the leaf's stomata close somewhat. Summertime dryness in some regions could exacerbate the potential for fire, creating the potential for increased amounts of smoke, while in other regions dust may become more of a problem.

International Coupling

While it is natural to look most intently at consequences within the US, our Nation is intimately coupled to the world in many ways. For example, what happens outside the US will affect economic markets, overseas investments, the availability of imported food and other resources, and the global environment that all countries share. Health-related impacts overseas are likely to be of importance to US citizens both because US citizens travel abroad for business and pleasure and because foreign travelers come to visit the US. Many resources, from water and hydropower-derived electricity to fisheries and migrating species, are shared across borders, or move and are transferred internationally. Finally, the US is largely a nation of immigrants, and when disaster strikes overseas, its citizens respond with resources and our borders are often opened to refugees. Clearly, all countries are connected to what happens outside their borders, and those of us in the US will be affected by what the societal and environmental consequences experienced by others.

Summary of Impacts

It is very difficult to accurately quantify the risk and importance of such a wide variety of impacts in a way that allows comparison with taking actions to change energy systems (IPCC, 1996c; IPCC, 2001c). At the international level, this is particularly difficult because issues of equity and cultural values more forcefully enter into consideration (e.g., what is the present economic value of the risk of the Marshall Islands being flooded over in 50 to 100 years?). Overall, there will likely be important consequences, some negative and some positive, that we are only starting to understand. Quite clearly, the present tendency to average across large domains is very likely to obscure rather large consequences for localized groups.

Reducing the Rate of Change of Atmospheric Composition to Slow Climate Change Will Require Significant and Long-Lasting Cutbacks in Emissions

In recognition of the potential for significant climatic and environmental change, the nations of the world in 1992 agreed to the United Nations Framework Convention on Climate Change (UNFCCC), which set as its objective the "stabilization of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." At the same time, the Convention called for doing this in a way that would "allow ecosystems to adapt naturally to climate change, … ensure that food production is not threatened, and … enable economic development to proceed in a sustainable manner." Defining the meanings of these terms and accomplishing the objective are both formidable challenges. For example, stabilizing the atmospheric concentration at double the preindustrial level (about 550 ppmv) would require international stabilization of the present per capita CO_2 emission level at about 1 tonne of carbon per person per year throughout the 21st century rather than allowing per capita emissions to double over this period, as is projected to occur in the absence of controls (recall that the typical US citizen is now responsible for emission of 5-6 tonnes of carbon per year and Europeans are responsible for about 3 tonnes of carbon per year). Limiting the CO_2 concentration to 550 ppmv would also require that global emissions for the 22nd century would need to drop by at least a factor of 2 below current global average levels (i.e., to about half of the 6 billion tonnes of carbon now emitted each year), meaning that per capita emissions of carbon would have to be about one-third the level of developing countries today. This would not mean that per capita energy use would need to be this low, only that net per capita use of fossil fuels (so emissions minus sequestration) would need to be this low. The IPCC (IPCC, 2001c) suggests that such reductions could be accomplished by meeting most of the world's energy needs using renewables and nuclear, and if there is also significant effort to improve the efficiency of energy end uses.

The Kyoto Protocol was negotiated as a first step toward achieving the UNFCCC objective. Even though its goal is relatively modest (i.e., cutting developed country emissions to about 7% below their 1990 levels) and would only begin to limit the rate of increase in the global CO_2 concentration, it has been especially controversial in the US. Even if fully implemented by all the developed nations through the 21st century (including the US, which has rejected it), the increase in the CO_2 concentration by the year 2100 would be only about 15-20% less than the currently projected rise to about 710 ppmv, and much less than the 50% cutback in emissions needed to move toward stabilization at 550 ppmv. Such analyses make it clear that reducing CO_2 emissions to achieve stabilization at 550 ppmv would thus require a multi-faceted approach around the world as well as in the US, including significant introduction of non-fossil energy technologies, improvement in energy generation and end-use efficiencies, and switching to natural gas from coal.

Absent such efforts on a global basis, the CO_2 concentration could rise to about 800-1100 ppmv (about 3-4 times the preindustrial level). Were this to occur, projections indicate that the resulting warming would be likely to induce such potentially dangerous long-term, global-scale impacts as the initiation of the eventual melting of the Greenland and the West Antarctic ice sheets (each capable of inducing a sea level rise of up to about 15-20 feet, or 5-7 meters, over the next several centuries), the loss of coral reef ecosystems due to warming and rapid sea level rise, the disruption of the global oceanic circulation (which would disrupt the nutrient cycle sustaining ocean ecosystems), and extensive loss or displacement of critical ecosystems that societies depend on for many ecological services.

What is clear from present-day energy analyses is that there is no "silver bullet" that could easily accomplish a major emissions reduction (e.g., see Hoffert et al., 2002). Achieving the UNFCCC objective over the 21st century is therefore likely to require a much more aggressive (although not unprecedented) rate of improvement in energy efficiency, broad-based use of non-fossil technologies (often selecting energy sources based on local resources and climatic conditions), and accelerated technology development and implementation.

Conclusion

A major reason for controversy about dealing with this issue results from differing perspectives about how to weigh the need for scientific certainty, about ensuring a reliable source of energy to sustain and improve the national and global standard-of-living, about capabilities for improving efficiency and developing new technologies, about the potential risk to "Spaceship Earth" that is being imposed by this inadvertent and virtually irreversible geophysical experiment, about the economic costs and benefits of taking early actions to reduce emissions (including what factors to consider in the analysis and how to weigh the importance of long-term potential impacts versus better defined near-term costs), and about the weight to give matters of equity involving relative impacts for rich versus poor within a nation, the developed versus developing nations, and current generations versus future generations.

Moving toward a consensus on these issues will require that everyone become better informed about the science of climate change, about potential impacts, and about potential options for reducing emissions. Moving toward collective action will require that the political system focus on finding approaches that tend to balance and reconcile these (and additional) diverse, yet simultaneously legitimate, concerns about how best to proceed.

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