# Climate Change:
# Human Driving Forces, Biophysical Basis, and Likely Impacts

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## Introduction

The issue of potential climate change, and the relation of various human activities to that potential change, looms as one of the greatest challenges facing humanity in the next millennia. The principal problem that makes this issue so important and, potentially intractable, is that most contemporary Western culture, and increasingly Eastern and Southern culture as well, is organized to generate more wealth through economic activity. Since the basic way that humans generate wealth is through carbon fuel-based industrialization, the pressure for increasing economic activity means essentially that all of human society is organized *de facto* to pump more carbon dioxide into the atmosphere.

There is a great deal of debate about the climate change issue, as indeed there should be for a problem of this magnitude. Since much of our economy is based on the very activities that generate the problem, and almost no one wants to be poorer, we have some very difficult decisions. Not surprisingly, interest groups and individuals with strong vested interests in the status quo vehemently oppose any restriction on the use of fossil fuels and they challenge the science of those who have argued for a large impact of human activity on climate. Indeed, it is interesting to see how many persons with little expertise in climatology have become self-appointed experts on climate change.

Reflecting the contentious nature of the debate, the two largest industries in the United States have different views on climate change. The automobile industry opposes any restrictions on the use of fossil fuels. On the other hand, the insurance industry is concerned about that the much larger payments they incurred in the 1990s due the many additional severe climatic events (hurricanes, tornadoes, etc.). The unprecedented floods of 1993 caused $20 billion damage, the droughts of 1988 $39 billion. Scientists suggest these could be due to a warming climate, and is just a precursor of even worse climate conditions ahead.

Given the large stakes, the fact that different players are likely to be effected in very different ways, and indeed a general widespread concern for the state of the Earth, we think it is important for a much broader public to understand the full nature of the problem. This includes the fundamental science involved, what we do or do not know with reasonable scientific certainty, the possible futures that await humanity and the Earth as a whole, and the choices before us. This chapter is meant to do that.

## The Driving Forces of Environmental Change

There are few aspects of environmental change that are universally agreed upon. This is due in part to the complexity of the factors that drive environmental change. This complexity has led to the development of simplified conceptual models that seek to identify the major causes of environmental change. The most well-known of these models is the "IPAT" equation (Ehrlich and Holdren, 1971):

$$\text{Impact} = \text{Population} \quad \text{x} \quad \text{Affluence} \quad \text{x} \quad \text{Technology}$$

$$I = P \quad \text{x} \quad A \quad \text{x} \quad T$$

$$\text{Impact} = \#\ \text{People} \quad \text{x} \quad \underline{\text{Economic Activity}} \quad \text{x} \quad \underline{\text{Environmental Impact}}$$

$$\text{\# People} \qquad\qquad \text{Economic Activity}$$

According to this equation, a population's impact on the environment is determined by: (1) population size (P); (2) affluence (A), which determines the economic activity per person; and (3) technology (T), which determines the amount of resource extracted or waste produced per unit of economic activity. Each of these factors is determined by decisions people make which in turn are influenced by a larger system of rules, ideas, attitudes, and beliefs. These rules and beliefs are organized in social and political institutions. Thus, to understand the root causes of environmental impact, we must understand how population, affluence, and technology affect the use of resources and the emission of wastes, and how social and political institutions influence people's choices about and attitudes towards family size, affluence, and technology.

## *Population*

A human population that has grown beyond its carrying capacity often is blamed for environmental problems such as species extinction, global climate change, resource depletion, and poverty in developing nations. Is population growth to blame? To evaluate this proposition, we must understand the factors that cause populations to grow and how this growth affects the environment.

The first modern attempts to count the human population were made near the end of the seventeenth century. Those early censuses put the human population at about 680 million (Whitmore, *et al*., 1992). To reach that level, the human population grew very slowly for hundreds of millennia. Since then, the human population has grown at an extraordinary rate. Between 1700 and 1750, the human population grew at an annual rate of 0.25%, which corresponds to a doubling time of 280 years. By 1850, the growth rate doubled to 0.55 percent per year, and by the 1960's the growth rate reached a peak of 2.06% per year. At that rate, the population doubles every 34 years (Figure 1).

World population currently stands at 6 billion persons and is growing at 1.33% per year, or an annual net addition of 78 million people. World population in the mid-21st century is expected to be in the range of 7.3 to 10.7 billion. The medium-fertility projection, which is usually considered as "most likely", indicates that world population will reach 8.9 billion in 2050 (United Nations, 1999). This represents a 50 percent increase relative to the present.

Population will to grow despite the fact that fertility rates are dropping rapidly in nearly every nation. But even if fertility rates dropped magically to replacement levels today, global population would grow for more than 50 years due to the age structure of the population. Many developing nations have a large fraction of their population below 15. As these people move into their reproductive years, the crude birth rate may rise significantly. This 'built-in' potential for growth is called population momentum. On the other hand, the population of most industrial nations is spread relatively evenly throughout the age classes and has relatively little tendency to grow.

### The Contribution of Population Growth to Environmental Change

Population growth often is blamed for environmental problems because the two seem to go hand-in-hand. More people mean more mouths to feed, more roads and houses, more cars, more gasoline use, and so on. If we hold affluence and technology constant, the economic activity required to support an additional person means more resources must be extracted and more wastes are generated. A few examples demonstrate this connection.

**Land Conversion for Food Production.** Population growth is possible only if food production expands. For most of human history, food production increased by converting forests and grasslands to cropland and pastures. For each person added to the world's population since 1700, an average of 0.3 hectares of forest was converted to agricultural land, predominantly cropland. As a result, about one-third of the non-ice land surface of the planet has been converted from forest, prairie, or wetland to cropland or pasture (Buringh and Dudal, 1987). Land conversion is the principal means by which humans control about 40 percent of global net primary production, which alters or eliminates many of the important environmental services provided by ecosystems such as flood protection, habitat for biodiversity, and maintenance of soil fertility (Vitousek et al., 1986). Thus, the expansion of food production systems arguably is one of the largest environmental changes caused by humans.

**Water Quality.** High population densities increase the amount of waste that each unit of landscape must process. In some areas high population densities generate huge quantities of nitrogen wastes that degrade water quality and harm human health. One of the leading causes of death in many poor nations are waterborne diseases caused by drinking, bathing, or playing in water contaminated by human feces. The quantity of nitrogen in the sewage released to these waterways is far greater than the rate of which bacteria and other organisms can degrade it to non-toxic forms. Most bodies of water in densely populated regions are polluted. Figure 2 shows that the concentration of nitrate in rivers increases with the number of people that live the land that drains into the rivers (Cole *et al*., 1993). Notice that the relationship includes rivers in both industrial and developing nations.

## *The Contribution of Affluence to Environmental Change*

Affluence is a critical determinant of environmental degradation because high rates of economic activity are associated with rapid rates of resource use and waste production. In general, increasing affluence tends to exacerbate environmental impacts. We demonstrate this with a few examples.

### Affluence and Greenhouse Gas Emissions

There is a strong connection between affluence, the use of energy and materials, and the release of wastes. Per capita GDP and per capita emission of carbon oxide are strongly correlated for the 113 nations for which data are available (Figure 3). This not an ironclad link. For example, Finland and Poland generate about the same amount of carbon dioxide per capita, but Finland's average standard of living is seven times that of Poland. These differences stem from differences in the types of energy used, the types of goods and services produced, the general level of technological development, and variety of social and cultural forces unique to each nation. Poland generates more carbon dioxide in part because it relies heavily on coal, while Finland uses less carbon-intensive fuels such as natural gas and electricity generated from hydropower.

### Affluence and Food Production

The average human needs 2,500 - 3,000 kcals of food each day. But the types of food used to satisfy this requirement differ greatly among nations. In addition to local tastes, affluence influences the types of foods eaten. In general, rich people get a larger fraction of their diet from meat than poorer people, who tend to get most of their diet from grains. People in wealthy nations such as the United States and Finland consume 90 to 100 kilograms of meat per year, while people in poor nations such as India and Egypt consume less than 20 kilograms.

Different diets have different environmental impacts (Subak, 1999). Eating higher on the food chain causes more environmental degradation because meat requires more land, energy and materials to produce (Figure 4). Because most of the energy is lost when transferred from one trophic level to the next, much more land is required to support a meat-based diet than a grain-based diet. In Europe, nearly 60 percent of all grain produced is fed to livestock, while in the United States the figure is 70 percent. Only 2 percent of the grain grown in India is fed to animals.

Compared to the production of grain, meat uses vast quantities of fossil fuels and water. One kilogram of corn requires 1,400 kilocalories to produce-- it takes about 30,000 kcals of fossil fuel energy to produce one kilogram of pork in an industrial nation. Other meats require nearly as much energy. Most of this energy is oil and natural gas used to power farm machinery and to manufacture fertilizer, pesticides, and other agricultural chemicals that are used to grow the grains fed to livestock. All told, producing the meat eaten by an average American each year uses the equivalent of 190 liters (50 gallons) of gasoline. Meat production also uses vast quantities of water. In industrial nations more than 3,000 liters (793 gallons) of water are used to produce one kilogram of beef.

## *Technology*

Population and affluence determine the level of economic activity, i.e. the quantity of goods and services produced. Technology is the recipe that defines the combination of capital, labor, energy, materials, and information that are used to produce a good or service. For most goods and services, different combinations are possible. For example, steel can be produced from an open-hearth furnace or an electric arc furnace. The open hearth method requires large amounts of coal, and thereby damages the environment through the extraction and use of coal, while steel made from the electric arc method requires large amounts of electricity, which implies a different combination of environmental impacts. This illustrates that technology can be a double-edged sword.

### The Role of Energy in Technical Change

Among the countless technologies humans have developed, only two have increased our power over the environment in an essential way. Georgescu-Roegen (1979) called these Promethean technologies. Promethean I was fire, unique because it was a qualitative conversion of energy (chemical to thermal) and because it generates a chain reaction that sustains so long as sufficient fuel is forthcoming. As Georgescu-Roegen (1982) described:

> The mastery of fire enabled man not only to keep warm and cook the food, but, above all to smelt and forge metals, and to bake bricks, ceramics, and

> lime. No wonder that the ancient Greeks attributed to Prometheus (a demigod, not a mortal) the bringing of fire to us (p. 30).

Promethean II was the heat engine. Like fire, heat engines achieve a qualitative conversion of energy (heat into mechanical work), and they sustain in a more complex way a chain reaction process by supplying surplus energy. Surplus energy or (net energy) is the gross energy extracted less the energy used in the extraction process itself. The Promethean nature of fossil fuels is due to the much larger surplus they deliver compared to animate energy converters such as draft animals and human labor (Cottrell, 1955; Odum, 1971; Cleveland *et al*., 1984; Hall *et al.*, 1986; Cleveland, 1993).

The unparalleled ability of fossil fuels, and especially oil, to produce economic wealth is due to another attribute: energy quality. This refers to the fact that heat units of different fuels have different abilities to do work. The ability of one heat unit to do work varies among energy types because heat is the lowest common denominator among fuels. But humans use energy for tasks other than supplying heat, so the standard practice of aggregating fuel types by heat equivalents misses important difference in energy quality. For example, a kcal of electricity used to power an electric locomotive can move a train about three times further than a kcal of diesel fuel used to power a diesel locomotive (Adams and Miovic, 1968). Open hearth and electric arc furnaces require different quantities of coal and electricity respectively to produce a ton of steel.

Kaufmann (1994) demonstrates the profound economic importance of the physical and engineering aspects of energy quality. It is not possible to measure in physical units the economic work associated with many services provided by fuels, such as heating homes, driving cars, and dispelling darkness. Furthermore, people want a particular service delivered in a particular way, such as motive power with safety, style, comfort, etc. Thus, the economic significance of a fuel is its marginal product: the amount of economic value generated by a heat unit. The results of Kaufmann's (1994) econometric model indicates that the marginal product of fuels in the U.S. economy varies over time, but that there is a consistent ranking of fuel quality: primary electricity is the highest quality, followed by oil, gas, and coal.

Energy quality plays a dominant role in determining the quantity of energy a society requires to produce wealth. The decrease in the energy/real GDP ratio in most industrial nations often is attributed to energy-saving technical change and substitutions caused by the energy price shocks. But detailed empirical analyses indicate that much of the variation of the energy real/GDP ratio is due to shifts changes in the composition of fuel use, and hence changes in the quality of fuel use. Much of the variation in the energy/real GDP ratio for the five largest industrial nations in the post-war period is due to changes in energy quality (Kaumfann, 1992; Cleveland *et al*., 1984; Ko *et al.,* 1998). Kaufmann (1992) finds no statistical evidence for autonomous energy saving technical change in this period. As he states:

> [This] should not be interpreted as an argument that substitution or technical change cannot reduce the amount of energy used to produce a unit of output...Technical change has reduced the amount of energy (as measured in heat units) used to produce a unit of output. But characterizing that technical change as "energy saving" is misleading. Over the last forty years, technical change has reduced the amount of heat energy used to produce a unit of output by developing new techniques for using oil, natural gas, and primary electricity in place of coal. These technical innovations ... take advantage of

> the physical characteristics of these energies that allow oil, natural gas, and primary electricity to do more useful work per heat unit than coal. This interpretation implies that technical change is not something shaped solely by the mind of man... but rather technical change is shaped in part by the physical attributes of energies available from the environment (p. 53).

### Technologies that Ease Problems: Fuel Efficient Cars and Waste Recovery

The global increase in gasoline consumption caused by the increase in population and affluence has been offset in part by changes in automotive technology. Rising gasoline prices in the 1970s forced automakers to produce lighter cars with smaller engines. These changes in technology reduced the weight of new cars, which helped increase the fuel efficiency to 21.6 miles per gallon in 1994 in the United States. If energy efficiency had remained at 1960 levels (14.3 miles per gallon), the United States would consume 50 percent more oil than it did in 1994. This technology improvement slowed the rate of which we deplete oil resources and the rate at which our cars emit harmful pollutants.

Waste recovery removes materials from the waste stream for the purpose of recycling and/or composting. Recovery improves environmental quality by reducing the need for landfill space and by reducing pollutants released from burning trash. Recovery also slows the depletion of nonrenewable resources. Producing a can from recycled aluminum uses 50 percent less fossil fuel than making the same can from ore

### Technologies that Worsen Environmental Problems: Feedlots

The preference for meat, which is associated with higher incomes, exacerbates the effect of a growing population on land conversion. The size of this effect depends on the technology used to raise livestock. One option is range-fed meat production. Here animals are allowed to roam across rangeland ecosystems, foraging for grasses, shrubs, and other native plants. In turn, the manure produced by the animals is a valuable source of nutrients for plants. Meat produced in this way uses very little fossil fuels, powered instead by the net primary production of grasslands or pasture. This method is sustainable if the number of animals and their feeding behaviors are managed properly.

Another technology is feedlots. Here the animal is kept in an enclosed area for the last two to three months of its life to accelerate growth and enhance its fat content. Feedlots exacerbate the environmental impacts of meat production because they are extremely energy and material intensive. Cattle are fed specially prepared mixtures of corn, barley, wheat, molasses, and other ingredients that require lots of energy and water to manufacture. Trucks, front-end loaders, conveyors, and grinders burn more fossil fuels to prepare and deliver the feed to the animal. As a result, a kilogram of beef produced in a feedlot uses three to five times the fossil fuel used in a range-fed operation.

The differences are even greater when one compares feedlots with a pastoral or subsistence method of production. A United States feedlot generates 463 kilograms of $CO_2$ per head; a pastoral system in the Sahel generates zero carbon emissions (Subak, 1999).

Feedlots also produce huge volumes of animal wastes that can contaminate rivers and groundwater. A feedlot with 10,000 pigs produces as much nitrogenous waste as a city of 10,000 people.

## Is There a Carrying Capacity of the Earth For Humans?

Carrying capacity is the maximum number of individuals of a population that can be maintained indefinitely by the life support services of a given area of the environment without degrading those life support services. In principle, the carrying capacity of non-human populations is straightforward. Each individual has roughly the same demand on its environment: food, habitat space for refuge, reproduction and waste assimilation, and so on. A given area of the environment has a relatively fixed amount of each resource that sets the carrying capacity for the population. The dynamics population growth is controlled by negative feedback loops that are characterized by density independent factors (e.g., weather) and density dependent factors (e.g., predation, disease, reproduction). A population can overshoot its carrying capacity due to a lag in the effect of density dependent factors. Overshoot is temporary because the negative feedback loop between population and density dependent factor tends to shrink the population when it exceeds its carrying capacity.

In reality, it is difficult to calculate the carrying capacity of non-human populations because populations often vary widely over time, often in response to external factors such as climate.

Applying the concept of carrying capacity to human populations is even more problematic because the relationship between human society and the environment is far more complex than that for non-human populations. There are several ways in which humans are fundamentally different from plants and animals. First, people use the environment to do much more than feed and clothe themselves. Most of the natural resources consumed in Finland or Japan are used to produce goods and services that are not necessary for biological survival. Thus, one has to define an average standard of living to even begin an assessment of carrying capacity. Second, there are rapid changes in the types and quantities of resources used by the human population. This flexibility implies that a critical resource now may be unimportant in the future, and that an unimportant resource now may be important in the future. Third, humans purposefully change their environment in ways that increase the amount of life support. Agriculture is an obvious example of this capability. Fourth, humans can increase carrying capacity by expanding the geographic extent of the environment from which they obtain life support. The Japanese economy often is described as an ‘economic miracle.’ The island of Japan is densely populated and has very few natural resources nonetheless, the people of Japan enjoy a rich lifestyle. Drawing life support from environments scattered across the entire planet produces that lifestyle. Almost all the paper and wood products used by the Japanese come from trees grown in Southeast Asia, and oil from the Middle East.

### *Indicators of Scale and Carrying Capacity*

The problems associated with estimating human capacity have not deterred people from making estimates. In 1679, Antoni van Leeuwenhoek, the Dutch inventor of the microscope, published the first quantitative estimate of the Earth’s carrying capacity: 13.4 billion people. Since then, there have been many attempts to estimate global carrying capacity (see Cohen, 1995 for a review). The estimates range from less than one billion to more than 1 trillion people. The enormous range in estimates is due in part to the range of methods employed. These range from assumed constraints from a single resource, usually food, assumed constraints from multiple resources (food and water), mathematical curve fitting of population growth rates, generalizations from observed population densities, and categorical assertion ("It's so because I say it's so.").

Despite all the pitfalls, there are some indicators of the scale of human existence relative to the global environment. These indicators measure human consumption or appropriation of key global resources or environmental services. Examples include:

- Humans are now the preeminent forces in many of the planet's material cycles. The release of carbon stored by fossil fuel combustion, deforestation, and other biomass burning contributes to the increasing $CO_2$ concentration in the atmosphere. We fix more nitrogen annually than natural processes through the production of fertilizers and the combustion of fossil fuels (Vitousek, 1994). Our mobilization of trace metals such as lead and cadmium is enormous relative to natural sources (Nriagu, 1990), resulting in their accumulation in soils to levels that cause serious human and ecosystem health problems in many nations (Thomas and Sprio, 1994).
- Humans consume or control about 40 percent of global terrestrial net primary production, the total food resource on the planet, (Vitousek, 1994).
- Humans use about 26 percent of total terrestrial evapotranspiration (water taken up and eventually released by plants) and 54 percent of water runoff that is geographically and temporally accessible (Postel *et al.*, 1996). Regional water scarcities are a growing constraint on economic development and are the source of a growing number of conflicts.
- Humans have fully exploited, overexploited or depleted two-thirds of the planet's marine fisheries (Food and Agriculture Organisation, 1994). Chronic overfishing has wreaked havoc with the ecology of marine ecosystems and the economies of local communities whose livelihood is based on fishing.
- About one-third of the non-ice land surface of the planet has been converted to human-dominated landscapes, predominantly cropland and pasture (Buringh and Dudal, 1987). The resulting loss of original habitat is a major driving force behind the loss of biological diversity, and with it ecosystem functions that support human existence in countless ways. The Global Biodiversity Assessment (Heywood, 1995) sponsored by the United Nations Environmental Programme, the product of 1,500 scientists working on this issue, documents the magnitude of the biodiversity problem. Based on predicted future rates of tropical forest loss, the corresponding loss of biodiversity is 1 to 10% of all species in the next quarter century. These rates of extinction would be approximately 1,000 to 10,0000 times the average expected "background" extinction rate.

These numbers describe a population whose demand for environmental life support is large relative to its environment. With population and affluence on the rise, these demands will rise regardless of any efficiency gains won by technical improvements.

## The Response of the Market and Technology to Environmental Problems

Most industrial nations use the market to guide economic decisions. The interaction of utility maximization by consumers and profit maximization by firms determines the type, quantity, price, and allocation of goods and services. This combination is said to be efficient because it is impossible to change the production and allocation in a way that makes some people better off without making others worse off. Put simply, an efficient allocation is the best (as measured by profits and utility) an economy can do with a given set of producers, consumers, and resources. By creating the incentive to minimize costs and produce what people want to buy, the market tends to reduce the quantity of natural resources extracted and wastes generated per unit of economic activity. That is why market economies tend to uses less energy and produce fewer wastes than centrally planned economies (CPEs). For example, Hungary (a CPE) used 2.2 times more energy to produce a unit of economic output than neighboring Austria (a market economy) in 1990. Hungary also emitted 2.3 times more $CO_2$ per unit of economic output.

Even though market economies tend to be more efficient than CPEs, markets frequently do not work as effectively as they are described in economic textbooks. The market's ability to generate an efficient outcome hinges on a critical assumption: firms and households have perfect information. This means that firms have information about all the costs associated with the use of capital, labor, energy, materials, and information. Similarly, consumers are assumed to have perfect information about all the costs associated with the consumption of a good or service.

In some cases, the information available to firms and households is far from perfect. In these cases, the outcome generated by the market is inefficient, or a market failure. This lack of information is called an externality. Externalities are costs imposed on society, such as depletion or pollution, that are not included in the price people pay for the good or service that causes depletion or pollution. From an environmental perspective, the largest failure is the under-pricing or complete lack of pricing for many ecological services.

Optimists believe that despite its imperfections, resource depletion and environmental degradation will elicit a response from the market that ultimately generates antidotes to those problems (e.g., Simon, 1996). An increase in the scarcity of a natural resource or an environmental service will cause its price to rise. The price increase will stimulate responses on the supply and demand side. Higher prices will stimulate increased exploration and production of the resource or service, convert non-economic resources to economically viable ones, encourage the development of substitutes, and generate new technologies that mitigate the severity of the problem. On the demand side, higher prices reduce demand and encourage recycling.

## Limits of the Market and Technology

To what extent can technical change de-couple the production of goods and services from energy and material inputs and waste outputs? To what extent can human ingenuity “substitute” for depleted resources and degraded ecosystem services? This is the core of the debate about limits to growth and sustainable development (Turner, 1997).

The idealized response of the market and technology to depletion and degradation is seductively simple. However, there are a number of factors that reduce or override the potential of the market to ameliorate environmental problems. These are: 1) rising affluence may not automatically lead to improvements in environmental quality; 2) improvements in the efficiency of energy and material use can produce a “rebound effect” that actually increases resource use or waste generation; 3) thermodynamic limits substitutions that decrease energy and material use; 4) human capital and natural capital are largely complements, which limits the degree to which the former can substitute for the latter; 5) human capital is made from and operates on flows of energy and materials, which limits substitution possibilities; 6) Ecosystems that provide critical life support services that have no human equivalent cannot be reduced below minimum threshold levels which once breached, produces an irreversible loss ecological service; 7) the market often does not provide the right signals for technical change; 8) technical change often has unanticipated side effects. We discuss these in turn.

### *Do Rising Incomes Improve Environmental Quality?*

A new line of argument actually has rising incomes reducing depletion and degradation. The hypothesis underlying environmental Kuznets curve (EKC) is that resource depletion and pollution tend to fall as incomes rise, producing an inverted U-shape function. The initial research on EKCs suggested that some pollutants follow an inverted-U curve with respect to income (Grossman and Krueger 1995; Shafik and Bandyopadhyay 1992; Panayatou 1993; Shafik 1994; Selden and Song 1994). These results have been extrapolated by some to be an omnipresent outcome of economic development. The theoretical EKC model consistently appears in the World Development Report of the World Bank (World Bank 1992), and in statements such as "the strong correlation between incomes and the extent to which environmental protection measures are adopted demonstrates that, in the longer run, the surest way to improve your environment is to become rich" (Beckerman 1992, p. 491).

These conclusions are the subject of considerable scrutiny by many analysts (Arrow *et al*. 1995, Stern *et al*. 1996) and special journal issues (Ecological Economics 1998; Environment and Development Economics 1996; Ecological Applications 1996). This body of work indicates the EKC hypothesis is just that: a tentative hypothesis about the relation between income an environmental quality. A number of unknowns, uncertainties, and errors have been identified:

- Many of the regression models that find the existence of an inverted U function may be misspecified or suffer from omitted variable bias. In particular, they omit important variables such as the composition of production and consumption, international trade and the density of economic activity, to name a few (Kaufmann *et al*. 1998).
- Most of the improvements in environmental quality identified in EKC studies have been achieved in part due to specific environmental policies, which are indirectly related to income.
- The inverted U curve has been examined for only a few pollutants, usually those that have local health effects that can mitigated with existing technology at moderate economic expense.
- None of the EKC work has assessed the broad array of ecosystem services that underpin our biological and economic existence.
- Different studies with similar data have produced different results (Ekins et al., 1994).
- The existing work provides limited insight into the actual mechanisms that diminish pollution after particular income levels.
- Thus, contrary to the sweeping claims of some analysts (Larson *et al*. 1986, Bernardini and Galli 1993) and potentially contrary to the seductive idea that growth itself is the antidote to depletion and degradation (Beckerman 1992), the quality and quantity of evidence does not yet support the hypothesis that the EKC is an ironclad, universal phenomenon.

### Countervailing Forces: Rising Affluence and the Rebound Effect

There is no guarantee that technical change will reduce pressure on the environment faster than overall economic growth increases that pressure. Wernick (1994) and others note that population growth and rising affluence increase energy and material use, offsetting substitution, technical change, and other forces that promote de-linking. Industrial growth in Japan has more than offset the significant improvement in the efficiency of fuel, electricity, and water use in industry (Jänicke *et al*. 1997). Aggregate economic growth in the US helped drive the consumption of wood products by enhancing the effects of an increased intensity of use of paper and by offsetting a decrease in the intensity of use of lumber (Waggoner *et al*., 1996). The decline in the intensity of use of metals in telecommunications and broader electronics and computer markets brought about by miniaturization has been offset by the overall growth in these industries (Key and Schlabach, 1986). Of course, the opposite effect also is possible; slower or negative growth can reinforce declining intensity of use. Tilton (1990) and Roberts (1988) find that slower growth of the global economy helped reduce the demand for many metals by reinforcing the decline in their intensity of use.

Another important force is the so-called “rebound effect.” Distilled to its essence, the rebound effect applied to energy is this: an energy efficiency gain looks to the consumer a lot like a price reduction. This spurs an increase in the demand for energy either directly through price elasticity effects (e.g., people buying more gasoline when its price drops), or indirectly through released purchasing power redirected to energy-using goods and services (Saunders 1992). The implication is that one cannot look at just an individual material or an individual sector to assess the net benefit to the economy from improved energy or material efficiency. The effects of change in efficiency in one sector or for one resource ripple through the economy, affecting energy and material use in other sectors and in future time periods.

There is theoretical and empirical evidence that supports the existence of a significant effect for energy. Saunders (1992) uses a macroeconomic Cobb-Douglas and CES (constant elasticity of substitution) production function to show that, in general, energy efficiency gains increase energy use by making energy appear effectively cheaper than other inputs, and by stimulating economic growth, which pulls up energy use. Several analysts have estimated the size of the rebound effect that is caused by gains in automobile efficiency in the US. The effect is measured by the percent increase in miles driven associated with a one percent increase in the energy efficiency of automobiles. Values range from 0.05 to 0.40, with most estimates between 0.1 and 0.2. This means that 10 to 20 percent of the motor gasoline saved due to increased energy efficiency is “lost” by increased driving. Khazoom (1980, 1987, 1989) claims that Lovins (1986) overstates the potential energy savings from more efficient appliances because he ignores the rebound effect. In a similar vein, Brookes (1990) argues that relying on energy efficiency to mitigate the greenhouse effect is fundamentally flawed because “reductions in energy intensity that are not damaging to the economy are associated with increases, not decreases, in energy demand.” Lovins (1988) and Grubb (1990) take issue with the arguments of Khazoom and Brookes.

### Thermodynamics Limits Substitution

Thermodynamics can tell us a lot about the limits to substitution and technology at the level of individual processes or industries. The limits to substitution are easily identified for individual processes by an energy-materials analysis that defines the fundamental limitations of transforming materials into different thermodynamic states and on the use of energy to achieve that transformation (Ruth 1993). These types of analyses have shown where technological improvements exhibit strong diminishing returns due to thermodynamic limits, and where there is substantial room for improvements in the efficiency of energy and material use. For example, the energy efficiency of power plants and the synthesis of ammonia are approaching their thermodynamic limits (Figure 5). In the area of energy technologies, thermodynamic analyses suggest good reasons for not pursuing research on thermal methods for generating hydrogen from water.

### *Complementarity Limits Substitution*

Production is a transformation process in which two agents of transformation, human labor and manufactured capital transform a flow of materials, energy, and information. The flow of energy, materials and services from natural capital is what is being transformed (the material cause), while manufactured capital effects the transformation (the efficient cause). For example, all machines require energy for their operation and they function by acting on a flow of materials from natural capital (Victor, 1994). Thus, adding to the stock of pulp mills does not produce an increase in pulp unless there also is the wood fiber to feed them. Material and efficient causes clearly are complements. Historically, manufactured capital and natural capital have been developed as complements, not substitutes (Daly, 1991). The stock of manufactured capital such as tractors, oil rigs, and fishing vessels has been increased with the express intent of increasing the use of natural capital such as fertile soil, oil deposits and fish populations. For these reasons, many ecological economists argue that this complementarity limits the degree to which the agents (machines) can be substituted for the flows (materials) they transform (Costanza and Daly, 1992; Victor, 1991, 1994; van den Bergh, 1997).

### *Physical Interdependence and Scale Limits Substitution*

There is a biophysical interdependence between manufactured and natural capital. The construction, operation, and maintenance of tools, machines, and factories require a flow of materials, energy from natural capital. Similarly, the humans that direct manufactured capital energy and materials (i.e., food and water). Thus, producing more of the “substitute,” i.e. manufactured capital, requires more of the thing that it is supposed to substitute for.

Conventional wisdom about economic growth does not account for this interdependence, and thus assumes a degree of substitutability that may not exist (Georgescu-Roegen, 1979; Cleveland et al., 1984; Ayres and Nair, 1984; Kaufmann, 1992; Daly, 1997). It is critical to distinguish between the micro- and macro- level. Substitution is fundamentally more constrained at the macro- level of analysis than at the micro-level (Stern, 1997). For example, home insulation directly substitutes for heating fuel, a clear substitution of manufactured capital for natural capital *within the household sector*. But interdependence means that insulation requires fuel to manufacture, so for the economy as a whole the net substitution of insulation for fuel is less than that indicated by an analysis of the household sector in isolation from the rest of the economy.

Empirical analyses of the substitution issue are few in numbers and varied in their results. Some suggest that manufactured capital is a good substitute for major metals (Brown and Field, 1979, while others find a wide range of substitutability between manufactured capital and aggregate material inputs that is highly dependent on *a priori* model specification (Moroney and Trapeni, 1981). Some studies find little or zero possibility for substitution between manufactured capital and specific strategic metals (Deadman and Turner, 1988). All of these are industry level elasticities, and most cover only major nonrenewable resources such as metals. There are no empirical estimates of the degree of substitution between manufactured capital and any major ecosystem service.

Models that account for scale and interdependency constraints find that over a broad range of plausible substitution possibilities, any reduction in environmental life support lowers the long-run growth path of the economy (Kaufmann, 1995). Degradation or depletion diverts more capital and labor to the extractive sector, reducing investment and/or consumption in the rest of the economy.

Inattention to scale also leads some analysts to ignore how most nations substitute or supplement domestic natural capital with trade. For example, Pearce and Atkinson (1993) suggest that the current paths of the US and Japanese economies are sustainable because they invest in human-made capital faster than they depreciate all forms of *domestic* human-made and natural capital. But all industrial nations use and in some instances degrade natural capital from foreign and global stocks, and thus live beyond the means sustainable by domestic sources. For example, the 30 largest cities in the Baltic Sea drainage basin use 200 $km^2$ of terrestrial and aquatic ecosystem for every 1 $km^2$ of urban area to produce their use of agricultural, forestry, and fishery products (Folke et al., 1996).

### *Irreversibility Limits Substitution*

Ecosystems are multi-functional. A forest produces a range of energy and materials (wood, chemicals) and services (habitat for biodiversity, climate regulation, flood protection). Some functions may be substitutable by manufactured capital, e.g., wood as a raw material. But species and their environment are connected in a complex web of interrelations that fundamentally are non-linear and evolutionary, with lags, discontinuities, thresholds and limits (Perrings et al., 1995). Change in ecosystems, whether “natural” or human-induced, often is not continuous. Rather, it often is episodic and rapid (Holling *et al*., 1995). Degradation of ecosystems, and hence the services they provide, often is irreversible. This means that some ecosystem services (e.g. climate regulation) are non-substitutable. In such cases no amount or type of human-made capital can replace natural capital; the elasticity of substitution is zero.

Ecosystems that provide critical life support services that have no human equivalent cannot be reduced below minimum threshold levels which once breached, produces an irreversible loss ecological service. Fuelwood collection and arable production in Vietnam has converted about one-third of the area to barren land (Perrings et al., 1995). In theory, the land, soil and vegetative cover could be recovered. In practice, the cost of rehabilitation and restoration is enormous and far exceeds societal resources. The degradation is, for all intents and purposes, irreversible. The essential nature of many ecosystem services and their potential for irreversible change are the basis for policies such as the precautionary principal and safe minimum standards.

### *Market Signals Aren't Always a Reliable Compass*

Another question is whether technology will follow the "right" direction (Gutés, 1996). Technological optimists make a critical assumption: the relative price of inputs accurately reflects their relative scarcities. If this is the case, the depletion or degradation of natural capital will lead to an increase in its price, and market forces will induce technological change towards saving or improving the productivity of natural capital. If prices fail to signal scarcity, there is no guarantee that technology will be biased in the "right" direction. There is ample evidence that in most nations market failures such as government regulation, subsidies, monopolies, and externalities significantly distort the price of energy and material resources. For most ecosystem services, markets, and hence prices, do not even exist.

### *Uncertainty, Ignorance, and the Unintended Side Effects of Technology*

Environmental problems such as global climate change have larger uncertainties that are not easily reduced. Understanding global warming requires information on atmospheric physics, ocean circulation, and global photosynthesis. Most importantly, it requires an understanding of the *interconnections* among those factors. There is enormous scientific uncertainty about those interconnections. For example, there is a lot we do not know about deep ocean circulation and how it affects climate. The uncertainties multiply when you link the atmosphere, the oceans, and vegetation together in a complex system that determines the planet's climate. Added to this is uncertainty about the human response to climate change. How will our economic well being be affected by a change in climate? What is the appropriate response of government to a change in climate? These are difficult questions that add to the complexity and uncertainty about climate change.

There are a multitude of examples of mechanical, medical, energy, chemical, and biological technologies that had the opposite of their intended of effect, or which had unanticipated side or "revenge" effects (Tenner, 1996). These effects often are displaced in time and/or space, making their presence more difficult to detect. The net effect has been a systematic underestimation of the nature-consuming aspects of technology and systematic overestimation of its nature-saving aspects (Doeleman, 1992).

Nuclear power, once projected to be "too cheap to meter," now has been abandoned by many nations due to higher than expected costs, reliability questions, and waste disposal problems. Tall stacks on power plants alleviated local air pollution problems, but caused longer term, more severe problems hundreds of kilometers away. Pesticides kill not only target organisms but also natural predators, thereby exacerbating crop damage. The deliberate or inadvertent introduction of alien plant and animal species has had devastating effects on native plant and animal species.

No one denies the immensely positive effects that technology has had on human existence. But it is prudent to fully account for the costs as well as the benefits of new technologies. History teaches us that unquestioning faith in the market or another human institution to selfgenerate technical antidote to environmental is myopic. Given the global dimensions of the current generation of environmental problems, it also is dangerous.

## Climate and Climate Change

Climatologists estimate that the average temperature of the planet has increased by about 0.6 °C over the last century (Figure 6). Since 1851, the first year for which scientists have direct measurements of the Earth's average temperature, nine of the warmest years have occurred since 1979. Scientists calculate the odds are between 30:1 and 100:1 that the recent warming is the result of random fluctuations in temperature. In short, most climatologists agree that the Earth is warming.

There is some disagreement as to the cause(s) of the temperature increase. The vast majority of scientists believe that human activity is responsible for some part of the temperature increase. The authoritative scientific source for the research on climate change is the Intergovernmental Panel on Climate Change IPCC (Houghton et al., 1996). The IPCC report is authored by 500 scientists from more than 40 nations and reviewed by additional 500 scientists. In its 1995 report the IPCC concluded that the weight of scientific evidence “suggests a discernible human influence on global climate” (Houghton et al., 1996, p. 4).

There are a few remaining skeptics, although they find themselves in an increasingly small minority. Some of these scientists argue that the temperature increase is “natural.” Climate has changed in the past due to changes in Earth-Sun geometry, volcanic eruptions, and changes in the outptut of energy from the Sun (Hartman, 1994). Skeptics charge that it is impossible to separate these natural forces from human ones such as the release of greenhouse gases, or they deny that warming itself actually is occurring (Easterbrook, 1995; Singer, 1995). With each passing month and year, however, the growing mountain of evidence that establishes a human role in climate change contradicts this small but vocal minority.

### *Long-Run Climate Change*

The repeating pattern of weather is known as climate. Climate represents the average weather conditions over a long period. Climate change is a shift in the long-term average of weather. This shift may generate warmer or cooler temperatures, more or less precipitation, higher or lower humidity, or stronger or gentler winds. Studies indicate that climate change is the rule rather than the exception (Oliver, 1992). Climate appears stable over a human lifetime, but this stability disappears when scientists compare temperature and rainfall over long periods. The most recent cool period lasted from 30,000 years before today until 12,000 years ago, during which large sheets of ice covered much of Europe and North America (Figure 7). Only during the last 5,000 years have the ice sheets been reduced greatly. The retreat of the ice sheets corresponds to the beginning of agriculture and the evolution of complex human societies.

During the previous 1,000 years, climate has warmed and cooled several times. The average temperature was relatively warm between 950 and 1250 AD. During this period, England was warm enough to support an extensive wine grape industry. Conversely, the average temperature was relatively cold between 1450 and 1880. During this period, which is known as "the little ice age" (Figure 7), the Vikings abandoned their settlements in Iceland because it was too cold to grow grain. Similarly, Renaissance paintings show winter scenes in which the large rivers of Europe froze such as the Thames. These rivers rarely freeze today.

## The Heat Balance of the Planet

### *Global heat transfer*

The warming and cooling of climate is caused by a change in the heat balance of the planet--the difference between the amount of heat energy that enters the atmosphere and the amount of heat that leaves the atmosphere and returns to space. All processes require energy for their operation, and the earth's climate and weather systems are no exception. This energy, like most of the other energy that runs earth systems, comes from the sun. Heat moves from one place to another by three means: 1). Radiation, or the transfer of radiant energy either through a vacuum (space) or a material (the atmosphere or a windowpane), 2). Advection, or the movement of parcels of warmer air or water from one place to another, and 3). Conduction, or the movement of heat by one group of excited molecules to another within a material (such as heat traveling up an iron rod placed in a fire). The first two of these are important for our consideration of climate change.

The solar constant is the amount of energy that reaches the outer layers of the atmosphere. The solar constant has varied over the lifetime of the planet, and this variation is one source of change in the Earth's climate. The little ice was caused in part by a slow-down in solar activity.

Once solar energy reaches outer atmosphere, the amount that actually reaches the surface is determined by the make-up of the atmosphere. Some of the solar energy is reflected (turned back to space) or scattered in different directions by materials in the atmosphere. Clouds reflect sunlight therefore; changes in cloud cover reduce the amount of solar energy that reaches the Earth's surface. Aerosols, the small particles that combine with water and reflect or scatter light before it reaches the Earth’s surface, also reduce this quantity. One of the most important sources of aerosols is sulfur emitted by volcanoes. Sulfate aerosols affect the heat balance two ways. These aerosols affect the heat balance directly by reflecting and scattering solar energy before it reaches the Earth's surface. Sulfate aerosols also increase the formation of clouds, which also reflect and scatter solar energy. Volcanoes periodically inject large amounts of sulfur into the atmosphere, where it remains for several years. During this period, aerosols can cool the climate significantly. The average temperature of the planet cooled by about 1° C in 1991 and 1992 following the eruption of Mt. Pinatubo in the Philippines.

Most of the sun's energy that reaches the Earth's atmosphere arrives as high energy, short wave radiation. If this radiation is not scattered or reflected, it will reach the Earth's surface. It does so because the gases in the atmosphere cannot absorb high energy, short wave radiation. The majority of that energy that is retained by the earth is trapped in the equatorial regions because these regions are at nearly right angles to incoming photons and because the area of that equatorial regions is larger than as you move poleward. But most of the heat lost from Earth is lost further toward the poles (Figure 8). How can this be? The principal reason is that the large thermal gradient generates fluid motions, including large-scale atmospheric movements such as the Hadley Cells (see below) and also ocean currents such as the Gulf Stream that move the thermal energy poleward. We next consider how this operates.

### *Atmospheric movement: Hadley cells*

The relatively large heating of the Earth's surface at the equator causes the air above it to rise. As it rises it cools, and since cooler air has less kinetic energy it can hold less water, so that water comes out of suspension, clouds form and precipitation occurs. The air masses gain even more energy from the condensation of the rain, which causes the release of the heat of vaporization (the heat energy required to vaporize liquid water). This additional heat causes the air masses to rise even further, cooling the air masses even further and generating more rain. This process tends to make it very rainy on or near the thermal equator, that is the place directly under the sun (Figure 9).

As the air rises it piles up over the equator. This relatively high pressure tends to push the air north and south at about a 15 km altitude. At about 30 degrees north and south this relatively dry air is no longer more buoyant than the air below it. Here it tends to sink. The sinking air warms. Warm air can store more water because it has more energy, and more energetic air can keep more water molecules in suspension. When these descending air masses hit the surface of the earth it generates a region of high pressure. This high pressure forces that air back towards the lower pressure areas on the equator (and also poleward). The air's potential to hold more water pulls moisture from the land, and creates the great deserts of 30 degrees north and south. The return surface airflow towards the equator creates the trade winds and completes the cycle. The entire process generates the circular air movements that dominate the climatic conditions in the tropics and subtropics.

This basic pattern, however, is complicated somewhat by the coriolus force, generated from the spin of the earth. The coriolus force causes these air movements (as well water currents and, apocryphally, artillery shells) to be shifted to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The resultant winds are called the trade winds, and they blow more or less from the northeast north of the equator and the southeast south of the equator as shown in Figure 9. This entire elliptical cycle of winds, going on average from the equator to 30 degrees north and 30 degrees south, are called Hadley Cells after the 18th century English meteorologist George Hadley. Hadley cells also exist between 30 and 60 and 60 and 90 degrees latitude.

These principal wind patterns produce very wet conditions at the equator. Regions just to the north and south of the equatorial regions are seasonally wet and seasonally dry. Very dry conditions are found at 30 degrees north and south, and areas of intermediate and variable moisture are found in the temperate areas. These rainfall patterns, together with the intensity of solar radiation, which obviously is less towards the poles, are the principal determinant of the earth's major climate patterns. But for our present purposes their main importance is that they move heat from equatorial region poleward. The main wind patterns also generate large-scale water movements such as the Gulf Stream that likewise transfer heat from equatorial region poleward. The water currents are far less important than the atmospheric movements for total heat transfer but, for example, make temperatures at any given location in Europe about 10 degrees warmer than they would be in America. Greenhouse gases interact with these large-scale fluid processes by decreasing the loss of radiant energy from the circulating masses as they move poleward from the region of the equator. One consequence of this is that if global warming indeed does take place it is expected that regions closer to the poles, such as the Northern parts of America and Europe and especially Canada and Fennoscandanavia, are expected to warm relatively more.

### *The Greenhouse Effect*

The land and ocean surfaces absorb incoming high energy, short-wave energy. As they do, the surfaces warm. This heat is radiated back to the atmosphere in the form of low energy, long wave radiation. The change from short wave radiation to long wave radiation is critical because atmospheric gases known as greenhouse gases absorb a significant fraction of this long wavelength radiation. Greenhouse gases include water vapor ($H_2O$), carbon dioxide ($CO_2$), methane ($CH_4$), chloroflourocarbons (CFCs) and nitrous oxide ($N_2O$). Together with aerosols, these gases are known as radiatively active gases, a term which describes their ability to absorb and reflect heat and therefore affect the energy balance of the atmosphere.

The atmosphere's ability to absorb energy with longer wavelengths and convert it to heat is known as the greenhouse effect. The greenhouse effect makes the atmosphere warmer than it would be if the *outgoing* long wave radiation passed through the atmosphere in the same way that *incoming* short wave radiation passed through the atmosphere. The greenhouse effect warms the atmosphere by about 35°C. Without the greenhouse effect, the average temperature would be a chilly -15°C.

The quantity of heat trapped by the atmosphere is measured by radiative forcing, which often is measured in units of watts per square meter. Radiative forcing can be thought of as the total amount of energy (watts) that is trapped by the gases that lie above a square meter of the Earth's surface, from ground level through to the top of the atmosphere.

The types and quantities of gases in the atmosphere determine the radiative forcing of the atmosphere. The types of gases present is critical because greenhouse gases vary in their ability to absorb long were radiation (Table 1). The ability of a gas to absorb long wave energy often is measured relative to the quantity absorbed by a molecule of carbon dioxide. CFCs are the most effective absorbers of long wave radiation--a chloroflourocarbon molecule absorbs 15,000 times more energy than a molecule of carbon dioxide.

The concentration of each greenhouse gas and its ability to absorb energy determine which gases play the most important role in the greenhouse effect. Carbon dioxide is the most abundant greenhouse gas. There are about 355,000 molecules of $CO_2$ for every billion molecules in the atmosphere (parts per billion, PPB). There are about 1,700 PPB of methane and 310 PPB of nitrous oxide. The amount of CFCs is so low that it is measured in parts per trillion. Multiplying the concentration by its ability to trap heat determines a gas’s contribution to the greenhouse effect. A single CFC molecule absorbs 15,000 times more energy than a molecule of $CO_{2,}$ but there are about a trillion molecules of $CO_2$ for every one molecule of CFCs.. The net result is that $CO_2$ is absorbs more heat than CFC and all other greenhouse gases, except for water vapor (Figure 10).

The concentration of a radiatively active gas depends in part on the time the average molecule spends in the atmosphere, which is called residence time. The residence time for most greenhouse gases is decades or longer. As a result, the concentrations of greenhouse gases are relatively well mixed throughout the entire atmosphere. This means that the concentration of $CO_2$ is about the same everywhere within a given layer of the atmosphere. On the other hand, the average sulfate aerosol remains in the atmosphere for a couple of years if injected high into the atmosphere, but only a week or ten days if emitted near ground level. This short residence time prevents a complete mixing, therefore sulfate aerosols have their greatest effect near their point of origin. Sulfate aerosols are emitted mainly in the Northern Hemisphere, so the radiative forcing of the atmosphere above the Southern Hemisphere is greater than that over the Northern Hemisphere.

### *The Concentration of Radiatively Active Gases*

Direct measurements of the atmospheric concentration of carbon dioxide are available starting in the 1950's (Figure 10). The atmospheric concentration of $CO_2$ has increased from about 316 parts per million in 1956 to about 370 parts per million in 1998. Notice that the concentration of carbon dioxide rises and falls each year. Changing seasons causes these annual fluctuations.

The rise in the atmospheric concentration of carbon dioxide began well before the 1950's. Scientists have been able to track the atmospheric concentration of carbon dioxide prior to 1956 by analyzing ice cores. Ice cores are tubes of ice that are withdrawn from glaciers. These tubes are over 2,000 meters long and ice at the bottom was formed nearly 160 thousand years ago. The ice contains tiny bubbles of air that were trapped when the ice was formed. By analyzing the air in bubbles from in different layers of the core, scientists can reconstruct the atmospheric concentration of carbon dioxide during the period that the core was formed. The results indicate that the concentration of carbon dioxide varied between 200 and 280 ppm prior to the Industrial Revolution (Figure 11). This means that the current value of 360 ppm is greater than any value over the last 160 thousand years.

The other greenhouse gases show a similar pattern of increase. The concentration of methane has risen dramatically over the last 100 years and also is near its maximum value over the last 160 thousand years. The atmospheric concentration of CFC's has increased steadily since the 1920's when human first developed these chemicals. Data that proxy the concentration of $N_2O$ and sulfate aerosols are available from 1860. They too, indicate that the atmospheric concentrations of these gases are increasing.

### *Humans Contribution of Greenhouse Gases*

The increase in the atmospheric concentration of radiatively active gases is due largely to increases in human activity that disrupts the global biogeochemical cycles of carbon and sulfur. By focusing on these cycles, we can understand how human activities increase the atmospheric concentration of carbon dioxide, methane, and sulfate aerosols.

Humans alter the global carbon cycle by accelerating some existing flows and by creating entirely new flows. On net, these changes increase the amount of carbon stored in the atmosphere as carbon dioxide ($CO_2$) and methane ($CH_4$). Large quantities of carbon are stored in the Earth's crust as fossil fuels such as coal, oil, natural gas, oil shale and tar sands. These fuels are the carbon remains of plants and microscopic organisms that accumulated in the crust over millions of years. This accumulation began to be reversed by the Industrial Revolution. By burning fossil fuels, we create new flows that return carbon to the atmosphere in the form of carbon dioxide and methane.

Most of the carbon in fossil fuels returns to the atmosphere as carbon dioxide, a byproduct of the combustion process. The amount of carbon dioxide emitted varies among fossil fuels (Table 2). Of the fuels currently in use, natural gas emits the smallest amount of carbon dioxide per kcal and coal emits the greatest amount. Alternative sources of fossil fuels, such as oil shale and liquefied coal emit even greater amounts of carbon dioxide per kcal. The increased emissions associated with coal and alternative sources of fossil fuels are important because the world may become increasingly dependent on these fuels as humans deplete the supply of oil and natural gas.

Some of the carbon stored in fossil fuels is returned to the atmosphere as methane. Methane is an important component of natural gas, therefore the production and transport of natural gas causes methane to leak into the atmosphere. The rate of leakage varies considerably among nations. Natural gas pipelines in Russia leak many time more methane than natural gas pipelines in the US in part due to poorer design and upkeep. Methane also escapes from coalmines. Miners have long feared methane in coalmines, which is known as 'coal gas,' because it can suffocate miners and cause explosions. As humans have increased their use of coal, so too has the amount of methane that escapes from coalmines.

Fossil fuels also store significant amounts of sulfur, so burning fossil fuels, especially coal, releases sulfur into the atmosphere. Over the last 150 years, there has been a significant increase in the amount of sulfur emitted by human activity (Figure 12). The effect of the increase in sulfur emissions on the heat balance of the planet has been enhanced by changes in technology. By building taller smokestacks, sulfur remains in the atmosphere for a longer period, which increases the amount of energy reflected by each molecule of sulfur emitted.

The general process by which humans change the amount of carbon stored in biota is deforestation. Clearing forests to make room for agriculture is the major driving force behind deforestation, followed by timber harvests for paper and building materials. As of 1980 there had been more carbon added cumulatively to the atmosphere from deforestation than from industrial additions, although as of 1980 industrial additions were some two to 5 times greater (Houghton et al., 1995). The reason is the much longer time span of deforestation and especially the clearing of the Americas since 1850 (Figure 13).

More recently there has been a great deal of debate about the rate of deforestation in the tropics. Some early reports suggested that tropical deforestation might add as much or more carbon to the atmosphere as industrial emissions. More recent analysis have tended to range from about 0.8 to 2 PG of carbon (one PG = $10^9$ tons) (Houghton, 1996a, 1996b; Detwiler and Hall, 1988), roughly equivalent to 10 to 25 percent of industrial additions.

Most of the carbon from deforestation goes directly into the atmosphere as carbon dioxide. In many places, farmers create new cropland by burning the forest. Forest fires in the Brazilian Amazon cause large amounts of carbon to flow from the forest to the atmosphere. Wood that does not burn immediately decays over time, and also releases carbon dioxide. Similarly, harvesting timber for use as a raw material also causes carbon to flow into the atmosphere. Wooden building materials and paper products dumped in landfills eventually rot and decay, releasing carbon to the atmosphere in the process.

Agriculture disrupts the carbon cycle in ways that also increase the atmospheric concentration of methane. Methane is produced by anaerobic (without oxygen) decomposition of organic material. The anaerobic microorganisms that live in rice paddies produce methane as a by-product. Livestock have an extra stomach, called a rumen, that contains bacteria, which break down plant material anaerobically and produce methane as a byproduct. Together, paddy agriculture and livestock account for a large fraction of the methane released emitted by human activity.

Human activity also has creates a new storage of carbon--landfills--and this storage generates a new flow of methane to the atmosphere. Much of the organic waste from kitchens, yards, and restaurants is dumped in landfills. The wastes eventually are covered with soil, and this cuts them off from oxygen. Anaerobic bacteria break down the organic wastes and produce methane as a byproduct. Some landfills produce so much methane that holes are drilled and the methane is captured and used as a fuel source.

### ***Future Emissions of Greenhouse Gases***

The combination of an increasing population and growing incomes imply an increase in energy use, agriculture, and other activities that release greenhouse gases. The rate at which society uses fossil fuels will have the greatest effect on the atmospheric concentration of carbon dioxide because this storage holds the greatest amount of carbon. There are about 10,000 gigatons of carbon stored in fossil fuels, which is about 15 times the amount of carbon dioxide currently in the atmosphere (Figure 14). On the other hand, there are only about 1,800 gigatons of carbon in biota and soils, which is only about twice the amount of carbon currently in the atmosphere.

How much will carbon emissions grow in the next century? Based on the IPAT equation, the rate of carbon emissions (I) will depend on population growth (P), economic development (A), and energy efficiency (T). If the world’s population reaches 9 billion, $CO_2$ emissions will increase by about one-third if affluence and technology remain the same.

But affluence will not remain the same. People also will become richer (or at least try to), and rising incomes may increase emissions even faster than population growth. The average US citizen emitted 20 metric tons of $CO_2$ in 1991, nearly 10 times the 2.2 metric tons emitted by the average Chinese person, or about 24 times the 0.8 metric tons emitted by the average citizen of India. These differences imply that the amount of $CO_2$ emitted could increase significantly as income levels in China, India, and other developing nations rise towards those of the US and other industrial nations.

Nor will technology remain the same. Increases in energy efficiency may slow emissions. Engineers have developed a host of technologies that use less energy to provide the same service. There are cars that can travel 150 miles with a single gallon of gasoline and there are light bulbs that can provide the same amount of light using a one-tenth the amount of electricity. The impact of these technologies on carbon emissions will depend on industry's willingness to produce them and people's willingness to buy them. Both of these decisions depend in part on government actions to slow climate change.

Uncertainty about all of these factors leads to a wide range of forecasts for carbon emissions. Some analysts forecast that emissions may double or triple over the next century while others forecast emissions to increase by a factor of five or seven (Figure 15). Despite the uncertainty, one conclusion is clear. The increase in the atmospheric concentration of carbon dioxide and methane that began last century will continue well into the next century.

On the other hand, the outlook for sulfur emissions is uncertain. Over the last 30 years, the shift away from coal to other fuels and the development of technologies that remove sulfur from the coal and its combustion by-products has reduced the quantity of sulfur emitted. This decline could continue if the use of pollution abatement technologies spreads to developing nations. On the other hand, emissions could increase if nations increase their use of coal as the world depletes its inexpensive sources of oil and natural gas.

## The Historical Relation Between Climate and Greenhouse Gases

There is a strong correlation between the Earth's temperature and the atmospheric concentration of greenhouse gases over the last 160 thousand years. During this span, warm periods correlate with high concentrations of carbon dioxide and methane, and vice versa (Figure 11). Did the increased concentration of greenhouse gases cause the Earth's temperature to rise, or did a rise in the Earth's temperature increase the concentration of greenhouse gases? Convincing arguments can be made for both sides of this "chicken -or-the-egg" question. We know that an increase in the concentration of greenhouse gases traps more heat and therefore can increase the Earth's temperature.

But it is also possible that rising temperatures increased the atmospheric concentration of greenhouse gases. The permafrost stores large amounts of methane. This methane could be released to the atmosphere if this soil melts as temperature rises. Higher temperatures also increase the rate at which organic material decays, which increases the flow of carbon from soils to the atmosphere. Thus, scientists are not sure whether changes in the concentration of greenhouse gases cause temperature to change, or whether changes in global temperature cause the atmospheric concentration of greenhouse gases to change. Without knowing the direction of this 'chicken-or-egg problem,' analysis of historical climate can not generate conclusive information about how future increases in the atmospheric concentration of greenhouse gases will affect climate.

### *Using Computers to Predict Future Climate Change*

Another approach to this problem uses computer models that simulate the planet’s climate system. The most complex of these models are ocean atmosphere general circulation models (AOGCMs). AOGCMs simulate the patterns of atmospheric and oceanic circulation based on the physical principles that govern the flows of energy and water. To track these flows, the models lay a grid across the land and ocean. At each grid point, the model tracks the flow of energy through the atmosphere to the land or ocean surface and back through the atmosphere towards space, or through the ocean towards the deeper layers. Differences in the rate at which energy heats the atmosphere, land surface, or ocean create gradients, which cause heat and water to flow in patterns we know as atmospheric and oceanic circulation (both surface and deep water).

AOGCMs are used to evaluate how the increase in the atmospheric concentration of radiatively active gases will affect climate. This effect is identified via scenario analysis which is akin to using the model to answer 'what if' questions. In the first step, the AOGCM is simulated with an atmosphere in which the concentration of radiatively active gases is held constant at their pre-industrial levels. This experiment establishes a reference scenario--what the climate would look like if humans had not altered the radiative forcing of the atmosphere over the last 200 years. The AOGCM then is simulated with an atmosphere in which the concentration of radiatively active gases increases at a rate similar to the historical record.

Comparison of these results with the reference scenario identifies the effect of human activity on climate.

Future concentrations are simulated using different scenarios for emissions. These scenarios are based on different assumptions about how population growth, energy use, and technological change will effect emissions. The difference between the climate simulated by this scenario and the reference scenario represents the climatic effect of changes in greenhouse gases and sulfates caused by human activity in the future.

There is a great deal of uncertainty about how emissions will change, and this is one reason that there is a great deal of uncertainty about how climate will change (Figure 15). To reduce this uncertainty, scientists investigate how climate may change if the radiative forcing of the atmosphere doubles relative to the start of the Industrial Revolution. The climate models indicate that this doubling will increase global temperature 1.5 - 4.5° C.

One scenario by climate models indicates a 4.2°C increase in temperature. This temperature rise is triggered in part by the increase in the atmospheric concentration of greenhouse gases and sulfates, but most of the increase is caused by an increase in the atmospheric concentration of water vapor (Table 3). The increased concentration of greenhouse gases triggers a positive feedback loop in which increases in radiative forcing increase temperature, which increases the atmosphere's ability to hold water vapor. Water vapor is a potent greenhouse gas, which increases the radiative forcing of the atmosphere, which increases temperature, and completes the positive feedback loop. This feedback loop is responsible for about a 1.6$^{o}$C increase in global temperature. The direct effect of doubling the radiative forcing of greenhouse gases accounts for about a 1.2 $^{o}$C increase in temperature. Another 0.8$^{o}$C increase is associated with a decline in cloud cover while another 0.4 $^{o}$C is caused by changes in albedo that are associated with a reduction in snow cover. The remaining 0.2 $^{o}$C is caused by other small changes in the climate system.

An increase in average temperature is only one aspect of climate change forecast by AOGCMs. As temperature warms, the location and strength of gradients will shift, causing flows of heat and water to change. These changes may alter the daily, seasonal, and geographic pattern of temperature and precipitation that make up the current climate. Relative to today's climate, AOGCMs forecast that the upper reaches of the Earth's atmosphere will cool, that surface temperature will increase most significantly at night, and that the greatest warming will occur in higher latitudes during the winter months. This latter affect is associated with a reduction in snow cover. Precipitation is forecast to increase globally but decrease over the middle portions of the continents.

Can we trust the predictions? AOGCMs are among the most complex tools used by environmental scientists because they test the limits of our knowledge of atmosphere science, mathematics, and computer science. Even though computers do not make mathematical errors, they still can be wrong. Mistakes occur because scientists may simulate the wrong processes, use the wrong form of an equation, or omit an important process.

Scientists know that all AOGCMs contain errors because there is a great deal of uncertainty about how the climate system really works. Clouds play a critical role in the heat balance of the atmosphere, but there is a great deal of uncertainty about how clouds are formed. As a result, many AOGCMs do not include equations to represent the formation of clouds. These and other shortcomings in our understanding about how climate works create a great deal of uncertainty about predictions for future changes in climate.

Scientists attempt to evaluate this uncertainty by ranking their predictions. They are most confident that the forecast for cooling in the upper atmosphere is correct, and very sure of other changes, such as the global increase in temperature and rainfall. Scientists are less sure about other changes such as which regions will warm the most.

## Detecting Climate Change

A basic understanding of the atmosphere indicates that the increasing concentration of greenhouse gases should trap more heat, and computer models indicate that this effect could raise the Earth's temperature by 1.5° - 4.5°C. But is the increased concentration of greenhouse gases responsible for some or all of the 0.6°C rise in global temperature over the last century? To investigate this possibility, scientists investigate whether climate is changing and if it is changing, are those changes caused by human activities that increase the atmospheric concentration of radiatively active gases.

Detection seeks to determine whether climate actually is changing. First, scientists choose an indicator to represent the Earth's climate. Some indicators measure climate directly. Data for the average temperature of the air and sea surface over the last 150 years show a tendency to increase. These increases are consistent with the global increase in sea levels (Figure 16). As the world's oceans warm, water become less dense, which causes it to expand. This expansion is partially responsible for the rise in global sea level. Other indicators include a reduction in sea ice in the Northern Hemisphere. This change is especially important because it is part of a positive feedback loop that accelerates the increase in global temperature.

Other indicators of climate change measure the response of biological systems to changes in climate. Scientists have analyzed remotely sensed images (photographs taken from satellites) of temperate and boreal forests taken between 1980 and 1994 (Myneni et al., 1998). The level of 'greenness' in these images indicates that the length of the growing season has increased by about a week in the spring and fall and that the maximum amount of biomass per hectare that is present in mid-summer also has increased (Figure 17). Myneni et al. hypothesize that a warming in high latitudes generates these changes, and warming in high latitudes is consistent with the forecasts generated by AOGCMs.

These changes suggest that the climate is changing. But scientists are not sure whether natural variation or a long-term change in climate causes them. Their analysis leads them to conclude that the observed change is unlikely to be due entirely to natural fluctuations of the climate system. It is difficult to judge how unlikely these changes are and this difficulty lies at the heart of the debate about whether climate is changing.

## Attributing Climate Change to Human Activity

Attribution is the process of establishing a cause and effect relation between human activity and the observed change in climate. The balance of evidence suggests that there is a discernible human influence on climate (Houghton et al., 1996).

Efforts to attribute climate change to human activities use two methodologies: statistical analyses of historical data and computer models of the climate system. Some of the strongest statistical evidence for the effect of human activity on climate comes from analyses that focus on differences in the rate at which temperature changes in the northern and southern hemisphere. Temperature changes in the Southern Hemisphere help predict temperature changes in the Northern Hemisphere, but temperature changes in the Northern Hemisphere can not help predict temperature changes in the Southern Hemisphere (Kaufmann and Stern, 1997). This pattern can be explained by differences in the atmospheric concentration of greenhouse gases and sulfates. The warming effect of greenhouse gases is spread evenly across the northern and southern hemispheres, but the cooling effect of sulfate aerosols occurs mainly in the Northern Hemisphere, where sulfates suppress the warming associated with greenhouse gases. As the concentration of greenhouse gases and sulfates increased over the last 150 years, differences in the radiative forcing of the atmosphere over the northern and southern hemisphere became large enough to produce the pattern of temperature change described by the statistical analysis.

Hemispheric differences in the atmospheric concentration of greenhouse gases and climate models to attribute climate change to human activity also use sulfate aerosols. When climate models are simulated with atmospheric concentrations of greenhouse gases and sulfates generated by human activity, the changes in temperature simulated by the climate models generate a distinct spatial pattern. In general, the Southern Hemisphere warms more than the Northern Hemisphere, and this warming is most pronounced in the lower levels of the atmosphere. This pattern is analogous to a human fingerprint--the unique pattern of atmospheric changes caused by human activity generates a unique pattern of temperature changes. The temperature changes recorded by satellites have become increasingly similar to this pattern over the last century. This 'match' indicates that human activities that alter the atmospheric concentration of greenhouse gases and sulfates are partially responsible for the increase global temperature.

## The Impacts of Global Climate Change

The 1.5 - 4.5° C rise in average temperature forecast by climate models due to a doubling the atmosphere's radiative forcing may seem trivial, but the Earth's average temperature was only 3-5° C cooler than today during the last ice age when most of North America was covered by a several kilometers of ice. Clearly, small changes in average temperature can have a significant effect on climate.

### *The Migration of Ecosystems*

Individual organisms and entire ecosystems survive and prosper under a relatively narrow range of climatic conditions. This specialization implies that the area occupied by specific biomes changes with climate. As climate changes, biomes expand their range into to regions where the climate is favorable, and disappear from regions where the climate is unfavorable.

Climate changes constantly, therefore the geographic distribution of biomes changes constantly. The vegetation that covered North America changed dramatically as the climate warmed between 10 and 5 thousand years ago. Boreal forests shifted north out of the US into northern Canada, and forests that thrive in warm and temperate climates expanded their range from the Gulf of Mexico northward along the Atlantic seaboard up to what is now New York.

For biomes to follow changes in climate, species must be able to migrate. When temperature or precipitation changes, a species must move to a new region with favorable conditions. If it cannot, it will become trapped in an unfavorable climate and disappears. During the warming that began 10,000 years ago, temperatures along the northern border of the US were too warm for Spruce trees, but made this region hospitable for hardwood species that thrive in warmer climates. The boreal forests had to shift its range northwards into Canada, or face being out-competed by hardwood species.

Biomes require a lot of time to shift their range. Trees in particular expand their range very slowly. As the climate warmed about 10,000 years ago, tree species in North America shifted their range between 100 and 400 meters per year. It took about 5,000 years for spruce tress to move the southern portion of their range from the southern Michigan to the Northern Michigan, a distance of only 500 kilometers. This slow rate of movement is important because the rates of climate change forecast by climate models is about ten times faster than the rates of changes that occurred after the last ice age.

Even if trees can move as fast as climate changes, other factors may block their path. Cities, highways, and agricultural fields block the transport of seeds by animals and wind. Equally important, the soil in a region with favorable climate may not be able to support the new ecosystem. Each tree species requires specific types of soil, and it may take a long period for soil to change in a way that can support new species. Trees such as the sugar maple and yellow birch in North America should be able to migrate from areas around the Great Lakes to areas just south of Hudson Bay. But this migration may be prevented by soil conditions. Sugar maples and yellow birch trees cannot grow in the sandy soils that are common in these regions because these soils cannot store sufficient quantities of water.

For mid-latitude regions, a global warming 1-3.5 °C over the next 100 years would be equivalent to a poleward shift of present isotherms by about 150-550 km, or an altitude shift of about 150-550 km. This compares to past tree species migration rates of 2-400 km per year (Kirschbaum et al., 1996). The rapid rates of climate change and the slow rates of ecosystem migration imply that forests may become trapped in areas where climate conditions cannot support them. This could cause the ecosystem to collapse and be replaced with a much simpler system. The biodiversity supported by the forests would be lost or reduced, as would all the life support services generated by the forest. The loss of forest area could reduce timber supplies, increase the frequency and severity of floods, and increase soil erosion and the subsequent clogging of waterways.

### *The Impact on Food Production*

There is a great deal of uncertainty about the effect of climate change on agriculture (Reilly, 1996). Some of the changes in climate forecast by climate models could increase food supply, while other changes could reduce food supply. It is impossible to compare the positive and negative effects, but it is highly unlikely that exactly the negative effects will balance the positive effects. Instead, food production will increase in some regions and decrease in other regions, which will create 'winners' and 'losers.'

There are two ways that climate change can increase crop production. Carbon dioxide is the raw material for photosynthesis; therefore an increase in the atmospheric concentration of carbon dioxide may act as a fertilizer and stimulate plant growth. The faster rate of photosynthesis could increase the production of corn, rice, and other crops. Doubling the atmospheric concentration of carbon dioxide may increase growth rates by 50 - 75 percent and may increase yield by 40 - 60 percent.

A general warming also will allow farmers to grow crops in areas where the growing season is too short (the period with temperatures above freezing). Corn requires a relatively long growing season, which restricts production in Europe to the central and southern portions of the continent. Even a small increase in temperature of 1° C could increase the area where corn is grown by nearly 1.3 million square kilometers, which is an 11 percent increase relative to 1988.

Alternatively, changes in climate could reduce food production. Climate models forecast that areas away from the coast will become drier. Interior areas such as the midwestern US often support significant levels of agricultural production. The loss of water may offset the positive effects of warmer temperatures and the increased concentration of carbon dioxide.

Climate change also may reduce food supplies by providing more suitable habitats for pests and diseases that attack crops. Mild winters and longer growing seasons may allow insects pests to expand their range and increase their rate of reproduction. Some scientists estimate that climate change could increase crop losses to pests by about one-third in North America and by nearly one-half in Africa.

### *The Impact on Sea Level*

Global mean level has risen 10-25 cm over the last 100 years (Figure 16). The average rate of increase in the past century has been higher than the rate averaged over the last several thousand years. It is likely that the rise on sea level has been due to the concurrent increase in global temperature (Warrick et al., 1996). The balance of scientific evidence suggest that global warming will increase sea level through a warming and expansion of the oceans, an increase in the melt rate of glaciers, and an increase in the melt rate of the Greenland ice sheet (Warrick et al., 1996).

The AOGCMs forecast sea level to rise 13 to 94 cm; the “best estimate” is 38-55 cm. Most of the projected rise is due to thermal expansion, followed by increased glacial melting. Glaciers are retreating all over the world. This is seen most dramatically in Glacier National Park, Montana, US, where there are only 27 $km^2$ compared to 99 $km^2$ in 1850. One model predicts that there will be no glaciers left in Glacier National Park by 2030 (Hall, 1995). The most uncertainty lies in the contribution of major ice sheet melting. Under the most catastrophic scenario (highly unlikely), in which the east Antarctic drops into the sea, sea level will rise about 200 meters. Even a 17 meter rise in sea level due to the loss of the west Antarctic ice sheet would drown several South Sea Island nations and many coastal cities.

A significant fraction of humanity and its infrastructure lives in the coastal zone. Sea level rise would have negative impacts on tourism, freshwater supply and quality, fisheries and aquaculture, and human health. Perhaps most importantly, it could destroy infrastructure, such as homes, factories, bridges, and roads. To avoid such damages, several scientists have suggested building dikes around heavily populated areas that are close to sea level. But protection of low-lying island states (e.g., the Marshall Islands, the Maldives) and nations with large deltaic areas (e.g., China, Egypt, India, Bangladesh) would be enormously expensive (Bijlsma, 1996).

A rise in sea level also would affect society indirectly by reducing the area and productivity of estuaries and coastal wetlands. Estuaries are among the most productive ecosystems on Earth and have very rich biodiversity. Estuaries process organic and toxic wastes, they are nurseries for many species of fish, and they reduce the strength and damage done by coastal storms. These life support services could be reduced if rising seas drown estuaries and wetlands. As with forests and farmlands, estuaries may not be able to migrate inland as sea level rises.

## The Search for Prometheus III

The Promethean nature of fossil fuels aside, they have distinct drawbacks. Their use has produced a major alteration of the planet's carbon cycle, which may be contributing to climate change. Fossil fuels are finite. World oil production will peak in 2020±10 years, and coal will follow suit a few decades later. More stringent restrictions on carbon emissions than those currently contemplated would shorten these lifetimes. It seems unlikely that we will tap the vast store of energy in tar sands and oil shales due to their high carbon intensities.

Thus, humanity faces a fundamental challenge: the need to replace fossil fuels with solar technologies that have Promethean qualities. Two qualities are critical. First, the new energy technologies must eliminate or substantially reduce carbon emissions. Second, they must approach the abilities of fossil fuels to generate economic wealth per heat unit. Solar technologies clearly meet the first criteria since they are free of carbon.

The extent to which they meet the second criteria is an open question because solar energy inherently is a lower quality than fossil fuels. The diffuse nature of incoming solar radiation requires a significant investment of energy and materials to capture, collect, and concentrate sunlight. This means that many solar technologies deliver a lower energy surplus than fossil fuels (Cleveland et. al, 1984; Hall et al., 1986; Gever et al., 1986). Equally important, the substantial "material scaffold" required to collect solar energy is made from fossil fuels.

Solar energy, therefore, currently is a "parasite" on fossil fuel systems because they cannot "reproduce" themselves (Georgescu-Roegen, 1979). Many biomass-based fuels such as ethanol are feasible recipes but fail the test of viable technologies because of low net energy yields and high environmental costs (Pimentel, 1991). On the other hand, some technologies such as solar parabolic collectors have become viable through innovations that improve their net energy yields (Cleveland and Herendeen, 1989). Photovoltaics and wind turbines also exhibit significant technical improvements. The issue is whether a sufficient number of solar technologies can move from "feasible" to "viable" status in terms of their net energy return, and whether they can be scaled-up in time to offset the economic effects of fossil fuel depletion.

## The Choices Before Us

On December 1 through 11, 1997, representatives from more than 160 countries met in Kyoto, Japan, to negotiate binding limits on greenhouse gas emissions for developed nations. The resulting Kyoto Protocol established emissions targets for each of the participating developed countries relative to their 1990 emissions levels. The targets range from an 8-percent reduction for the European Union (or its individual member states) to a 10-percent increase allowed for Iceland. The target for the United States is 7 percent below 1990 levels to be reached during the period 2008 to 2012.

What are the chances that the United States, and other nations as well, will meet their targets? Frankly, we think the chances are close to zero. Emissions in the United States continue to rise, driven by economic growth and the concomitant increase in fossil fuel use (Figure 18). The Department of Energy's most recent forecast is for emissions to be nearly 1.5 times their 1990 level by 2020 if we follow a "business-as-usual" path. We have yet to see any plausible combination of changes in population, affluence, technology, institutions, or personal attitudes that would come even close to meeting the Kyoto target.

Although technology will be important, without deliberate constraints on population and affluence levels it will have little net effect. That leaves us with essentially three difficult choices that few want to face and probably no political leader would dare advocate:

1) Business-as-usual. By doing this, we would, in effect, be saying "to hell with the atmosphere." This approach assumes that the problems generated by attempting to solve the $CO_2$ issue are greater than those generated by $CO_2$ itself. This is essentially the strategy that is in place and that most nation's, following Kyoto or not, are following.

2) Go nuclear big time. Some of the cost and reliability problems of nuclear energy have been solved; others remain, such as long-term waste disposal. Few anti-nuclear crusaders are willing to examine the overall safety record of the nuclear industry versus the alternatives. For example, running a thousand MW nuclear power plant for a year in the US kills on average about one person, probably a uranium miner in the Southwest. To run a thousand MW coal plant kills on average about ten people, 5 miners, 4 of emphysema from air pollution, and one at railroad crossing. Extrapolated into the future we might add, however, many are killed by the possible increase in heat-induced deaths, as evidenced. Perhaps, by the several hundred deaths in the United States during the 1999 summer heat. We remain very unsettled about the possibility of nuclear terrorism and some other issuers, but it is incorrect to say that the impacts of nuclear are long lasting and fossil fuels are not. They both are.

3) Accept a reduced standard of living. Most other alternatives involve a slower rate of growth in our standard of living and quality of life, or perhaps even an absolute reduction. Have fewer children, make and spend less money, drive smaller cars fewer miles (or not at all), design cities so that people can walk to work and shopping and so on, rather than live in the greener areas and work in the cities. There are many possibilities here, but most of them will be asking people to do what they have already chosen not to do, and hence will be perceived by most as getting poorer.

We do not see any other alternatives. We think that the various technical advances that are being made can fit into any of these three approaches rather well, but technology cannot work alone. Now any candidate who wants to run on one of these three platforms, please step forward.

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## Figure Legends

Figure 1. Long run population growth and the United Nations’ projection for the future.

Figure 2. The average annual nitrate ($NO_3^-$) concentration in 42 rivers of the world and the corresponding watershed population density. Open circles represent tropical rivers (From Cole et al., 1993).

Figure 3. The relationship between per capita GDP and per capita $CO_2$ emissions (Data from World Resources Institute).

Figure 4. The quantity of water, fossil fuels, and land required to produce one kilogram of grain and one kilogram of meat in the United States.

Figure 5. The thermal efficiency (Btu of fuel input per kilowatt-hour of electrical output) of power plants in the in the United States.

Figure 6. Global and hemispheric temperature anomalies, 1856-1998. The observations are annual deviations from the average temperature from 1961-1990. (Climate Research Unit, University of East Anglia, http://www.cru.uea.ac.uk)

Figure 7. Long-run global temperature change (From Oliver, 1992).

Figure 8. The radiation budget for the planet (From Trenberth, et al., 1995)

Figure 9. The general pattern of global atmospheric circulation, showing the Hadley Cells between 0° and 30°, 30° and 60°, and 60° and 90° latitude.

Figure 10.The contribution of various greenhouse gases to radiative forcing of the atmosphere (From Schimel *et al.*, 1995).

Figure 10.The concentration of carbon dioxide in the atmosphere above Mauna Loa, Hawaii (Climate Modeling and Diagnostics laboratory, National Oceanic and Atmospheric Administration, US Dept. of Commerce: http://www.cmdl.noaa.gov/info/ftpdata.html)

Figure 11.Long-run atmospheric concentrations of carbon dioxide and methane based on the Vostok ice core data.

Figure 12.Anthropogenic emissions of sulfur.

Figure 13. Emission of carbon from fossil fuels and deforestation (From Houghton et al., 1996).

Figure 14.The global carbon cycle (From Houghton, 1997).

Figure 15.Scenarios of carbon emissions from the IPCC, and forecasts of temperature change generated those scenarios of carbon emissions (From Houghton et al., 1996).

Figure 16.Six long sea level records for major world regions (From Warrick et al., 1996).

Figure 17.Normalized Difference Vegetation Index (NDVI) data processed from measurements of Advanced Very High Resolution Radiometers (AVHRR) on board the afternoon viewing NOAA series satellites (NOAA-7, 9 and 11). The vegetation index anomalies at latitudes north of 45°N (vertical axis) were found to exhibit an increasing trend. This linear trend corresponds to a 10% increase in seasonal NDVI amplitude over a 9 year period (1981-90). During the same time period, annual amplitude in the record of atmosphere $CO_2$ measured at Point Barrow, Alaska, was reported to have increased by about 14%. (From Myneni et al., 1998).

Figure 18. The implications of the Kyoto Protocol for the United States. The circles represent historical emissions of CO2. The dashed line is the forecast for emissions from the Dept. of Energy's reference case scenario of economic growth and energy use. The dashed line is the United States' target under the Kyoto Protocol (7 percent reduction from 1990 levels). The arrow represents the approximate path needed to meet the target by the 2008-2012 deadline.