# *Minimizing the greenhouse effect*

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The issue of climate change is by its nature potentially divisive, so caution may be in everyone's long-term interest. International collaboration is essential as no single nation or region is likely to want to bear all costs of mitigation and adjustment. The political obstacles to global collaboration are substantial, however, as different nations and regions have conflicting interests. Creating an effective international system for rationing and curtailing greenhouse gas emissions will take time. In the meantime, other opportunities for collaboration exist. The development community should outline a policy and research program for sustainable economic development that addresses the implications of the greenhouse effect. Clearly the energy sector should get strong attention, but such sectors as agriculture and urban systems are also of importance as emitters of various greenhouse gases — and agriculture could be a sink for carbon.

## What we know

We have known since late in the last century that the earth's climate system could warm because of atmospheric emissions and the radiant properties of industrial and agricultural "greenhouse gases." The theory of the "greenhouse effect," conceived more than a century ago by the French mathematician, J-B. Fourier (1827), was given support by Tyndall's studies (1861) on the absorption of heat by gases. The Swedish physical chemist Svante Arrhenius (1896) first calculated that a global warming of 3.2 to 4.0 degrees Celsius (C.) would result from a doubling of the earth's atmospheric concentration of carbon dioxide, a level that could be attained sometime in the next century. The theory of the greenhouse effect has passed from conception to hypothesis to the consensus view that it is both real *and* probably the driving force behind global climate change in our day (Jaeger 1988a).

The greenhouse effect is both normal and essential to life on earth. Without it, the earth would be more than 30 degrees C. (60 degrees Fahrenheit) cooler, and life as we know it would not exist. It is the additional greenhouse effect — the legacy of industrial revolution — that poses a threat to society. The extent and character of future changes will reflect human choices — about the use of fossil fuels, among other things.

The emission of greenhouse gases is expected to increase the global mean temperature more and faster than ever before in mankind's history. Current models predict a warming of 1.5 degrees to 4.5 degrees C. within the next century. The earth's temperature rose only 0.5 to 0.7 degrees C. in the last century, and probably has not varied more than 1 to 2 degrees C. in the last

10,000 years, or 6 to 7 degrees C. in the last million years. During the development of human infrastructure in the last 7,000 years, the average global climate has not been 1 degree warmer or colder than today's climate (Revelle and Waggoner 1983a).

Climate is a statistical description of the mean state of the atmosphere and the variability of the atmosphere, ocean, ice, and land surfaces over time. Climate is conventionally described in terms of historic means, variances, and probabilities (Rosenberg 1987). Climates have been accurately measured instrumentally in some locations for more than a century.

Climatic events that occurred before routine instrumental measurement became established (100 years ago) — and their relation to biogeochemical changes — are by no means unknown. Data from specific climate-related patterns in biological and mineral materials — recovered at time-related positions in sediments and ice cores — have been the main tools for measuring long-term climate change. These data — like "fingerprints" of different climate-influenced ecosystems — provide the basis for reasonably accurate descriptions of prehistoric variations in climate.

The global climate warms largely because certain long-lived industrially and agriculturally generated atmospheric trace gases — mainly carbon dioxide ($CO_2$), chlorofluorocarbons (CFCs), halons, methane ($CH_4$), tropospheric (ground-level) ozone ($O_3$), and nitrous oxide ($N_2O$) — trap some of the radiant heat that the earth emits after receiving solar energy from the sun, in some ways as glass enclosures trap heat (hence the "greenhouse effect").

We have solid physical evidence of anthropogenic (man-made) emissions of long-lived actively radiating trace gases that contribute to the greenhouse effect. We do not have solid scientific consensus on how these gases will affect the earth's climate. It is still not possible to say definitively, for example, that the global warming of 0.5 to 0.7 degrees C. that has been observed over land masses in the past century is the result of the greenhouse effect. Air temperature data indicate that five of the warmest years on record occurred in the 1980s, and some scientists have claimed statistical proof of the impact of the greenhouse effect (Hansen 1988), but others question whether we will ever be able to answer the question, Is this the year the greenhouse effect began to bite? Recent events do, however, illustrate what might be expected if the greenhouse effect were now under way.

### Industrial greenhouse emissions

Greenhouse gases are accumulating rapidly and changing the chemical composition of the earth's atmosphere. Human activities are increasing greenhouse gas concentrations worldwide, intensifying the greenhouse effect. The gas that contributes most to the greenhouse effect is carbon dioxide; burning fossil fuels (coal, oil, and natural gas) releases to the atmosphere carbon that had been buried in the earth for 100 million years.

The next most important greenhouse gases are methane, chlorofluorocarbons, and nitrous oxide. Much methane is produced by the anaerobic (in the absence of oxygen) decay of organic matter such as agricultural (rice paddy and livestock) emissions and urban wastes. Methane also leaks during the extraction and transport of fossil fuels, a fact that should be considered when evaluating the relative greenhouse contribution of different fossil fuels (Abrahamson 1989). The level and lifespan of methane in the atmosphere are increased by the emissions of carbon monoxide that result from incomplete combustion of carbon-based fuels in industry, households, and transport — and from the burning of savannahs and forests in land-clearing and slash-and-burn agriculture. Although not a greenhouse gas itself, carbon monoxide interferes with the atmosphere's self-cleansing capacity by destroying chemical scavengers such as OH radicals, which are present in the atmosphere and would otherwise attack and break down air-borne methane. Thus it extends methane's atmospheric lifetime and its ultimate greenhouse warming effect. Chlorofluorocarbons — inert gases used as refrigerants, aerosols, foaming agents, and solvents — do not occur naturally but are industrially produced. The sources of nitrous oxide have not been fully characterized, but almost half of the emissions are probably from such natural biosystems as tropical forests and estuaries. Most of the nitrous oxides emitted as a result of human activity are released by soil processes, accentuated by various agricultural practices, land clearing, and tropical deforestation. Other sources of nitrous oxide, such as fuelwood burning, fluidized bed combustion, and the combustion of automobile exhausts, are the result of

**Table 1 Net enhancements of the greenhouse effect**

| Compound | (1) Atmospheric concentration (parts per million) | (2) Annual increase (1985) (percent) | (3) Atmospheric lifespan (approx. years) | (4) Relative greenhouse efficiency ($CO_2$=1) | (5) Cumulative greenhouse contribution (1985) (percent) | (6) Present marginal greenhouse contribution (1985) (percent) |
|---|---|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 346[a] | 0.4 | 100[b] | 1 | 50 | 46 |
| Chlorofluoro-carbons (CFCs) | 0.001 | 5.0 | 100[c] | 15,000[c] | 17 | 24[c] |
| Methane ($CH_4$) | 1.7 | 1.0 | 10[d] | 32[d] | 19 | 18[d] |
| Tropospheric ozone ($O^3$) | 0 02 | 0.5 | 0.1 | 2,000 | 8 | 7 |
| Nitrous oxide ($N_2O$) | 0.3 | 0 3 | 150 | 150 | 4 | 5 |

a Preindustrial concentration: 260 parts per million

b. The estimated lifetime of atmospheric carbon dioxide assumes a dynamic equilibrium between the ocean and atmosphere unlike the lifetimes of other greenhouse gases, which are determined largely by chemical breakdown (Bach 1988) The statistical lifespan (calculated as the average atmospheric lifetime) of a single carbon dioxide molecule as a result of physical removal processes is four years (Laut and Fenger 1989).

c. For chlorofluorocarbons presently in use. These estimates may vary, with compensating shifts in the percentage breakdown in column 6

d These estimates may vary, with compensating shifts in the percentage breakdown in column 6.

Source· Columns 1-5, Bach 1988; Laut and others 1989. Column 6, World Bank estimate, highlights the relative priorities for possible mitigation of trace emissions as a function of their greenhouse contributions at the margin of increasing atmospheric loading. Footnotes, World Bank.

combustion at low temperatures.

Carbon dioxide is the least efficient of the greenhouse gases in its capacity to absorb infrared radiation. The other gases, because of their higher absorptive capacities, contribute substantially more to the greenhouse effect than the same amount of carbon dioxide (see table 1). Column 4 shows that greenhouse gases vary in their efficiency at absorbing infrared radiation.

For example, using $CO_2$ as the baseline unit (equalling one) for absorptive capacity, a molecule of methane has 32 times the greenhouse effect of $CO_2$, and the CFCs average 15,000 times the effect of $CO_2$. Column 5 presents the current cumulative level of past greenhouse contributions, by compound; column 6 shows what each of the greenhouse gases contributes at the margin. What they will contribute to increases in the greenhouse effect will be a function of their relative atmospheric concentrations, rates of annual increase, and radiative absorptive capacities. These figures indicate where the opportunities for reducing greenhouse emissions lie and are useful for evaluating the most cost-effective measures to be taken by the development community.

Breakdowns of carbon dioxide emissions by economic sector are not available for the world but a breakdown for the United States in 1985 is shown in table 2. Here sectors are treated as independent in their greenhouse effects, but they may be interdependent. Some industrial, transport, and residential building users generate all or part of their own electric power, for example, so these percentage distributions are only first-order estimates.

**Table 2 U.S. $CO_2$ emissions by sector, 1985**

*(percent)*

| | Percent of total |
|---|---|
| Electric utilities | 32.5 |
| Transportation | 31.0 |
| Industry | 24.7 |
| Residential buildings | 11.8 |
| | 100.0 |

Source. Personal communication, G. Marland, Oak Ridge National Laboratory, U.S. Department of Energy.

How much more methane contributes to the net greenhouse effect than carbon dioxide does depends on the period of time — or decision horizon — for which their relative effects are compared. Once methane is released to the atmosphere it is vulnerable to the attack of such chemical scavengers as OH radicals. Thus, although methane's greenhouse warming effect is initially 32 times as great as that of carbon dioxide on a molecule per molecule basis, its present expected lifetime in the atmosphere is only 10 years — so its net cumulative effect declines from 32 to only four or five over carbon dioxide's longer lifespan. The contribution of methane and its byproducts to the warming effect will be given more weight for shorter decision horizons and less weight as the decision horizon is longer because methane's lifespan is shorter than that of carbon dioxide. Moreover, the breakdown of methane may involve a complex array of additional greenhouse gases. Thus, in 10 to 20 years the gross warming effect induced by methane emissions and byproducts could be substantially higher than these figures suggest.

And the various greenhouse gas emissions themselves interact synergistically. Methane is more effective per molecule as a greenhouse gas than carbon dioxide, so even small amounts of carbon monoxide (CO) increase the greenhouse effect significantly by increasing methane's lifespan. CO is produced by inefficient combustion in automobiles and industrial and household furnaces. It is worth considering ways to reduce CO emissions, such as introducing appropriate energy efficiency and process control technologies. And since CO is a combustible waste, finding more efficient ways to burn it would also provide more energy.

Recent onsite measurements and remote sensing observations confirm that substantial carbon monoxide is being released not only from fossil fuel combustion in industrialized urban areas but also from extensive tropical and savannah burning to clear land for agriculture in South American and African developing countries (Newell and others 1989). So the OH radicals, which give the atmosphere a natural self-cleansing capacity, are much more at risk than had originally been thought.

Although most CFCs are produced and used mainly in the industrialized world (see table 3), developing countries could become important producers and users of CFCs. But, if they had easy access to affordable replacements or substitutes for CFCs, their harmful effects on the environment would be attenuated. Some of the most promising near-term CFC substitutes, such as HCFC-22, break down relatively rapidly within the troposphere, but also have comparatively short atmospheric lifetimes — 15 to 25 years — more like that of methane than of contemporary CFCs, which have lifetimes of 100 years or more. As with methane, however, estimates of the relative greenhouse warming effect of such "new" CFCs will vary with the length of the decision period.

**Table 3 World production and use of CFCs, 1985**
*(percent)*

| | CFC production[a] | CFC use[b] |
|---|---|---|
| United States | 31 | 29 |
| W. Europe, Japan, Canada, Australia, New Zealand, E. Europe, Soviet Union | 59 | 55 |
| Developing countries | <3 | 16 |
| | | 100 |

Sources:
a. Chemical Manufacturers Association
b. U.S Environmental Protection Agency.

*In short, the relative greenhouse effect of different emissions over time is the combined result of their radiative forcings (changes) per molecule, interactions with other gases and sinks, resulting atmospheric lifespans, and the length of the decision period used for the estimate.*

### Patterns of change in climatic risk

*All current long-term projections of climate scenarios are conjectural, not literal.* At the present time, scientists generally do not agree on a paradigm for anticipating climate change. Some climate scientists believe that the climate system tends to shift suddenly in equilibrium as boundary conditions change. Others contend that the climate system is linear, more deterministic than probabilistic in nature.

Oceanographer Wallace S. Broecker (1987) is concerned that we may have been "lulled into complacency" by model simulations suggesting a gradual warming over the next century. Broecker argues that the models' fundamental architecture denies the possibility of critical interactions that we know prevail in the real world. Unfortunately, we are aware of the possibility of so-called "flip-flops" in the climate system, but do not yet know how to incorporate them into our models or predictions.

A system's stability is a function of both the size of its domain of stability and its resilience, or its ability to maintain its structure and patterns of behavior in a disturbance (Holling 1986). And disturbances may be the result of positive feedback as well as external shocks. In a climate system, we may not be able to pinpoint thresholds along the boundary of the stability domain, but we do know that by pursuing the right approach to mitigating greenhouse emissions, we might be able to avoid climatic change altogether. Policymakers should not lose sight of this fact.

Long-term paleoclimatic records indicate that the earth does not respond to atmospheric forcing (changes in its chemical composition) either smoothly or gradually. Rather, the climate responds in sharp shifts that may involve large-scale transformation of the earth's climate system. These records also show that changes of 6 degrees C. in air temperature have been typical of the earth's climatic shifts — and have been *positively correlated* with changes in the concentration of carbon dioxide in the atmosphere. But none of these events has occurred in recorded human history.

Other feedback effects may be either positive or negative. For example, the feedback effects of a changing global cloud cover depend upon the type of cloud and may tend to be negative (because of enhanced solar reflectivity) or positive (by behaving as an insulating blanket, reflecting infrared radiation back to the earth's surface). A shift from one type of cloud to another in the process of climate change may thus induce a flip-flop. The ocean also manifests complex feedback interactions within the climate system. Moreover, the ocean is an important sink for $CO_2$ not only through its direct physical and chemical absorption, but also through its capacity to sustain plankton-based biochemical and photosynthetic transformations of inorganic carbon into deep sea sediments. The processes by which clouds and oceans affect climate are not well understood and require increased attention.

Empirical evidence strongly suggests that the probabilities of certain *extreme weather events* are correlated in a nonlinear way with mean temperatures. Experience has shown that the probability of extreme temperature events critical to the economy (such as consecutive daily temperatures exceeding 95 degrees F) increases as mean temperatures rise. As mean temperatures rise, so does the likelihood of natural disasters — which currently claim more than $40 billion in global resources and at least 250,000 lives annually. Ninety-five percent of these deaths occur in the poorest countries of the world, while 75 percent of economic losses occur in the wealthiest countries (Kates and others 1985).

Some simulations show a nonlinear relationship between *precipitation changes and the amount of runoff* available to supply irrigation within river drainage basins. In one such study, a 10 percent decrease in precipitation decreased runoff 25 to 40 percent, depending upon the size and mean runoff of the watershed (Nemec 1988). In another study, a 10 percent increase in average annual precipitation, combined with a 2 degree C. rise in average temperature, produced an 18 percent decrease in runoff. To completely counteract the effects of the 2 degree C. warming, a 28 percent increase in precipitation would be necessary (Revelle and Waggoner 1983b).

Some computer simulations with climate models suggest that with global warming the earth's hydrological cycle and resulting precipitation will not only become more intense, but that many areas presently dependent upon rain-fed agriculture will become hotter and drier. They suggest in particular that midcontinent, midlatitude areas that now produce substantial grain may experience *drier summer soil* and an increased risk of *drought*. In some scenarios, grain crops could fail simultaneously in all the earth's breadbaskets.

Similarly, some areas that have been dry may get more precipitation in a warmer world. And changes that by agricultural convention are viewed as positive may be undesirable for the successful adjustment of some species and ecosystems.

Recent international scientific assessments have led to the conclusion that should the anticipated greenhouse warming take place, *global sea levels could rise* 20 to 165 centimeters over the next century, mainly because of the thermal expansion of oceans. Such an increase would bring about *flooding* in many coastal areas, induce *saltwater intrusion* into aquifers, and *submerge wetlands*, the vital spawning grounds for commercial fisheries. At least 10 to 15 percent of the arable land, populated areas, and economic productivity of such areas could be lost. These estimates do not include the considerably less probable scenarios of the melting of continental ice sheets in the Antarctic and Greenland, which would substantially increase progressive or sudden rises in sea level.

Another probable result of the anticipated rise in global mean temperatures would be a decrease in the natural thermal gradient on the earth's surface between the poles and the equator. A likely result will be *major shifts in the global patterns of wind and ocean currents.*

## Why the development community should be concerned

Confronted by serious risks that may be menacing, cumulative, and irreversible, uncertainty argues strongly in favor of action and against complacency. There is a real choice (Waltz 1987). The world can continue with business as usual or it can reassess policies and resource commitments — in light of the risk of climate change, but with a view to endorsing precisely those actions that make economic, social, and environmental sense on their own merits. This approach can help buy time in which to learn more about the climatic and policy responses that might make sense later and can help us prepare for them if necessary. As Louis Pasteur stated, "In science, chance favors the prepared mind."

Several factors may influence the efforts of individual countries to deal with the greenhouse problem and to reach the international consensus needed:

- Industrialization is indisputably the principal source of trace gas emissions that increase the risk of (and uncertainties about) global climate change.
- The effects of climate change are likely to be widely dispersed.
- Some countries are far more dependent than others on such natural resources and systems as agriculture, forests, fisheries, and monsoon patterns — systems that depend heavily on climate. And these countries often have far fewer resources available for adapting to or mitigating change than other countries do. They are also more vulnerable to such natural disasters as floods, drought, violent storms, and rising sea levels (Gleick 1987).
- Developing countries have a greater need to increase their energy resources, so they also need to focus on policies and measures to mitigate the greenhouse effect.

The stability domain of the present climate system is unknown, so a critical threshold to turbulent change might inadvertently (perhaps avoidably) be crossed. But the climate system, like all systems, also has an inherent resiliency. Doing the right things now may increase our chances of avoiding truly disruptive climate change altogether.

## Opportunities in economic development

Delay could mandate more extreme policy measures later, so taking action now seems prudent. Investing in energy efficiency is the best way of "buying" insurance against the hazards of the greenhouse threat, particularly since many options are economically, technically, and politically feasible. Failure to buy this insurance could increase both the risk and the cost of disaster, especially if there is a flip-flop in the climate system. Investing in energy efficiency is not only the quickest and most effective alternative for mitigating the greenhouse problem, it is also the least expensive (Keepin and Kats 1988, Goldemberg and others 1988).

Decisionmakers face the task of determining what specific investments or policies must take the risk of climate change into account (Waltz 1987). If industrial growth and energy demand take off as expected in many countries, without improving energy efficiency or restraining the use of chlorofluorocarbons, the result will be far more greenhouse gas emissions than are technically needed to meet the goals of development.

Agriculture generates less greenhouse gas than industry does. The stock of carbon in existing forests is about equal to the quantity of carbon now in the atmosphere, but the planet's storehouse of known fossil fuels contains at least 15 times more carbon than either forests or the atmosphere. So deforestation or forestation *alone* can play only a minor role decreasing carbon dioxide levels in the atmosphere. The extensive burning of rainforests does emit substantial amounts of methane and methane-enhancing carbon monoxide, so reversing policies that encourage such burning should be a high priority. Other opportunities for mitigating the risk of, or adapting to, climate change are discussed below.

### Mitigating climatic risks

The climate system is resilient but this resilience is at growing risk of being overwhelmed if steps are not taken to reduce global accumulations of greenhouse gases. One risk is the possibility of abrupt and turbulent transitions, the final outcomes of which are unpredictable and adaptations to which are seriously constrained. The best strategy would be to reduce the risk of turbulent change by more aggressively pursuing mitigation measures.

#### Industry and energy

Industrial policy responses can particularly help reduce emissions of carbon dioxide and chlorofluorocarbons (CFCs). And energy efficiency policies, including those for reducing CO emissions, may significantly reduce the atmosphere's methane content (Arrhenius 1986). Methane emissions through leakage are prominent in the transport and mining of fossil fuels and the generation and distribution of natural gas (Abrahamson 1989). Fortunately, most leaks can be remedied by adopting improved leakproof natural gas handling systems and technologies.

The anaerobic breakdown of organic material in urban sewage, landfill, and agricultural waste also emits a great deal of methane. The controlled burning of such methane — preferably in association with energy production — would shift the net mix of greenhouse gases away from more absorptive methane toward less absorptive carbon dioxide, while increasing the total supply of energy.

Economic sensitivity analyses and uncertainty studies with global models confirm that end-use energy efficiency is the single most important technological factor determining future carbon dioxide and carbon monoxide emissions (Keepin and Kats 1988, Goldemberg and others 1988). And considerable emissions reductions are possible outside the energy industry. For example, 17 percent of global carbon emissions are associated with energy production to heat, cool, and light buildings. New houses often require as little as 25 percent or less of the energy of earlier designs, and it costs no more to build energy-efficient office buildings than inefficient ones (Rosenfeld and Hafemeister 1988). Recent advances in industrial process control technologies and drive systems, as well as in consumer appliances, offer dramatic opportunities to reduce energy demand and thus emissions of CO and $CO_2$.

#### Reducing carbon dioxide emissions

The main source of carbon dioxide emissions is the energy sector. Industry (including agriculture) accounts for the largest share of energy use in highly industrialized countries — nearly 43 percent of the energy consumed in the OECD in primary energy equivalent terms in 1985 (Farrell 1987), and nearly 60 percent of total commercial energy production in other countries generally.

The four basic industrial policy response options for reducing $CO_2$ and CO emissions in any economic sector are:

- Energy efficiency and conservation.
- Alternative energy sources.
- Changes in production processes.
- Emission control.

An integrated systems approach to energy policy across all sectors, consistent with sustainable development and the likelihood of climate change, needs to be elaborated. Such an energy strategy must stress increased energy efficiency, synergy among different greenhouse gas emissions (sources and sinks), reduced use of fossil fuels, and the use — where advisable for development — of alternative energy sources such as cogeneration, advanced biomass, and solar, wind, hydroelectric, and possibly nuclear power. Renewable energy technologies such as photovoltaics and hydrogen-based energy, now cost-effective only in limited applications, are rapidly improving in efficiency. Their technical attractiveness in particular applications, such as long-range energy transport and storage, should improve their market potential in industrialized countries, which could stimulate their earlier adaptation by developing countries.

Many developing countries are now beginning a period of rapid expansion in energy- and materials-intensive industries, as they strive to raise their living standards. The industries of many of these countries are far less energy-efficient than those in developed countries. To a certain extent, this energy differential is the result of government subsidies, inappropriate technologies, and poor management skills. Reforms in energy pricing can reduce costs by reducing energy use and can also reduce environmental damage.

A recent study demonstrated that a $10 billion investment in cost-efficient improvements in electricity end use could reduce expected demand for new generating capacity by 22 gigawatts. The capital cost for installing 22 GW of additional capacity would be about $40 billion (Keepin and Kats 1988, Geller 1986, Geller and others 1988, Goldemberg and others 1988).

A related study of energy conservation options in Brazil showed that relatively low electricity tariffs — particularly for industrial customers — were a strong disincentive to investments in conservation. Brazil assembled more efficient air conditioners for export than it produced for sale at home. A 300 percent trade tariff on imported rotary compressors used in the air conditioners effectively inhibited their sale and use within Brazil (Geller and others 1988).

Changes in manufacturing industry process control technologies can measurably reduce $CO_2$ emissions. In the cement industry, for example, where world production has been increasing at an average annual rate of about 6 percent since the 1950s, a variety of cement manufacturing alternatives exist, some of which release more $CO_2$ than others (Goldemberg and others 1988). Carbon dioxide is emitted in the calcining phase of cement-making, when calcium carbonate ($CaCO_3$) is converted to lime (CaO). For every ton of cement produced, 0.14 tons of carbon are emitted as $CO_2$ from this reaction. Generally, even more $CO_2$ is emitted from the fuel used to drive the process.

The energy requirements for cement-making vary from a low of 4 gigajoules per ton in Sweden and Japan to 7 gigajoules per ton in the United States. Energy is used to heat the kiln and grind the raw materials and clinker. Energy requirements vary for dry and wet methods of production. The wet method is more costly as water is added and must be evaporated afterwards, which requires more energy per ton produced. Other technologies — such as suspension preheaters, flash calcining, cold processing, or using less energy-intensive cement than Portland cement — can all reduce the energy costs of cement production 10 to 15 percent (Goldemberg and others 1988).

$CO_2$ emissions are thought to be largely irreversible. The U.S. Electric Power Research Institute (EPRI) estimates that deep ocean burial of $CO_2$ emissions would cost about $426 billion — to eliminate only 30-35 percent of U.S. emissions. So it appears doubtful that, even if proven technically feasible, such technologies would be economical.

Other policy options for reducing carbon dioxide include such emission control interventions as carbon fuel taxes and tightening automobile fuel efficiency standards.

### *Reducing chlorofluorocarbon emissions*

The Montreal Protocol for the Protection of the Ozone Layer, which went into effect on January 1, 1989, calls for staged reductions in consumption, production, and trade in CFCs. Its effectiveness will depend upon the level of participation and compliance. Despite any drop in emissions resulting from implementation of the protocol, the greenhouse effects of CFCs may be expected to linger because of CFC survival rates of 65 to 110 years in the lower atmosphere (Bach 1988). Compliance standards for developing countries, based on per capita measures, are more lenient than for other countries. Replacement technologies either exist or can be developed for most CFC applications, albeit at some cost — and it will take some time. In the meantime, countries can agree not to export inefficient and obsolete CFC-leaking technologies to other countries.

The issue of chlorofluorocarbon emissions and ozone depletion is closely related to the greenhouse issue, but is different in important ways. Mechanisms to mitigate ozone depletion include producing CFCs with shorter lifespans, thereby preventing them from ever reaching the ozone layer. The greenhouse effect of these more short-lived CFCs is still substantial, however, and in the short term (10-20 years) is almost equal to that of present CFCs. Thus, the introduction of these short-lived CFCs would resolve the ozone depletion issue, while the greenhouse effect of CFCs would remain the same. Thereby, one of the cheapest instruments for reducing the risk from climate change is lost.

## Agriculture and rural development

The proportionate size of the various compartments of the carbon cycle have important implications for greenhouse warming in the agricultural sector. The amount of carbon in the atmosphere is roughly comparable to the amount in the biosphere, and the amount in soils is half again (1.5 times) as much as either. By contrast, 15 times as much carbon as is found in the atmosphere is stored in the ground as fossilized carbon and peat, and an overwhelming 75 times as much carbon is stored in the oceans.

Reversing the trend toward deforestation could be a cost-effective means of reducing net carbon dioxide emissions in many countries. Policy attention should be given to shifting cultivation, the use of fuelwood, and land use property rights. The destruction of tropical rainforests to develop agriculture and livestock releases large amounts of carbon monoxide, carbon dioxide, and methane — thus amplifying the impact of deforestation by enhancing atmospheric concentrations of methane. But most greenhouse gases are produced by the highly industrialized sectors. The practical potential for modifying the greenhouse effect through deforestation or reforestation is ultimately limited and should be kept in proper perspective.

Reforestation attempts, however, must compete against other demands for land use within the biosphere and must allow for the fact that to remain effective over the long term, the carbon must somehow be sequestered and the process renewed as the trees mature. Efforts to reduce emissions and increase sinks for carbon would be improved if agricultural techniques could be developed to exploit soil's inherent capacity to store carbon by gradually increasing its organic components. Such opportunities are likely to be greatest in the developing world, where much of the land has already been seriously degraded. They would not compete with the efficient productive use of land.

Methane emissions from ruminating livestock could be reduced by an estimated 25 to 75 percent (Gibbs and Lewis 1989). Methane production from ruminants is probably caused by inappropriate cattle breeding and feeding and by unsuitable environments in stables in intensive animal husbandry. The potential range for converting carbon intake to methane in animal husbandry is large, because output (milk, carcasses, and manure) represents only 10 to 25 percent of the input (feed) in energy content. The livestock industry has not begun reducing methane emissions from animal husbandry (Arrhenius 1986). It is technically feasible, but livestock produce only 15 percent of all methane and contribute only 3 percent of the greenhouse effect.

## Adjusting to climatic risk

### Industry and energy

The risks of climatic change are so imprecisely described that it is neither possible nor desirable to invest now in specific local and regional projects anticipating climatic transformation. But the increasing likelihood of climatic changes suggests the prudence of considering the economic and financial feasibility of building more resilience into the planning and design of industrial and energy infrastructure. The least probable scenario is "no climate change." It may pay to scale down or delay large or long-lived projects — buying time with smaller, shorter-lived ones — to observe what actually happens climatically in particular regions and countries.

### Infrastructure and urban development

If ocean levels were to rise because of thermal expansion, rising seas would inundate coastal areas and could decimate large areas of coastal wetland. The economic threat to coastal wetlands alone could be hundreds of billions of U. S. dollars.

In the years ahead, the costs of shoreline protection may rise and the relative effectiveness of alternative measures could change. A one-foot rise in sea level would erode most shorelines more than 100 feet, by some estimates. What this means for coastal, especially delta, communities hardly needs elaboration. Proposals for building or expanding ports, coastal cities, housing, or coastal developments or engaging in coastal agricultural activities — any of which could seriously affect economic development because of their multiplier effects on employment and incomes — should be reconsidered. Smaller, more flexibly designed projects with shorter lifetimes are strategically advantageous for planning such projects as dams, irrigation, and ports.

With changes in precipitation, water supplies for irrigation, dams, and sewage systems might all be threatened. With climate change, the recharging of groundwater reserves could obviously be a serious problem that should be kept in mind in defining the scale of infrastructure projects that involve water resources, such as dams, irrigation, and sewage facilities.

#### Agricultural and rural development

In agriculture, the uniformity of plant gene pools and the mechanized synchronization of plant growth and development have made crops more vulnerable to large-scale shifts in weather systems (Rosenberg 1987, Rosenberg and others 1989). Climate change itself may threaten the survival of the natural (wild) gene pool, so we must systematically ensure that an adequate gene pool survives and is sustained. Climatic change also makes crops and livestock vulnerable to extreme weather events such as floods, drought, pests, disease, and soil erosion.

In past long-term temperature changes, forest boundaries have shifted as fast as 1 kilometer a year. Computer-simulated projections of greenhouse-related global increases in surface temperature for the next century suggest faster changes than paleoclimatic records indicate as having occurred before the industrial era. These projections imply that suitable growing areas for forests and agricultural products could shift at an unprecedented pace. This would disrupt mainly forests and unmanaged ecosystems. It is not too early to begin thinking about how such processes might affect investments in agriculture and forestry.

#### Population and human resources

As the risk of hydrological and temperature change increases, so does the potential for worrisome shifts in vector diseases that threaten animal and human populations. Patterns in nutrition, famine, morbidity, mortality, and migration could also change. Investment planning should address such risks.

### The key: energy efficiency

The right energy policies in the next few decades could substantially mitigate global warming through greenhouse gas emissions. Energy efficiency, particularly in end uses, appears to be essential for coping with climatic change. And energy conservation makes good economic *and* environmental sense.

Uncertainties prevent us from knowing how a given level of emissions will affect the rate and magnitude of climate change. And uncertainties about the impact of greenhouse gas buildup are pervasive. But the uncertainties are not about whether the greenhouse effect is real or could raise global temperatures, but about the magnitude and timing of warming regionally and the prospects for cooperatively resolving the results globally.

We can guess about when various levels of warming will occur based on choices we might make now and later. Delaying policy moves toward energy efficiency would substantially increase the global potential for future warming. Fortunately, technical options are available that — if necessary and given sufficient political and economic will — could stabilize greenhouse gas emissions.

Most countries could significantly improve their production efficiency in greenhouse-gas-emitting industries. Such steps would be economically worthwhile even if climatic change were not a risk. But atmospheric emissions could escalate in many countries, so it is crucial for all countries to help stabilize the level of greenhouse gases.

The sooner the international community becomes committed to increasing energy efficiency in all sectors of the global economy — especially end-use energy efficiency — the more time we will have to cushion the inevitable adjustments that may ultimately have to be made by the most vulnerable economic sectors and geographic regions of the world.