CANMET

Canada Centre for Mineral and Energy Technology

Centre canadien de la technologie des minéraux et de l'énergie

Energy Research Laboratories

Laboratoires de recherche sur l'énergie

ENERGY AND GLOBAL WARMING

energy.
pollution.
fuels.
emissions.

ERL 92-054 (TR)

01-000462-0

Energy, Mines and Resources Canada

Énergie, Mines et Ressources Canada

Canada

THE ENERGY OF OUR RESOURCES • THE POWER OF OUR IDEAS

L'ÉNERGIE DE NOS RESSOURCES • NOTRE FORCE CRÉATRICE

ENERGY AND GLOBAL WARMING

by
G.K. Lee and F.D. Friedrich

July 1992

CANMET
Energy Research Laboratories
Division Report ERL 92-54 (TR)

ABSTRACT

The greenhouse effect is a natural phenomenon essential to life on earth. Global warming may result if the natural balance is upset by greenhouse gases emitted from human activities. The most important of these gases is carbon dioxide (CO_2) from the combustion of fossil fuels. Although atmospheric concentrations of greenhouse gases have been increasing since the beginning of the industrial revolution, evidence of global warming is inconclusive. Global circulation models of the earth's climate predict higher temperatures as CO_2 concentrations increase but their results have not been verified by measurable trends. Concern remains because if global warming occurs it could cause disastrous changes in climate.

The nature of the various greenhouse gases, where they originate and what becomes of them are reviewed. CO_2 from coal is emphasized because it is the world's most abundant fuel and is likely to be used increasingly in the foreseeable future. Strategies for reducing CO_2 emissions include technology for generating heat and electricity more efficiently, switching to low-carbon or carbon-free fuels, and reducing energy requirements through conservation. The capture, disposal and use of CO_2 are also discussed. New technologies are described which offer potential for producing energy from coal and other carbon-based fuels with reduced emissions of CO_2. Some are commercially available whereas others still require research and development.

The inconclusive evidence for global warming, the world's heavy dependence on fossil fuels, and the global nature of the problem deem it unlikely that worldwide CO_2 emissions can be reduced or even maintained at their present levels. Major developing nations such as China and India, which must increase energy production to meet the needs of their people, have few alternatives to indigenous coal. Even modest increases in either their population or their per capita energy consumption will result in massive CO_2 emissions. However, the rate of increase can be mitigated if all new energy production facilities employ the most efficient, cost effective and ecologically sustainable technology available. Canada can play a leadership role by contributing its expertise in all forms of thermal energy technology, energy conservation, and research and development. Maximum benefit will be achieved if the developing nations immediately implement our best proven technology to satisfy their escalating energy demand. More advanced, developing technology should be transferred only when its reliability is fully established.

RÉSUMÉ

L'effet de serre est un phénomène naturel indispensable à la vie sur la Terre. Il peut se produire un réchauffement à l'échelle de la planète si les gaz à effet de serre produits par l'activité humaine viennent rompre l'équilibre naturel. Le plus important de ces gaz est le dioxyde de carbone (CO_2) qui provient de l'utilisation des combustibles fossiles. S'il est vrai que la concentration des gaz à effet de serre dans l'atmosphère a augmenté depuis le début de la révolution industrielle, les données concernant un éventuel réchauffement planétaire ne sont pas concluantes. Les modèles de circulation atmosphérique globale prévoient que les températures s'élèveront si la concentration de CO_2 augmente, mais leurs résultats n'ont pas été vérifiés par des tendances mesurables. La préoccupation demeure, toutefois, car un réchauffement planétaire entraînerait des changements climatiques désastreux.

Ce rapport examine la composition des différents gaz à effet de serre, leur origine et leur transformation. L'accent est mis sur le CO_2 provenant du charbon, car c'est le combustible le plus abondant dans le monde et que sa consommation va probablement augmenter dans un avenir prévisible. Les stratégies de réduction des émissions de CO_2 comprennent notamment le recours à des technologies permettant de produire de la chaleur det de l'électricité de manière plus efficiente, l'utilisaton de combustibles à faible teneur en carbone ou sans carbone, et la réduction de la demande par les économies d'énergie. Il est aussi queston du captage, de l'élimination et de l'utilisation du CO_2. Le rapport décrit en outre de nouvelles technologies qui permettent de produire de l'énergie à partir du charbon et d'autres combustibles à base de carbone tout en réduisant les émissions de CO_2. Certaines de ces technologies sont déjà commercialisées, tandis que d'autres en sont encore au stade de la recherche-développement.

Le manque de données concluantes au sujet du réchauffement planétaire, la forte dépendance du monde à l'égard des combustibles fossiles et l'ampleur mondiale du problème nous permettent de douter qu'il soit possible de réduire les émissions de CO_2 ou même de les stabiliser à leurs niveaux actuels. Pour des pays en voie de développement importants, comme la Chine ou l'Inde, qui doivent augmenter leur production énergétique afin de satisfaire les besoins de leur population, il y a peu de solutions en dehors du charbon local. Un accroissement même minime de leur population ou de leur consommation d'énergie par habitant aura pour résultat une production massive d'émissions de CO_2. Toutefois, cette augmentation peut être ralentie si toutes les nouvelles installations énergétiques emploient les technologies les plus efficients, les plus économiques et les meilleures sur le plan du développement durable. Le Canada peut jouer un rôle de leader en fournissant son expertise en techniques de production d'énergie thermique, en économies d'énergie et en recherche-développement. On obtiendrait un maximum de résultats si les pays en voie de développement mettaient en oeuvre dès maintenant nos meilleures technologies, celles qui ont fait leur preuve, pour répondre à une demande sans cesse croissante. Les technologies plus sophistiquées ne doivent être transférées qu'une fois leur fiabilité pleinement démontrée.

CONTENTS

TABLES

No.

FIGURES

WHAT IS THE GREENHOUSE EFFECT?

The earth's climate is a vast, complex energy transfer system. Its primary energy source is short-wave radiation from the sun, which reaches the earth's atmosphere at a global annual rate of 340 watts per square metre (W/m^2). Some of this is reflected by and some is absorbed by the atmosphere, and some passes through the atmosphere to be absorbed by the earth. The earth in turn gives off heat to the atmosphere and to space by long-wave radiation, by the upward movement of warm air, and by the latent heat in evaporated water which forms clouds. These energy flows are shown in Fig. 1.

Fortunately, certain gases in the atmosphere, the "greenhouse gases", are capable of absorbing long-wave radiation. They capture most of the radiant energy leaving the earth and re-radiate a large part of it back to the earth. This is called the greenhouse effect. If these gases were not present, the average temperature of the earth's surface would be about -20°C not the +15°C we now experience. The greenhouse effect is a natural phenomenon essential to life on this planet. Over the eons it has managed to maintain the surface of the earth within the narrow band of temperature necessary for life, although not always at the present distribution of temperature and climate.

Only a few of the gases which occur in nature are capable of absorbing infrared or long-wave radiation. The most abundant is water vapour (H_2O). Others are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). These gases vary in abundance, in their relative ability to absorb infrared radiation or retain heat, and in their decay time in the atmosphere.

The earth's climate responds in complex ways to many factors. Some effects, called negative feedbacks, tend to stabilize it. Others, called positive feedbacks, tend to accelerate a change in one direction or another. Some effects are easy to predict; for example, the dust and sulphur dioxide from volcanic eruptions have a cooling effect because they block solar radiation. The effects of other factors are less clear. For example, what are the net interactions between temperature and water? Does the increased evaporation resulting from an increase in temperature lead to more cloud cover, reducing the solar energy reaching the earth and therefore tending to stabilize the temperature? Or does it melt some of the reflective snow and ice cover, thereby increasing the solar energy absorbed and amplifying the temperature increase?

What has recently become a source of grave concern is evidence that the balance of the greenhouse effect may be irretrievably altered by human activity and irreversible global warming may occur.

GREENHOUSE GASES AND GLOBAL WARMING

One might expect temperatures at the surface of the earth to rise if greenhouse gases in the atmosphere increased. This is supported by studies of drill cores from the Antarctic icecap. They provide a climatic history of the area going back 160,000 years. Concentrations of CO_2 and CH_4 were measured in bubbles of air trapped when the ice was formed, and temperatures at that time were estimated from features of the plant species found in the ice. As Fig. 2 shows, the correlation of temperature with greenhouse gas concentration is remarkable. But which is cause and which is effect and are there other critical factors which may be more important or are being overlooked?

We also know that the atmospheric concentration of most greenhouse gases has been rising since the beginning of the industrial revolution. Fig. 3 shows that CO_2 has increased by 25% and CH_4 concentration has doubled. This undoubtedly is the result of human activity; CO_2 is the major product of the combustion of fossil fuels whereas CH_4, the main component of natural gas, escapes in significant quantities from fossil fuel production operations such as coal mining, oil and gas wells, and natural gas distribution systems. Other uncontrolled sources of CH_4 are sanitary landfills and backyard composters, where it is formed by decomposed garbage.

Human activity is entirely responsible for the presence of another important family of greenhouse gases, chlorofluorocarbons. These are the notorious chlorofluorohydrocarbons (CFCs) which are used as refrigerants and propellants in aerosol cans. They do not occur in nature. Although their concentration in the atmosphere is still only about one part per billion their greenhouse potential is enormous because they are very stable (estimated decay time 110 years) and, per molecule, they can absorb and re-radiate 14 900 to 17 700 times more infrared radiation than CO_2. However, if concentrations of CFC's diminish as a result of the Montreal Protocol, CO_2 will remain as the most important greenhouse gas because its abundance and long decay time offset its lower greenhouse effect. In the absence of CFCs, CO_2 may become responsible for as much as 75% of the greenhouse effect.

The issue of global warming is this: since atmospheric concentrations of greenhouse gases are clearly rising due to human activity, it is reasonable to expect a corresponding rise in the mean temperature of the earth's surface, and the consequences of that may be disastrous.

Climatologists have predicted the global mean temperature rise that could occur if atmospheric CO_2 levels increase to a value twice that of pre-industrial times. The numbers vary from 1.9 to 5.2°C. The mid-range of these predictions would anticipate temperature rises of about 0.3 °C per decade, throughout the next century, with corresponding rises in sea level of 6 cm per decade. The rise in sea level would be caused by some melting of icecaps but mainly by thermal expansion of the oceans. The expected results include flooding of coastal cities such as that shown in Fig. 4, increased evaporation leading to drought in inland areas, and more widespread and more violent storms.

Evidence already exists that temperatures are rising. The available temperature data since 1861 indicate a rise of about 0.5°C over the past century. However, it is impossible to ascertain whether this is due to increased emissions of greenhouse gases, our imperfect understanding of long term carbon flows, cyclical solar activity, or simply a natural fluctuation such as the earth has often experienced. Remember that the Vikings were farming in southwestern Greenland about 1000 years ago during what climatologists call the early medieval warm phase. Furthermore, some of the temperature data are suspect; urban development and volcanic activity in the vicinity of weather stations tend to raise local temperatures.

The global climate is not amenable to experiments that would clearly establish the effects of increasing greenhouse gas concentrations. Conversely, it could be disastrous to wait 50 to 100 years to see what happens, so climatologists have developed mathematical models, or computer simulations of the earth's climate, and these are used to make predictions. While many assumptions and simplifications are necessary, great advances have been made over the past 20 years in the development of global circulation models or GCM's, which represent the best diagnostic tool available to us.

Climate models developed in Canada, the USA and the UK predict similar trends if CO_2 in the atmosphere is doubled from the pre-industrial concentration of about 280 parts per million by volume (ppm). They indicate that temperatures will rise and that the greatest changes will occur in high latitudes in winter. The predictions vary considerably in the degree of warming. For the Canadian arctic in winter, one model predicts that if CO_2 concentrations double, the mean temperatures will be higher by 12 to 14°C, but another predicts a rise of only 2 to 4°C. Predictions for southern Canada in summer range from little change to increases of 8°C. For the drought sensitive southern prairies, predictions of soil moisture range from a slight decrease to a slight increase, with probably greater variations year to year than we now experience. The predicted northward migration and decline of Canada's boreal forest with a doubling of CO_2 concentrations is shown in Fig. 5.

Some authorities view the similar trends in climate model predictions as proof of their validity. Others are more sceptical and argue that we are a long way from knowing enough about meteorology to prepare reliable models. The sensitivity to minor changes in assumptions is exemplified by the model of the UK Meterological Office. When it assumes that clouds are composed entirely of water and have fixed radiative properties, it predicts a mean temperature rise of 5.2°C for a doubling of atmospheric CO_2 concentrations. When it assumes that clouds consist of water and ice, in proportions calculated according to temperature, and that radiative properties are still fixed, the predicted mean temperature rise is 3.2°C. When it assumes that radiative properties of clouds vary according to the proportions of water and ice, then the mean temperature rise associated with a doubling of CO_2 concentration drops to 1.9°C.

It has also been pointed out that if a doubling of CO_2 concentration brings a mean temperature rise of 2 to 4°C, we should have experienced some of that already. The pre-industrial CO_2 concentration was about 280 ppm. It is now about 350 ppm and other, more potent, greenhouse gases have also increased, bringing the effective CO_2 concentration to about 420 ppm. This is halfway to a doubling of the pre-industrial level and, according to the models, should have brought about a temperature rise of at least 1 to 2°C, but available data indicate a rise of only 0.5°C in the last 100 years. Furthermore, most of this warming occurred prior to 1945, when CO_2 concentrations were much lower than now, and the warming has been most evident in the southern hemisphere, where it should have been delayed by the thermal inertia of the oceans. Also, there has been no evidence of the predicted increases in Arctic or Antarctic winter temperatures.

These models are powerful predictive tools, but it is important to note that they provide general indications of possible trends rather than infallible forecasts of definitive climatic changes. Their questionable reliability, however, is not a cause for complacency. Clearly human activity is substantially increasing the atmospheric concentrations of greenhouse gases and it is entirely reasonable to expect climatic and associated ecological changes as a result. We cannot accurately predict the nature, severity and extent of such changes. The less we know, the more careful we must be. However, it is important that technological and regulatory remedies are consistent with the costs of implementation and the probability of success.

SOURCES AND SINKS

The global warming potential (GWP) of the greenhouse gases emitted in 1990 is shown in Fig. 6. It considers their concentrations, decay times in the atmosphere and their heat retention capacity relative to CO_2 as shown in Table 1. It should be noted that the fairly good correlation between annual rises in average global temperatures with CO_2 does not necessarily provide a reliable prediction of future events and is at best circumstantial. Other major climatic factors such as changes in cloud cover may exert more influence on global warming than the greenhouse gases.

CARBON DIOXIDE

Fig. 7 shows the cumulative CO_2 emissions caused by human activity from 1800 to 1987. More than 50% of these emissions came from land use changes, most of which were in the southern hemisphere. The remainder were energy related with coal, oil, natural gas and mineral processing contributing about 28%, 14%, 5% and 1.4%, respectively.

The role of human activities in the buildup of atmospheric carbon is shown by the simplified global carbon cycle in Fig. 8. The quantities are those for 1978. The atmospheric exchange of carbon by natural processes accounts for almost 97% of the total flows. These major sources and sinks are essentially in balance with 120 gigatonnes per year (Gt/a) of carbon being recycled through photosynthesis and 100 GT/a of carbon being exchanged with the aqueous environment. The annual CO_2 increase in the atmospheric reservoir, measured at 3 Gt/a of carbon has its origins in 5 Gt/a of carbon from fossil fuel combustion and 2 Gt/a of carbon from the destruction of forests and soil by human activities. The difference between the 7 Gt/a of carbon emitted and the 3 Gt/a of carbon measured in the atmosphere indicates the presence of unaccounted-for carbon sinks or errors in the estimated flows. Atmospheric decay times of $C0_2$ vary from 7 to 250 years depending on the carbon transformation involved, with 100 years cited as an average.

The massive amount of carbon in the deep ocean and the lithosphere occurs primarily as carbonate compounds whereas the relatively small proportion of organic carbon in sediments occurs as fossil fuel.

METHANE

The global methane burden from both natural and human emissions is estimated to total between 360 and 780 Gt/a with roughly 40% being from natural sources, primarily wetlands. Cattle, rice growing, and biomass burning account for 60% of the human component with the remaining 40% being generated by landfills, natural gas leakage and coal mining at about 20%, 15% and 5%, respectively.

Methane eventually changes to CO_2 by reacting with hydroxyls in the air. However, carbon monoxide (CO) emissions, generated primarily from transportation sources, can react preferentially with hydroxyls thereby delaying conversion of CH_4 to CO_2. The net effect would be to enhance the global warming potential of CH_4 by extending its decay time from 10 to possibly 20 years.

NITROUS OXIDE

Global nitrous oxide emissions are estimated at 10 to 34 megatonnes per year (Mt/a). About 33% of this amount is due to human activities with fossil fuel combustion, biomass burning and agriculture being equal contributors. The remaining 67% is from natural aqueous and soil emissions. The long decay time and high heat retention properties of N_2O make it an effective greenhouse contributor despite its low atmospheric concentration.

CHLOROFLUOROCARBONS

Atmospheric CFCs all originate from human activities. The current levels are about 1.0 parts per billion (ppb) and their rate of growth in the atmosphere has been measured at 5-6%/a. This rapid growth is expected to decline steadily as the manufacture and use of CFCs are phased out by signatories to the Montreal Protocol, assuming that the developing countries do not increase their use of CFCs in response to industrial and social pressures. The use of substitute or "soft" CFCs is a step in the right direction, but even these will exert a noticeable effect on global warming potential.

OZONE

Ozone in the lower atmosphere or troposphere is produced by the oxidation of methane and CO and by the migration of O_3 from the upper atmosphere or stratosphere. Tropospheric O_3 acts as a greenhouse gas even though levels only range from 0.01 to 0.1 ppm and decay times are only a few days. Conversely, stratospheric O_3 levels are ten times higher but serve as a shield against solar ultra-violet radiation rather than as a contributor to global warming.

The anticipated phase-out of CFCs by the industrialized countries leaves CO_2 and CH_4 as the major greenhouse gases that will continue to be released by human activities. CO_2 is by far the more dominant of the two because of its long atmospheric life and the inevitable increase in fossil fuel use over the next 35 years.

WORLD CARBON EMISSIONS

In 1989 fossil fuels produced 5.9 Gt of carbon emissions with coal and oil each responsible for 40%, natural gas 15% and industrial processes 5%. These global emissions have increased dramatically; about 400% from 1.6 Gt of carbon per annum in 1950. There are wide regional variations depending on the extent of industrialization, population, urbanization, fossil fuel consumption and availability, and energy demand. Dividing the world into three economic regions - industrialized countries, former centrally planned economies (FCPE - formerly the USSR and eastern Europe), and developing countries, makes large shifts in the pattern of carbon usage evident. Between 1950 and 1987, the industrialized countries' proportion of carbon emissions decreased from about 74 to 44% whereas the FCPE and the developing countries increased from 18 to 26% and 8 to 30%, respectively. Fossil fuel use accelerated in the FCPE due to highly energy intensive industries and inefficient energy use, and in rapidly developing countries such as India and China due to increased industrialization and electrification. Efficiency of energy production and utilization in the industrially mature countries of the Organization for Economic and Co-operative Development (OECD) have improved significantly. However, this may be due in part to a migration of energy intensive manufacturing industries to developing countries and their replacement by low energy, high technology goods and services.

Figure 9 shows the emissions of carbon per capita in 1988 for several nations. The industrialized countries, led by the USA at 5.4 t carbon per capita, and the FCPE countries led by Czechoslovakia at 4.0 t carbon per capita, continue to rely heavily on fossil fuels. The world average for carbon emissions is much lower; 1.2 t carbon per capita. By comparison, highly populated countries such as China at 0.5 t carbon per capita and India at 0.2 t carbon per capita, emit considerably less than the world average. This disparity has serious future ramifications because the world population, currently at 5.3 billion, is growing at 1.7%/a. By 2025 over 70% of this population increase will occur in the developing countries with the populations of China and India each reaching 1.15 billion. Most of the future energy needs of the developing countries will likely be generated by, or derived from indigenous coal reserves. As they grow in population and industrial strength their CO_2 emissions will increase sharply. When that is added to the slower rates of increase in the industrialized countries, the net result is an increase in carbon emissions of about 3%/a, leading to ambient atmospheric CO_2 levels of about 480 ppm by 2035. Clearly, population growth is a major factor affecting global emissions of greenhouse gases. Technical and economic solutions are available to reduce the rate of growth but are probably inadequate to stabilize or reverse it.

CANADIAN CARBON EMISSIONS

Canadian greenhouse gas emissions for 1987 are shown in Table 2. They were equivalent to 203 Mt of carbon and accounted for slightly more than 1.5% of the total global warming effect as determined by their GWP.

The CO_2 generated from burning 114 Mt of carbon in fossil fuels was directly responsible for 56% of this amount. At 4.4 t carbon per capita, Canada ranks second to the USA, as the world's most prolific per capita emitter of carbon from fossil fuel utilization.

The proportion of CO_2 emissions from the different fossil fuels used in Canada in 1988 was oil 44%, natural gas 28%, coal 26% and industrial processes 2%. On a market sector basis, electricity production, mostly from coal, generated 23% of these emissions and transportation, mostly from oil, accounted for 35%. The industrial, commercial and residential sector relied heavily on natural gas principally for space heating, process energy or chemical feedstocks.

The distribution of CO_2 emissions across Canada varies widely depending on socio-economic development associated with availability of natural resources, type of industrial activity, sources of electricity and degree of urbanization. As shown in Fig. 10, Alberta with less than 10% of Canada's population generated 2.5 times more carbon per capita than the Canadian average in 1985. Quebec, however, with 28% of the population emitted only 20% of Alberta's carbon per capita. Clearly workable strategies for the reduction, control or allocation of national CO_2 emissions are very complex. For example, should a province bear responsibility for the CO_2 emitted from a fossil fired generating station dedicated to producing electricity for export to another province or country? Quick, easy solutions are unlikely. To limit global CO_2 emissions to 1990 levels by 2005 is an ambitious goal that will require aggressive, concentrated international action on: collaborative research, technology transfer, monetary assistance, legal responsibility and judicial enforcement.

Fossil fuels will continue to be the cornerstone of Canada's and the world's energy supply well into the 21st century. The use of coal will increase steadily as reserves of oil and gas are depleted. However, promising options exist which may be available for the development of strategies and technologies to minimize Canada's CO_2 emissions over the next few decades.

CO_2 REDUCTION STRATEGIES

Greenhouse gas emissions from carbon-based fuels including coal, oil, gas, peat, wood and garbage can be substantially reduced, but not eliminated by implementing available technologies that involve a) generating and transmitting more useful energy per unit of fuel from stand alone electricity or heating systems, b) combining the production of heat and electricity in an integrated station, c) shifting to low-carbon or carbon-free energy sources, d) consuming less energy per unit of work or product and e) using biomass and organic wastes for fuel. Each of these is described below:

a) The generation and transmission of more useful energy per unit of fuel is accomplished through increased equipment and process efficiency. Examples are chimneyless gas furnaces that operate at seasonal efficiencies of 92% compared with 60% for conventional units, the generation of electricity from coal at 38% rather than 33% efficiency by using improved boiler and generator designs, and the reduction of heat and electricity losses by over 20% during transmission through better insulation.

b) By combining heat and electricity production, using a system known as cogeneration, substantial energy savings can be made. In a typical fossil fuelled power station only about 33% of the fuel energy ends up as electricity. The remaining 67% is lost; 52% of it is absorbed in the massive quantities of cooling air or water used to condense steam back to boiler water and 15% is vented up the stack with the flue gases containing CO_2.

If a conventional power station can be linked to a large, nearby heating or cooling load, over 80% of the fuel energy can be put to use. This reduces fuel consumption and corresponding CO_2 emissions by 45 to 54% compared with providing the electricity and heat from separate plants. Cogeneration is widely used in Europe and Asia for producing electricity together with energy for climate control in buildings and for supplying industrial processes such as oil refining and papermaking with refrigeration and heating needs.

c) Possibilities exist for replacing high carbon fuels with low carbon fuels or carbon-free energy sources but they are limited by the availability of supplies and conversion technology. Relative to coal, oil and natural gas produce 20% and 40% less carbon per unit of energy, for the same efficiency of conversion. That means less CO_2 would be emitted if all or part of the coal or oil that is now being burned for electricity generation was replaced with natural gas, or if electrical space heating generated from high carbon fossil fuels was replaced with on-site natural gas fired systems. Carbon-free energy sources include nuclear, tidal, solar, wind and geothermal heat. Hydrogen, although carbon-free, is not a fuel source; it is a manufactured product like electricity and is therefore accountable for any CO_2 associated with its processing, storage, delivery and use.

At present, Canada's primary energy mix comprises 76% fossil fuel; 9.5% nuclear, 10% hydro and 5.5% renewable. Specific to each of these is a range of economic, environmental and technical benefits and penalties associated with production, transmission and utilization.

d) Process and consumer applications that accomplish the same end result with reduced energy consumption can profoundly affect carbon emissions. A wide range of strategies, generically called energy conservation, have been highly successful in slowing the growth of energy consumption in the industrial countries, particularly since the oil crisis of 1973. Some of the more effective measures are improved home insulation and fenestration with reductions of over 67% in oil or gas consumption, switching to fluorescent from incandescent lights with up to 70% reduction in electricity use, and new steelmaking processes that have reduced the energy per tonne of product by 75%.

e) Combustion of biomass including firewood, vegetation waste, municipal garbage and burnable industrial refuse does not contribute to CO_2 emissions over the long term. Combustion merely speeds up the release of CO_2 that normally occurs while biomass decays to methane, which in turn changes to CO_2 after about 10 years. Moreover, the quantity of CO_2 released may be more than offset by the CO_2 absorbed by the rapid growth of young trees and new crops. Biomass energy plantations that obtain fuel from a cyclical harvest of rapidly growing trees, or crop wastes such as sugar cane residues, are therefore CO_2 neutral or better.

CO_2 CAPTURE, DISPOSAL AND USE

Several chemical processes have been proposed to remove CO_2 from flue gas, but to date they offer little encouragement. Recent studies indicate that an as yet unproven installation to remove 90% of the CO_2 from a conventional 500 megawatt electric (MWe) power station will increase plant capital costs by over 60%. If the CO_2 pipelining and disposal equipment are included the total capital cost more than doubles. Furthermore, the energy consumed in the removal, transport and disposal of CO_2 reduces the electrical output by almost 35%. To achieve the same net output, plant construction costs would increase by over 350% from 1130 to 3830 dollars per kilowatt ($/kW).

Another process strips hydrogen from the fossil fuel and uses it for direct combustion without any release of CO_2, or for production of low carbon liquid fuels such as methanol. The solid carbon residue can be used, stored for later recovery, or disposed of. However, if coal is the feedstock, only about 10% of its energy content is used. A CO_2 neutral option would be to coprocess biomass with coal using the hydrogen from both feedstocks and the carbon from the biomass to produce transportation grade alcohols. Costs of these hybrid high hydrogen fuels are not well-defined, but are likely to be high.

Disposal of CO_2 in depleted oil and gas wells, underground brine formations and the deep ocean have all been advocated as long-term storage options. Oil and gas wells are known to exist in gas tight rock structures, and would offer secure storage. However, the conversion of underground brines to stable carbonates is uncertain in view of the hydrochloric acid produced. Deep ocean burial should be viewed with extreme caution because the stability of CO_2 at depth and the possibility of large-scale upwellings with catastrophic releases of CO_2 are unpredictable.

The opportunities for using CO_2 from fuel combustion are limited because the available quantities are 1000 times greater than current demand. Nonetheless, economic uses of CO_2 merit consideration even if it is re-emitted to the atmosphere within a short time. Two large-scale applications which can use low purity CO_2 are injection into oil and natural gas reservoirs to enhance recovery, and a curing medium to obtain high strength concrete products such as blocks and pipes. Smaller scale applications include the use of high purity CO_2 for food preservation and the manufacture of polycarbonate plastics. Solid carbon can be used in road paving and construction materials.

As indicated previously, atmospheric CO_2 is effectively converted to biomass by photosynthesis. Afforestation and rapidly growing food crops serve as carbon sinks until the biomass is burned or decays. A 1000 km^2 forest would consume the CO_2 emitted from a 1000 MWe coal-burning power station. According to Environment Canada, the large expanse of boreal forests in Canada may serve as a carbon sink that sequesters more CO_2 than is produced nationally each year.

ADVANCED CLEAN COAL TECHNOLOGIES

WORLD COAL RESERVES

Coal, one of the world's most important energy sources, comprises more than 70% of the world's easily and economically recoverable fossil fuel reserves. But unlike oil and natural gas, coal reserves are widely distributed and coal prices are dictated by free market forces. For these reasons the global coal demand is forecast to increase by about 40% over the next 15 years, and most of the increase is expected to occur in countries with large indigenous deposits, primarily for electricity generation. Proven world reserves of coal, natural gas and oil are calculated to last 202, 58 and 41 years at 1988 rates of consumption. But these lifetimes will in all probability be shorter because of the forecast increases in annual consumption.

ELECTRICITY GENERATION

Advanced coal-to-electricity processes can result in CO_2 reductions of above 30% without impacting on output. Most of these advanced processes utilize elevated instead of atmospheric pressure to burn coal or coal-derived products. They can be further optimized by coupling the production of high quality energy for electricity and low quality energy for heating or process steam, resulting in CO_2 reductions of 55% or more for the same useful output as existing processes.

Two technologies that are prime candidates for commercialization by 2005 are now being demonstrated. The first, known as integrated gasification combined cycle or IGCC, converts the coal under high pressure and high temperature to a clean gaseous fuel which is burned in a gas turbine to produce electricity. The hot exhaust gases from the combustion process are then utilized to produce additional electricity in a conventional steam cycle. The second technology, pressurized fluidized bed combustion or PFBC, burns coal directly in a furnace that resembles a container of boiling liquid. This powers a form of combined cycle in which combustion gases at high pressure generate electricity by means of a gas turbine while those at low pressure generate electricity through a steam cycle.

A variant of these two processes called a topping cycle employs two PFBC's - one to convert part of the coal to fuel gas and the second to burn the remaining char. Electricity is generated by a gas turbine burning the fuel gas, and by a steam turbine which uses steam generated by the burning char and by extracting heat from the gas turbine exhaust gases.

Three longer-term technologies that are still in an early stage of development but show promise as CO_2 abatement options are pressurized flame combustion, fuel cells and magnetohydrodynamics (MHD). Unless driven by other than market forces, these technologies are unlikely to be demonstrated before 2015. In pressurized flame combustion, powdered coal is burned in much the same manner as in a liquid-fuelled rocket engine. Like the PFBC process, electricity is generated from both the hot combustion gases and steam produced as a byproduct while controlling combustion temperatures.

Fuel cells continuously convert fuel gas from coal to electricity by electrochemical reactions. Electrical conversion efficiencies of above 55% have been postulated. The difference between the chemical energy supplied and the electrical energy generated appears as low grade heat which must be constantly removed. The continuous supply of electricity from fuel cells distinguishes them from batteries which provide electricity for short periods from stored electrochemical energy.

MHD processes convert thermal energy directly to electricity by injecting ultra high temperature, high velocity gases from a coal-fired combustor with traces of an alkali through a channel containing a magnetic field. The hot exhaust gases are used to produce steam for additional electricity generation.

The above technologies can be combined with heating or cooling loads to achieve overall cycle efficiencies above 80%. By replacing all or part of the combustion air with oxygen, electrical output can be increased and CO_2 capture, if required, can be achieved more efficiently. However, separating oxygen from air is an expensive, energy intensive process.

CO-PRODUCTION OF ELECTRICITY, HEAT AND CHEMICALS

The aforementioned clean coal-to-energy processes could be coupled to chemical manufacturing plants to produce a wide range of products including transportation fuels, plastics and organic liquids. The synergism resulting from co-producing energy and carbon-based chemicals would result in the efficient and effective use of fossil fuels with significant CO_2 reductions. Operational flexibility may also be increased; when electricity demand drops, chemical production can be increased, thus allowing a maximum return on investment on the more expensive fuel conversion equipment.

However, accelerated implementation would require a change in current short-term business practices, the support of long-term government incentives and the demonstration of prototype technologies to encourage utilities and chemical producers to integrate their operations. Separate but nearby energy and chemical plants now exist in Denmark and have produced savings by steadily decreasing the energy requirements.

CANADIAN ELECTRICITY PERSPECTIVE

As the largest single consumer of coal in Canada, the electric utility industry consumed about 40 Mt of coal which accounted for 20% of Canada's CO_2 emissions in 1988. This CO_2 figure, which is forecast to increase to 28% by 2005, comprises less than 0.6% of the global CO_2 from human activities. According to the OECD, Canada's installed capacity to generate electricity from coal will increase by 23.3% from 17.6 to 21.7 gigawatts (GW) between 1989 and 2000. However, the installed capacity of other means of generation is expected to increase more rapidly, with the installed coal-fired capacity decreasing from 17.8 to 15.6% of the national total capacity. This indicates that coal-fired facilities will be used more intensively. Projections indicate a small but steadily increasing shift to the use of natural gas for electricity, either alone or in combination with coal until about 2005. But unless there is greater public acceptance of nuclear fission reactors and massive hydro developments, and unless new reserves of indigenous oil and natural gas are found, it is anticipated that coal will supply an increasing share of Canada's electricity needs at least until 2025.

As shown in Fig. 11, Canada along with Australia, China, the USA and the Confederation of Independent States (CIS) are endowed with most of the world's coal resources. Canada's readily accessible coal reserves, estimated at 6 Gt, correspond to a 150 year supply at 1990 rates of consumption. This far exceeds our conventional oil and natural gas reserves which could be largely depleted within 35 years. This suggests that longer term Canadian interests would be best served by developing and demonstrating more efficient, environmentally friendly processes to convert coal to electricity, and by conserving our higher quality fuels for applications where coal is less suitable.

The Canadian utility industry is currently unable to sponsor large-scale demonstrations of unproven, costly technologies because electricity rates are subject to public review. This poses a dilemma because governments are increasingly looking to utilities to implement research programs that address future industry and public needs. It is therefore imperative that energy strategies should provide leadership continuity, research stability and strength, clearly defined regulatory schedules and goals, adequate and targeted financial incentives, and a 5 to 10 year horizon for commercialization of high-risk projects. Abrupt and arbitrary shifts in energy and fiscal policy tend to undermine progress on projects before system reliability and operational costs can be demonstrated, to delay the timely application of an innovative technology and to discourage investment by private sector partnerships.

STRATEGIC ISSUES

Well reasoned strategies to mitigate the potential of global warming are impeded by three complex issues: the sparse evidence available, the world's dependence on carbon-based fuels and the truly global nature of the problem.

First, the evidence of climate change due to human activity is inconclusive, but by the time we know with certainty the situation may be irreversible. It was recently reported that emissions from the eruption of Mount Pinatubo in the Philippines are estimated to have a global cooling effect twice as powerful as all the carbon dioxide put into the atmosphere since the beginning of the industrial revolution. This is not necessarily good news. The cooling trend is expected to end in two to four years; in the meantime it is more difficult to establish whether the long-term trend is indeed one of global warming.

The second issue is the heavy dependence of our energy infrastructure on carbon-based, and more particularly, fossil fuels. Some authorities estimate that to stabilize our present climate, CO_2 emissions must be reduced by 50 to 80%. We must face the fact that this probably cannot be achieved, at least for many decades, the reasons for which are both practical and political.

While the fossil fuels vary in carbon intensity, with coal being the highest, even if there were sufficient resources of natural gas to fully displace coal and oil, and even if the technology were available for natural gas to fully displace oil in the enormous transportation sector, a 50% reduction of CO_2 emissions could not be achieved. Substantial CO_2 reductions can be achieved through conservation; a reduction in consumption equals a reduction in emissions. But here, too, there are limits. It takes energy to produce energy-conserving technology such as extra insulation or high-efficiency light fixtures. We don't know much about the break-even point of conservation. In the past, decisions have been based solely on a return on investment which includes the cost of generating energy but not of mitigating environmental impact..

What has just been said about energy conservation applies in large measure to more efficient means of energy generation and conversion. As explained previously, the generation of electricity from fossil fuels is often inefficient - about 33% by the conventional cycle which is now in widespread use. For coal, it could be increased to about 40% by employing integrated gasification combined cycle (IGCC) technology, which would mean a 20% reduction in CO_2 emissions for the same output in electricity. This is a significant gain, but still far from the estimated requirement of a 50% reduction or more. Furthermore, this more efficient technology has about double the capital cost, which reflects in part the additional energy required for its manufacture. Cogeneration, the combined production of heat and power, offers utilization of over 80% of the chemical energy in the fuel, but the capital costs of the systems for generating electricity and distributing heat are high.

Alternatives to energy from fossil fuels are numerous but problematic. Hydraulic power is limited in quantity and location. Its development often presents severe ecological disruption. Renewable fuels such as biomass and methanol also contain carbon and are not widely available at low cost. Solar and wind power are available in units of relatively small output and at a high cost which reflects, in part, a high energy component in their production. Nuclear power is well established for large blocks of electricity, but again at high capital and operating costs. Also, the health, security and financial risks associated with extended long-term storage of radioactive wastes could be an unacceptable burden for future generations.

A recent study indicates that for the same investment, the United States could avoid emitting 2 to 10 times more carbon through electricity savings than through an expanded nuclear program. It concludes that even a 600% increase in the current world electricity supply from nuclear plants by 2025 would have little effect on global CO_2 emissions, unless accompanied by large improvements in electricity end use. The conservation of energy through more efficient use of fossil fuels and electricity is by far the most cost-effective option for ameliorating the growth in carbon demand.

The foregoing considerations suggest that substantial reductions in CO_2 emissions from human activity can only be achieved if the world substantially reduces its consumption of energy. Unfortunately, political pressures oppose this direction. In the 10 year period beginning with 1980, world-wide energy consumption increased by 20%, with coal providing about 28% of the additional supply. In 1988 the delivered energy per head of population in Canada was about 15 times higher than in China and about 35 times higher than in India. This is not simply a reflection of lifestyle; it is also a reflection of the industrial development which supports our lifestyle and which the developing nations see as essential for meeting the needs of their people.

The two largest populations in the world, India and China, have large reserves of coal and depend heavily upon them. Consumption figures for power generation and industrial purposes are about 185 Mt/a for India and about 750 Mt/a for China. If these two countries increase their per capita energy demand and their population even by modest amounts, it will mean enormous increases in coal consumption and CO_2 emissions, but will still leave them far below Canadian standards. Conversely, the industrialized nations seem no more willing to reduce energy consumption or to reduce deforestation than the developing nations. At the recent Earth Summit in Rio de Janeiro about 150 countries agreed to seek the approval of their national governments for a Convention to limit CO_2 emissions to 1990 levels. About 10 countries including Canada, the United States and China have satisfied the Convention which requires 50 signatures before enactment.

The third issue impeding effective action to forestall global warming is the truly international nature of the problem. A local reduction does not effect a local improvement. Unless the nations of the world act in concert, those who do may achieve little beyond their own economic disadvantage. This contributed to the thwarting of a Canadian proposal at the Earth Summit to implement a legally binding schedule of national CO_2 emmissions by the year 2000. The reduction in CO_2 that would result if Canada achieves a stabilization at 1990 levels in all probability will not be detectable globally. In light of that, will future governments be willing to fulfil the commitment? Considering that the shutdown of Canada's entire fossil energy system would only achieve a 2% reduction in 1990 global CO_2 emissions, can we be anything more than ineffectual bystanders?

Indeed, Canada's leadership potential is great, but it must be focused outward, not inward. What we can accomplish internationally is far more important than what we can accomplish within our own borders. Our strengths lie in our practical expertise in all forms of thermal energy technology and climatology, coupled with strong research and development capabilities in both areas. Canada's most valuable contribution to mitigating global warming can be the application of its expertise to energy projects in the FCPE and developing nations.

With respect to coal, Canadian utilities generate electricity routinely and reliably from a wide range of coal ranks and qualities using efficient, available and proven technology. Canada boasts world-class research facilities for existing and advanced technologies such as pulverized coal firing, fluidized bed combustion, coal gasification and coprocessing. They encompass a long history of mitigating various forms of pollution at the source. Cogeneration and other forms of energy cascading have been commercialized by Canadian industry and Canadian products are exported to many countries.

As an example of how Canadian expertise could be put to maximum benefit, consider that China uses about 110 Mt/a of coal for power generation. Even doubling its coal-based electricity supply would only make a slight change in China's energy production per capita, but if the additional power was generated at the same efficiency as the existing system, about 25%, that would require an additional 110 Mt/a of coal. If Canadian expertise made it possible to generate the new power at 33% efficiency, a level typical for Canada, then only about 83 Mt/a of coal would be required. The improvement in efficiency would avoid the use of about 27 Mt/a of coal, equivalent to about two thirds of Canada's entire 1988 annual coal consumption for electricity.

The foregoing example involved only the application of good but very conventional technology. Much greater gains can be achieved through more efficient energy cascading, and through the application of innovative Canadian expertise in energy conservation. Another strategy would be to accelerate the commercialization of advanced renewable energy sources for use in remote and tropical areas where electricity is essential, albeit in small quantities. For example, modern solar or wind generators could replace small, inefficient, fossil-fuelled units.

A WORKABLE STRATEGY

To be effective, Canada's global warming strategy must be realistic. We must recognize that Canada and the world will depend heavily on carbon-based fuels for at least another generation, and therefore, CO_2 emissions probably will increase. However, many things can be done to reduce the rate of increase, and the quicker they are implemented the greater the benefit will be. We should continue to develop and implement more efficient proven methods of energy production, such as combined cycle and cogeneration. Likewise, we should practise a high degree of conservation in energy utilization. These are established techniques with known economic and ecological benefits. We should also forge ahead with research and development on emerging technologies such as fuel cells, solar and wind power, and on innovations in energy conservation. Finally, recognizing that global warming may indeed occur, we should maintain a strong research effort in climatology.

Canada now has economic, efficient, reliable and above all, proven energy technology applicable to the range of fossil fuels that are likely to supply most of the near-term increase in world energy demand. We can make our best contribution to reduce CO_2 emissions by making our expertise available to the developing nations. More advanced technology should follow as soon as its reliability and practicability are ensured. A strong research and technology capability in clean coal utilization, energy conservation and global modelling of climatic change will enhance Canada's opportunities for leadership in the effective use of the world's fossil and renewable energy resources.

TABLE 1 - GLOBAL WARMING POTENTIAL OF GASES RELATIVE TO CO_2*

GREENHOUSE GAS (GHG)	1990 CONCENTRATION PPM	RELATIVE HEAT RETENTION	DECAY TIME, Years
CO_2	353	1	120
CH_4	1.7	21	10
N_20	0.3	206	150
CFCs	0.0008	12400-15800	60-130
0_3	0.05	--	0.2 - 3

* Per molecule

TABLE 2 - 1987 CANADIAN GREENHOUSE GAS EMISSIONS

GHG*	Natural	Mt	Human	
CO_2	Combustion and decay	135	Combustion	409
			Agriculture	84
			Processing	6
				499
CH_4	Fires and wetlands	25.1	Landfill	1.9
			Farm Animals	1.2
			Energy & Other	0.7
				3.8
N_2O	Forests and grasses	< 1	Transport	45
			Fossil Fuels	10
			Wood Burning	10
			Fertilizer	44
			Acid Production	32
				141
CFC		0.0	Refrigeration	0.06
			Solvents	0.02
			Aerosols	0.02
			Products	0.07
				0.17
O_3	(Tropospheric)	0.0	VOC	10.5
			CO	10.5
			NO_x	1.9
				22.9

* GHG - Greenhouse gas

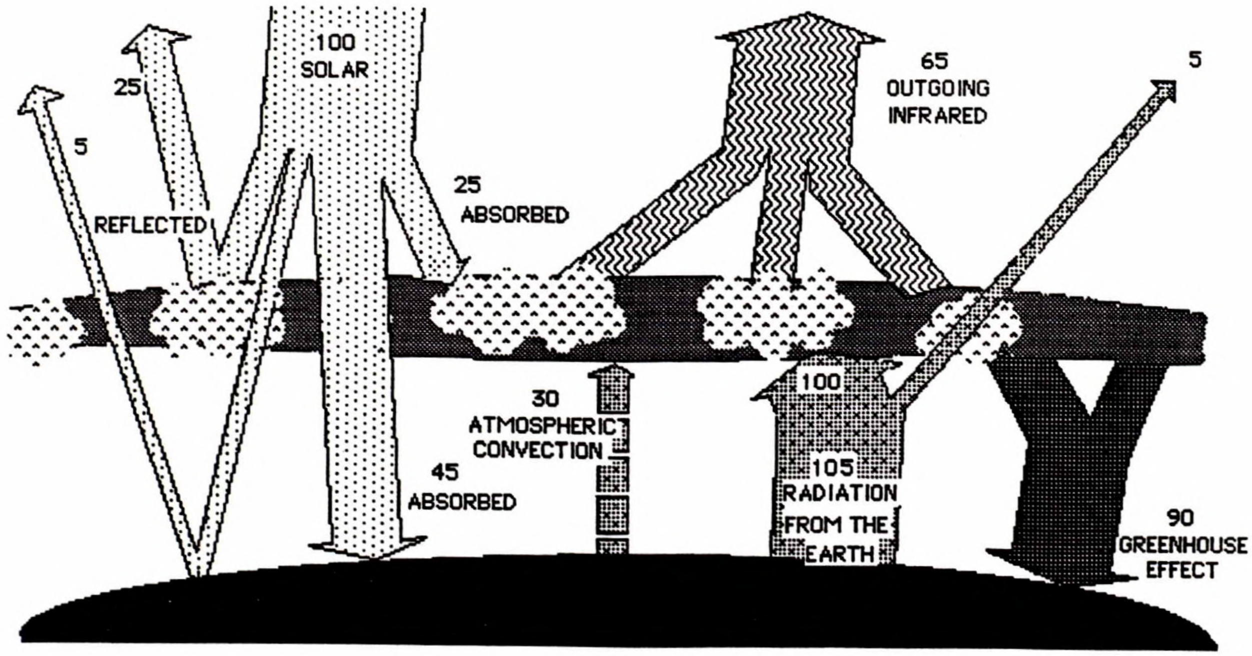


Fig. 1 - The greenhouse effect

The earth and the troposphere absorb 70 of every 100 units of incoming solar radiation (right), outgoing atmospheric convection and terrestrial radiation increase the tropospheric absorption to 155 units of which 65 are re-emitted to outer space (centre). The remaining 90 units which are trapped in the troposphere by greenhouse gases, radiate toward and heat the earth causing global warming (right).

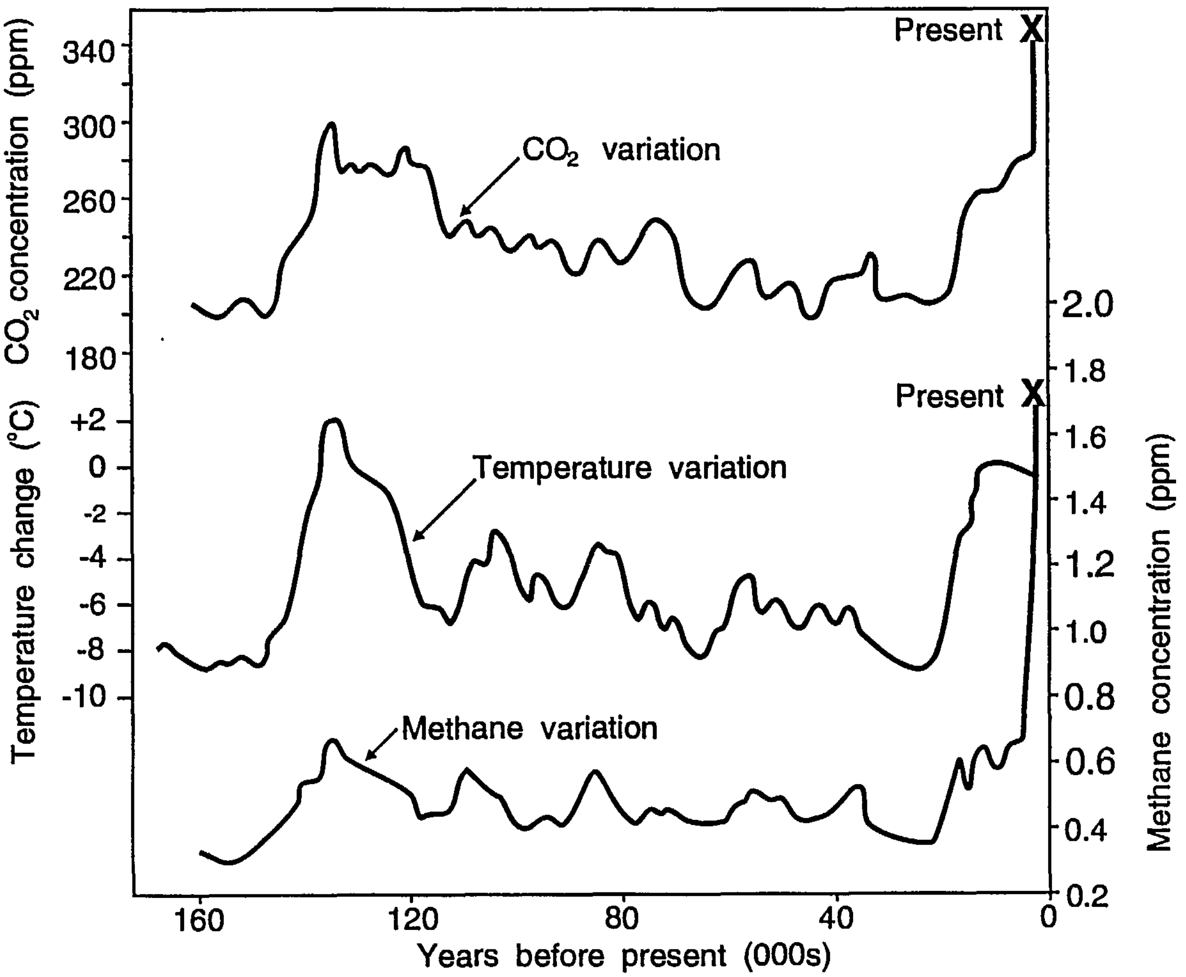


Fig. 2 - Historical CO_2 and CH_4 trends

Variation of temperature over Antarctica and of global atmospheric carbon dioxide and methane concentrations during the last 160 000 years, as inferred from Vostok ice cores from Antarctica.

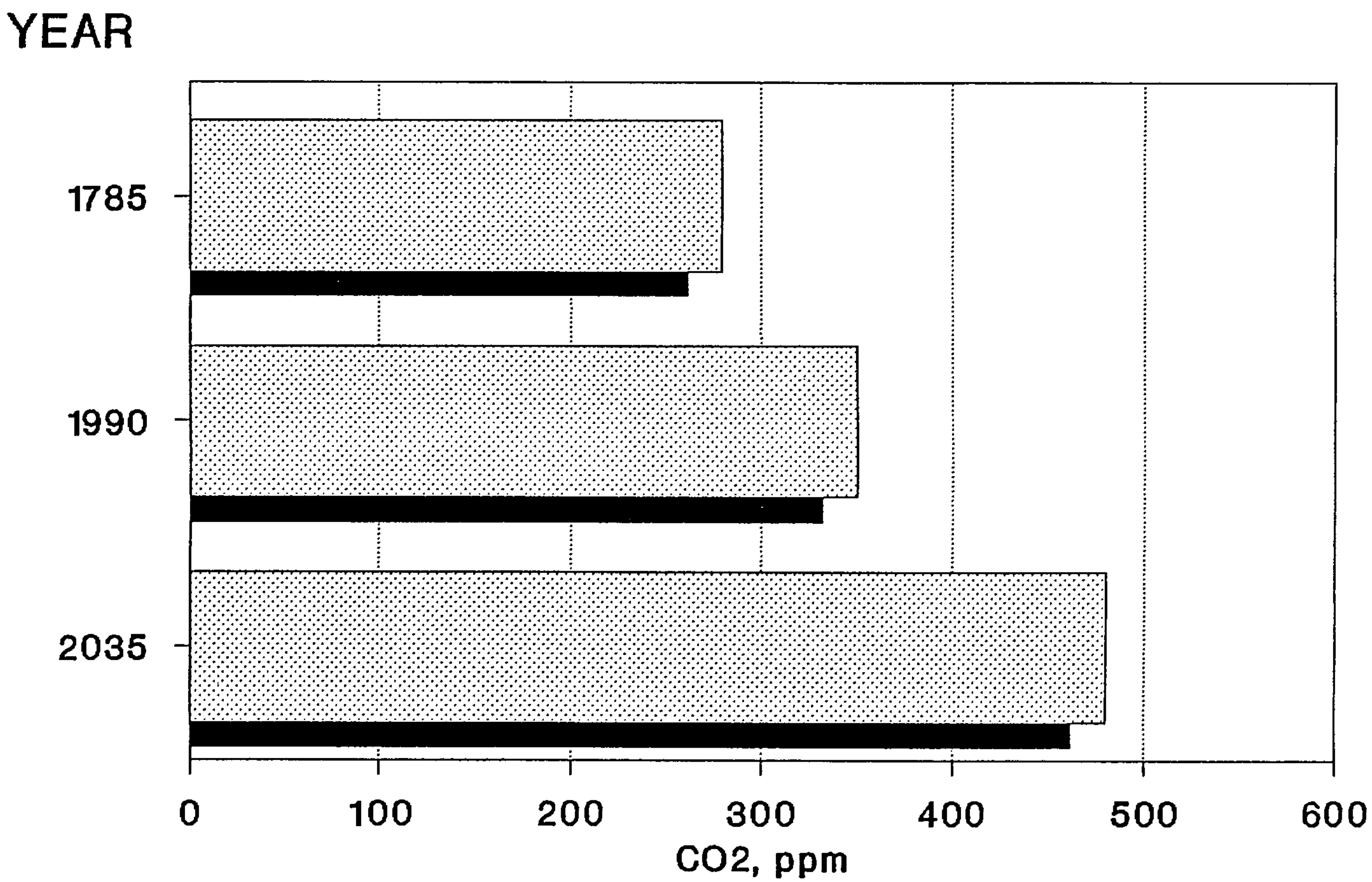


Fig. 3(a) - Major Greenhouse Gases (CO_2): Past, Present, Projected

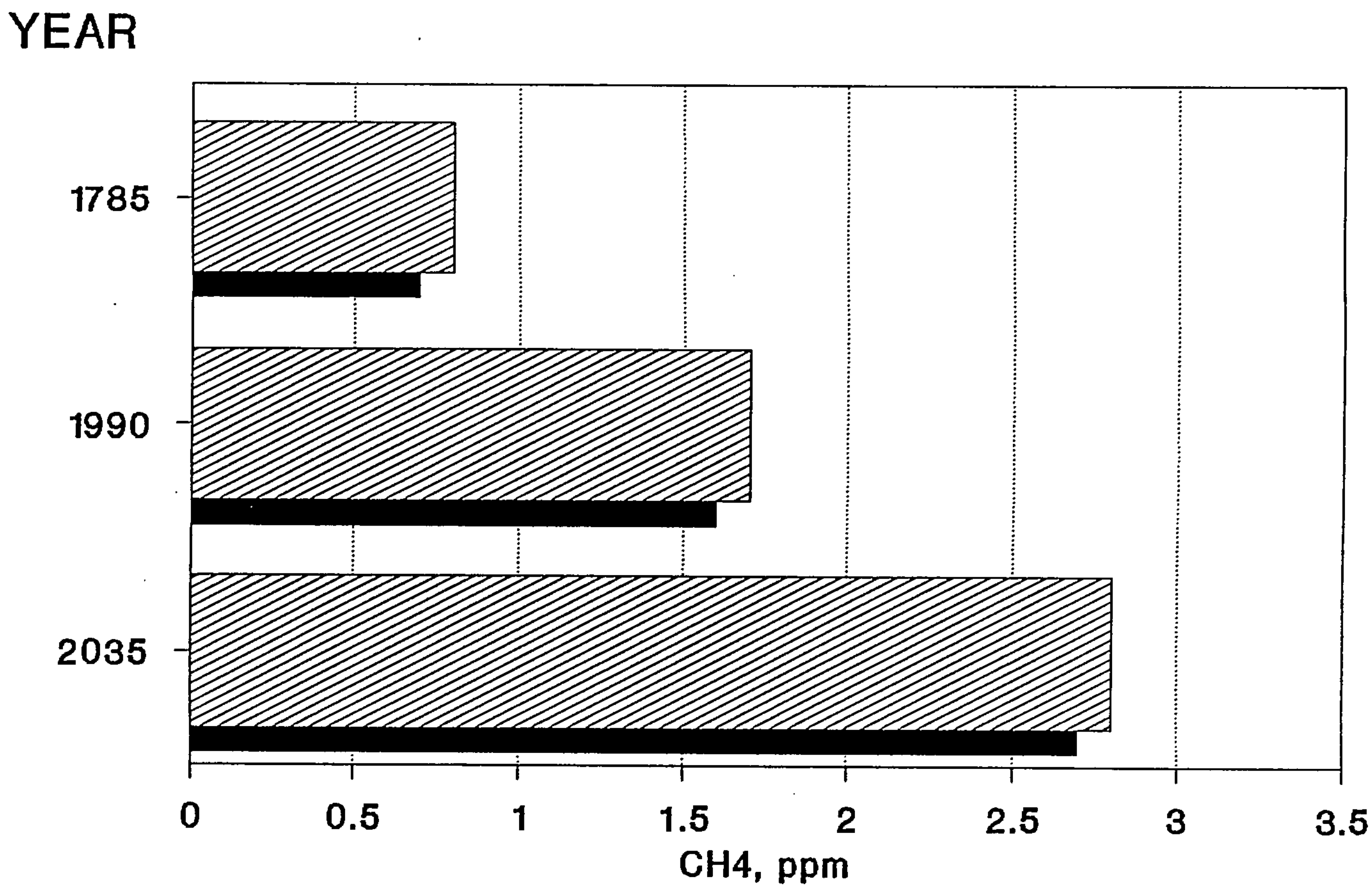


Fig. 3(b) - Major Greenhouse Gases (CH_4): Past, Present, Projected

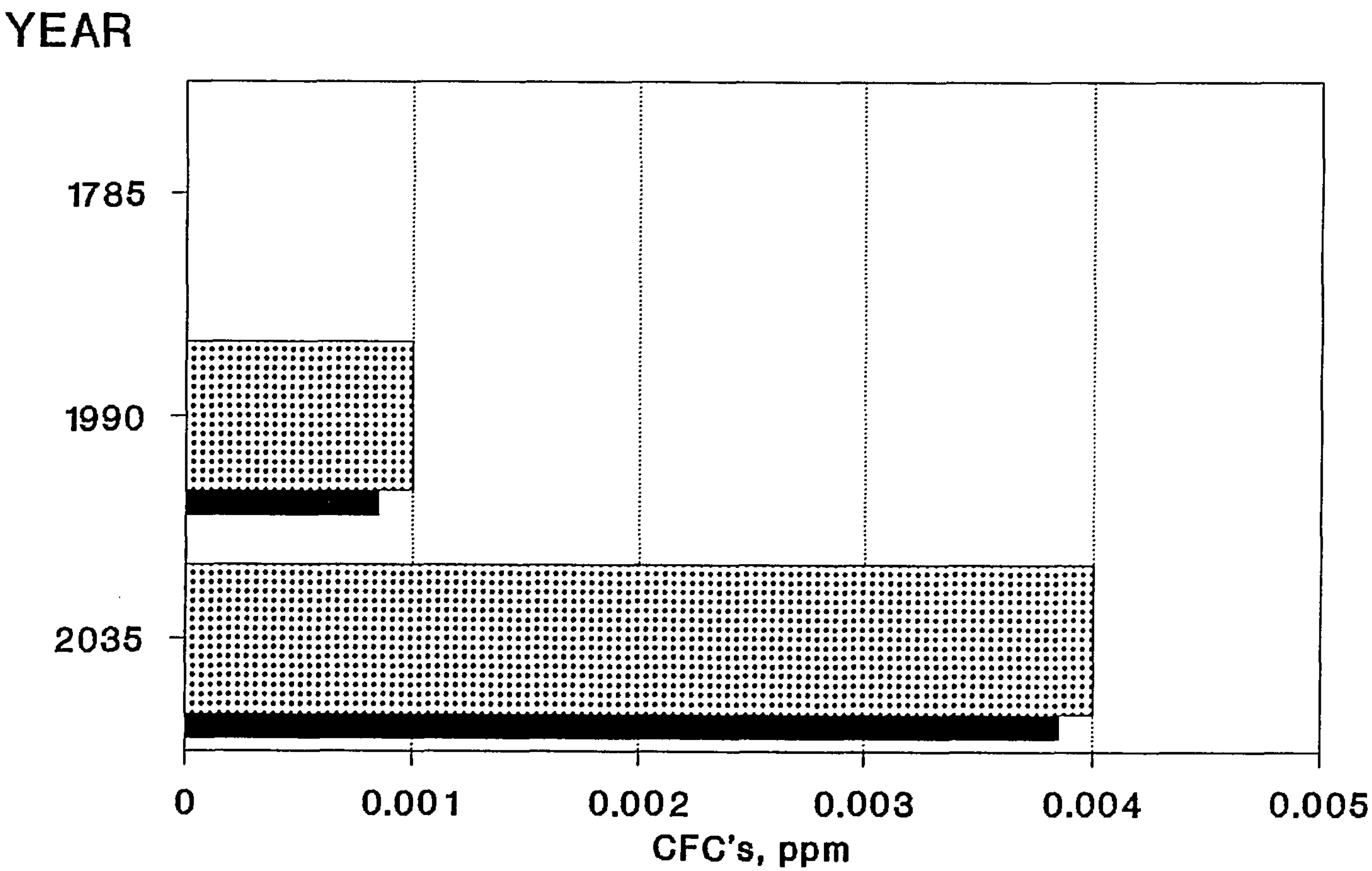


Fig. 3(c) - Major Greenhouse Gases (CFC's): Past, Present, Projected

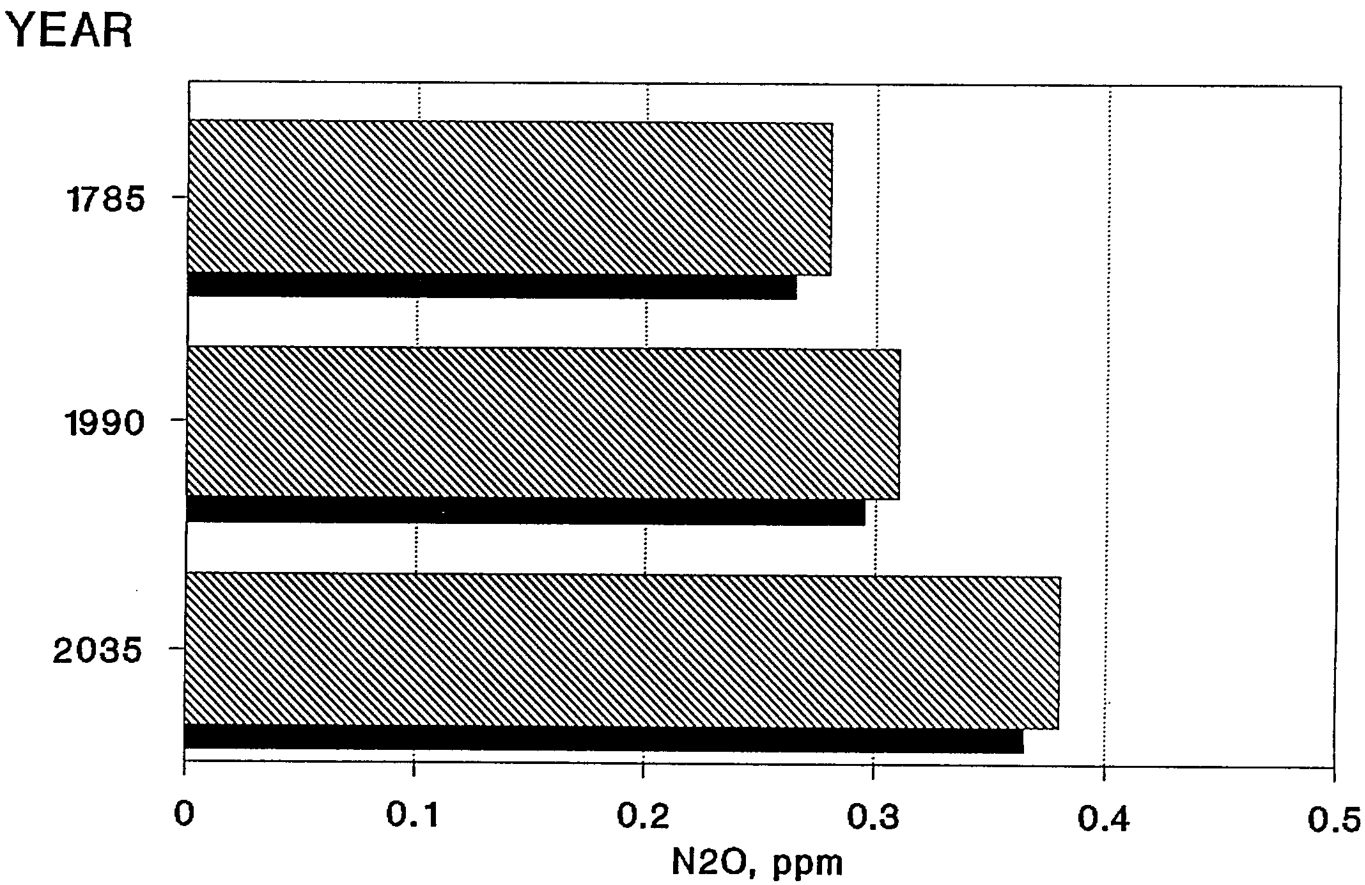


Fig. 3(d) - Major Greenhouse Gases (N_2O): Past, Present, Projected

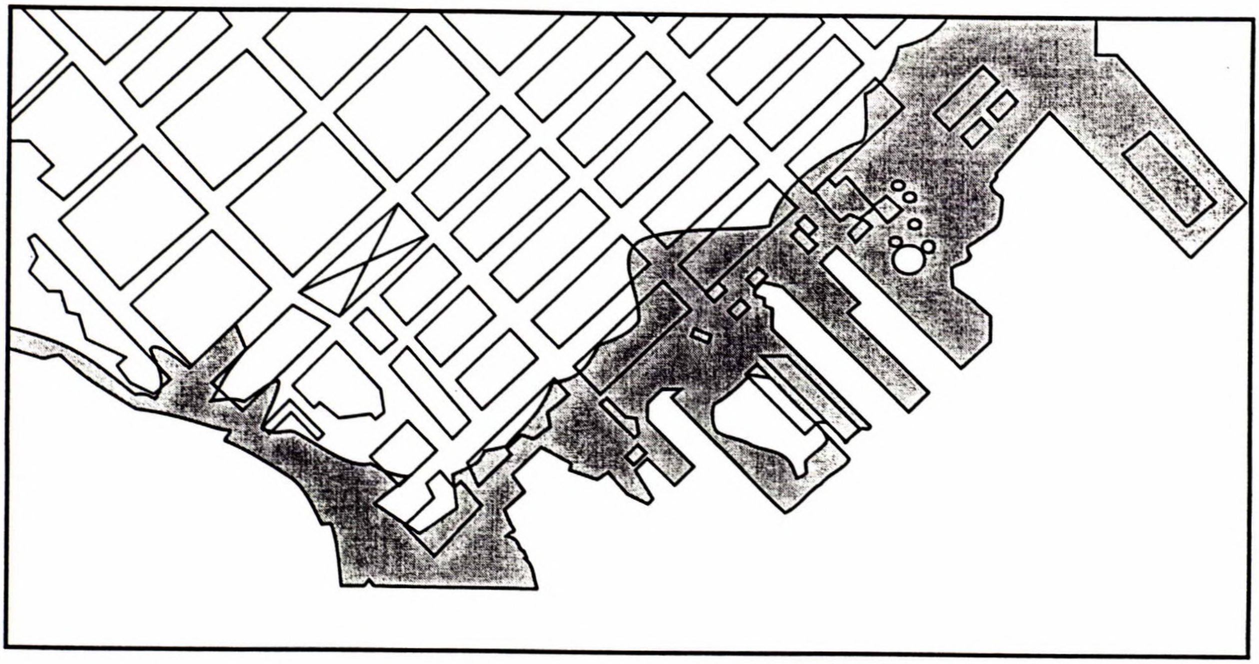


Fig. 4 - Flood threat to Charlottetown with global warming

Flood threat to Charlottetown waterfront by a 1 m rise in sea level around P.E.I.
Floods on a 20 year cycle would submerge the shaded area.

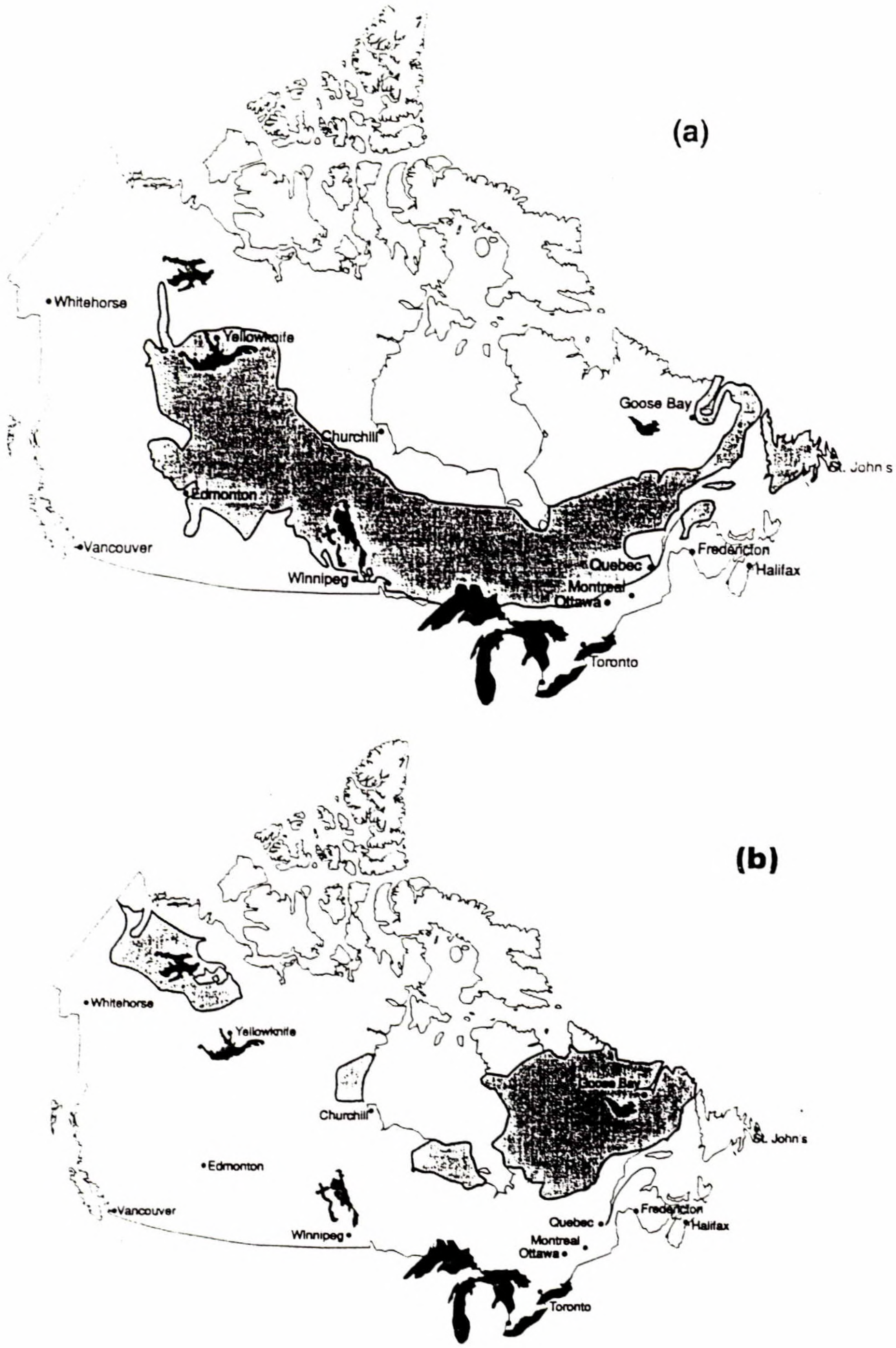


Fig. 5 - Decline and migration of boreal forests with global warming

Decline and northward migration of Canada's boreal forests a) present, b) doubling of atmospheric CO_2 according to the Goddard Institute of Space Studies model.

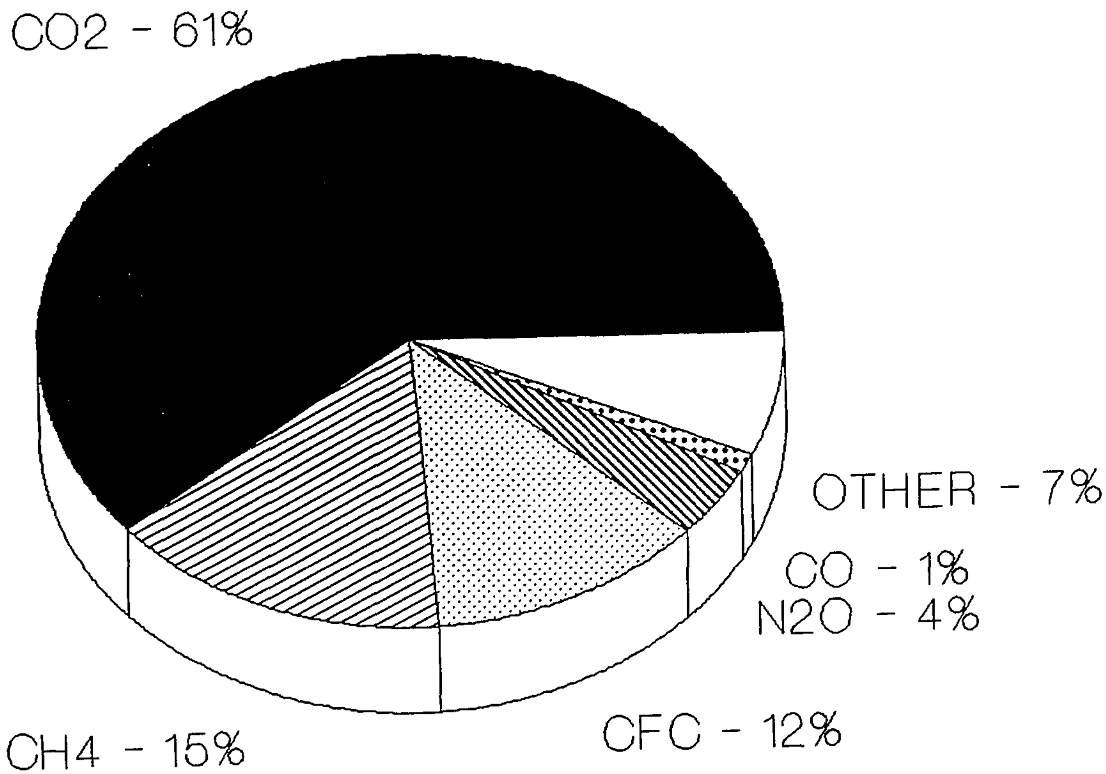


Fig. 6 - 100 Year Global Warming Potential of 1990 Greenhouse Gases

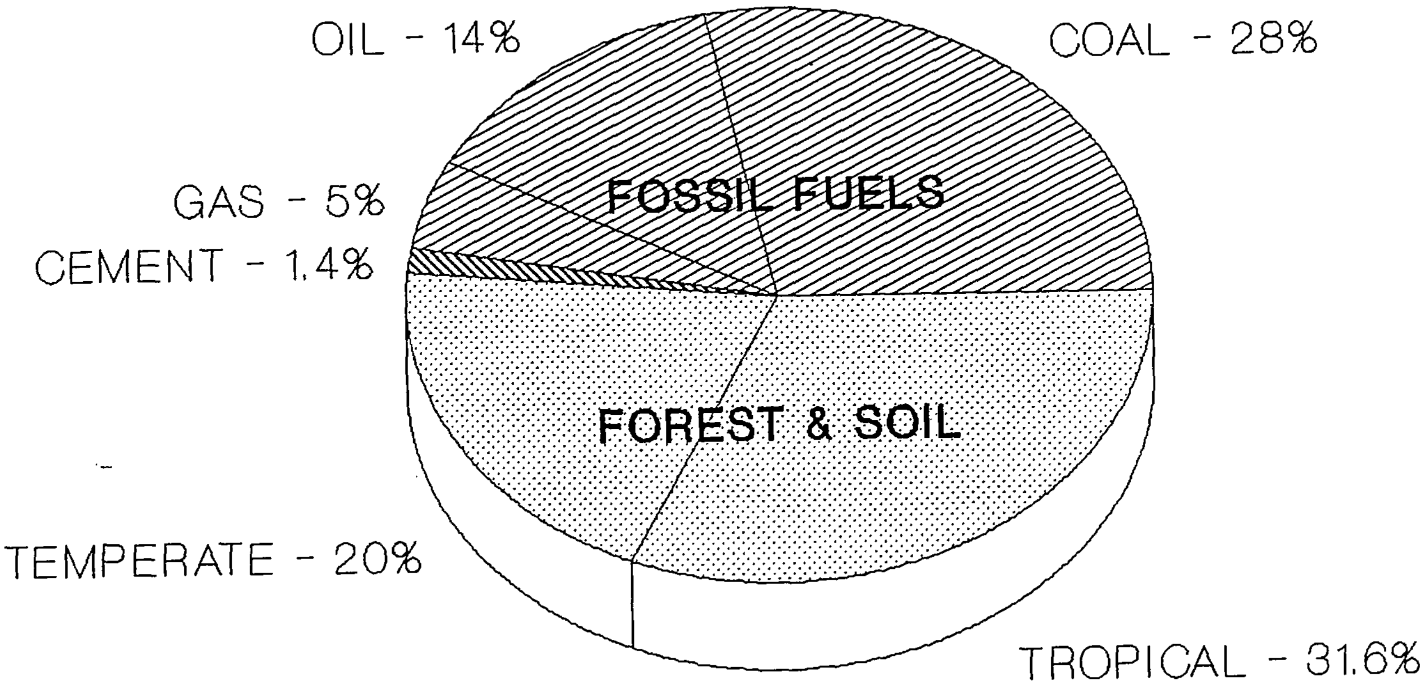


Fig. 7 - CO_2 Generated From Human Activity Between 1800 and 1987

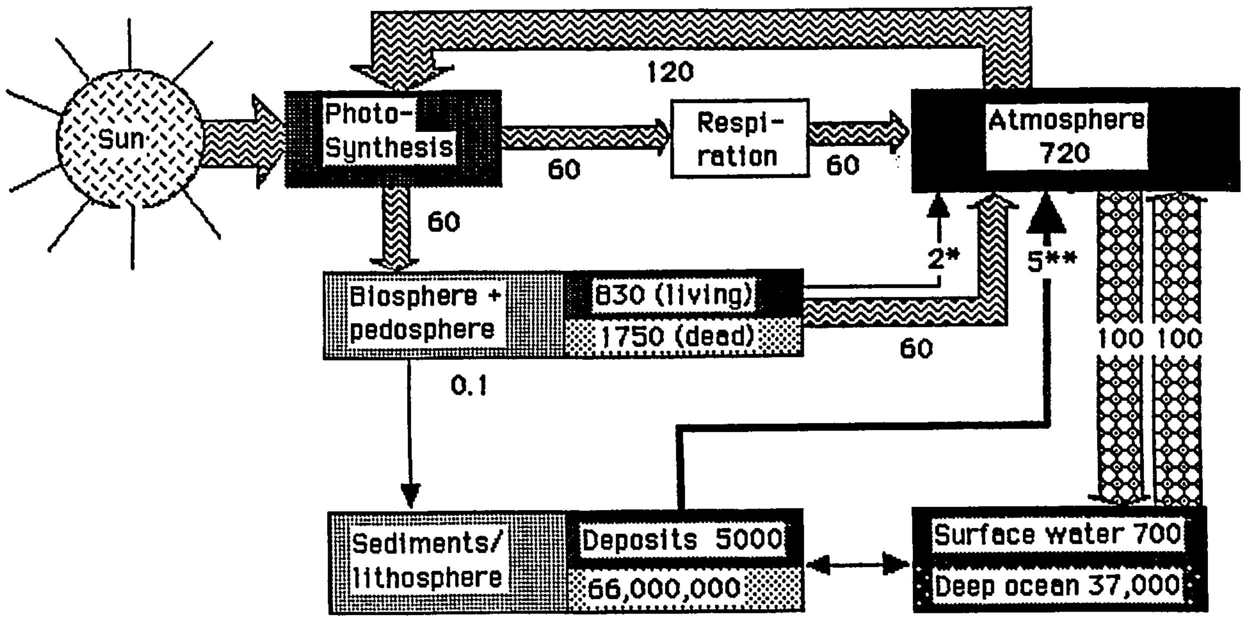


Fig. 8 - Global carbon cycle.

Reservoirs are in Gt of carbon and flows are in Gt/a of carbon, * denotes wood and soil destruction by human activities and ** denotes fossil fuel combustion.

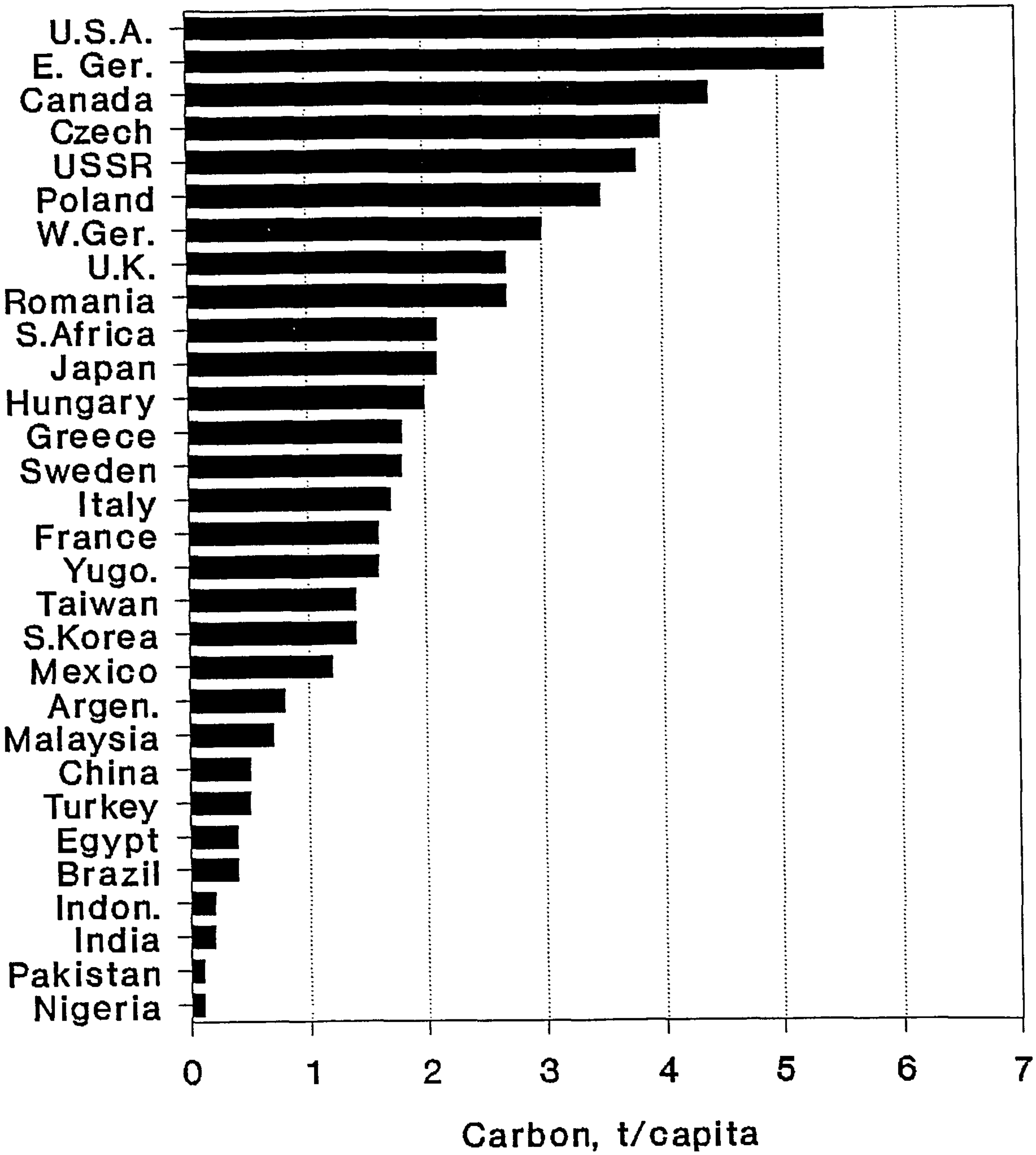


Fig. 9 - 1988 International Carbon Emissions

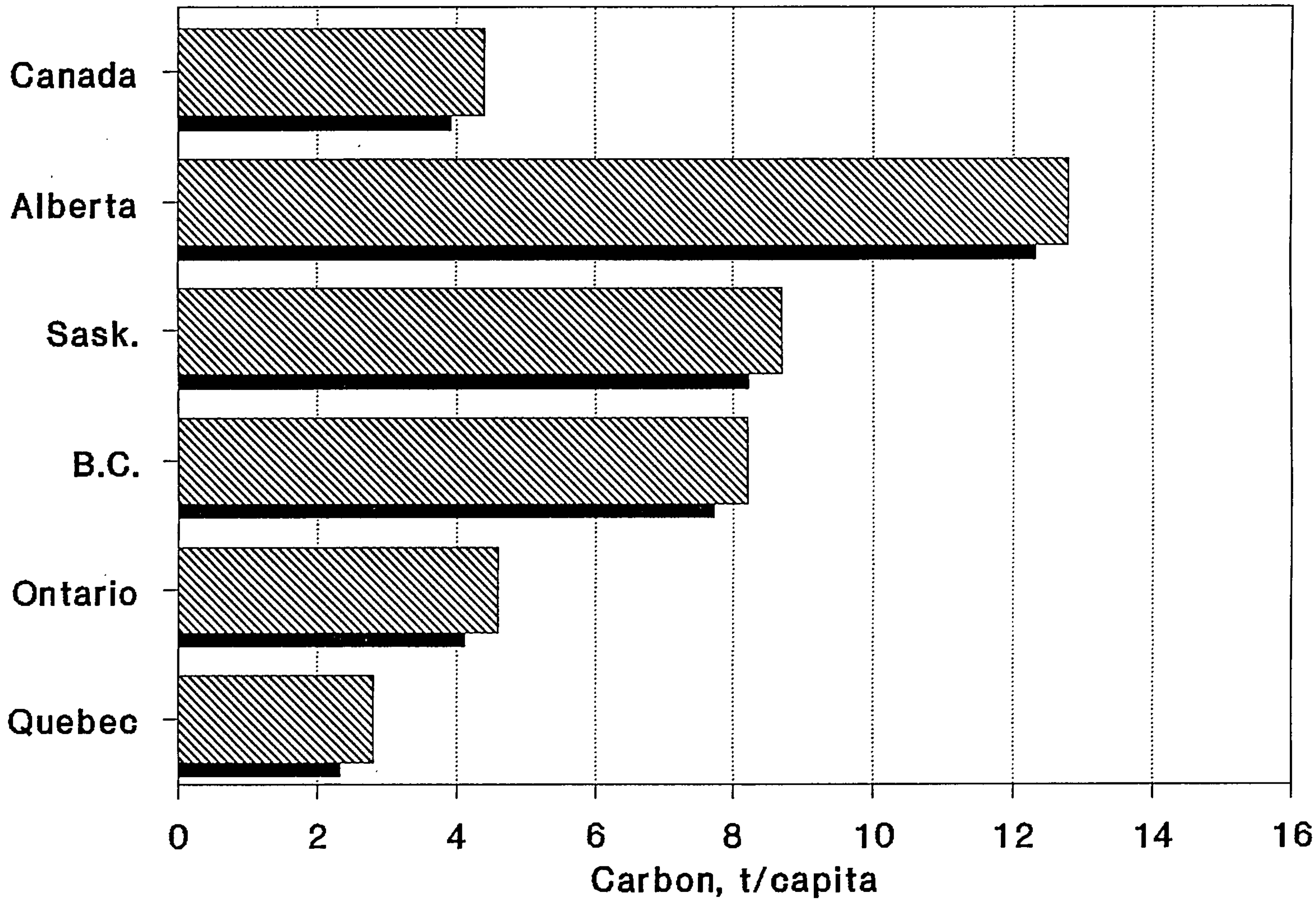
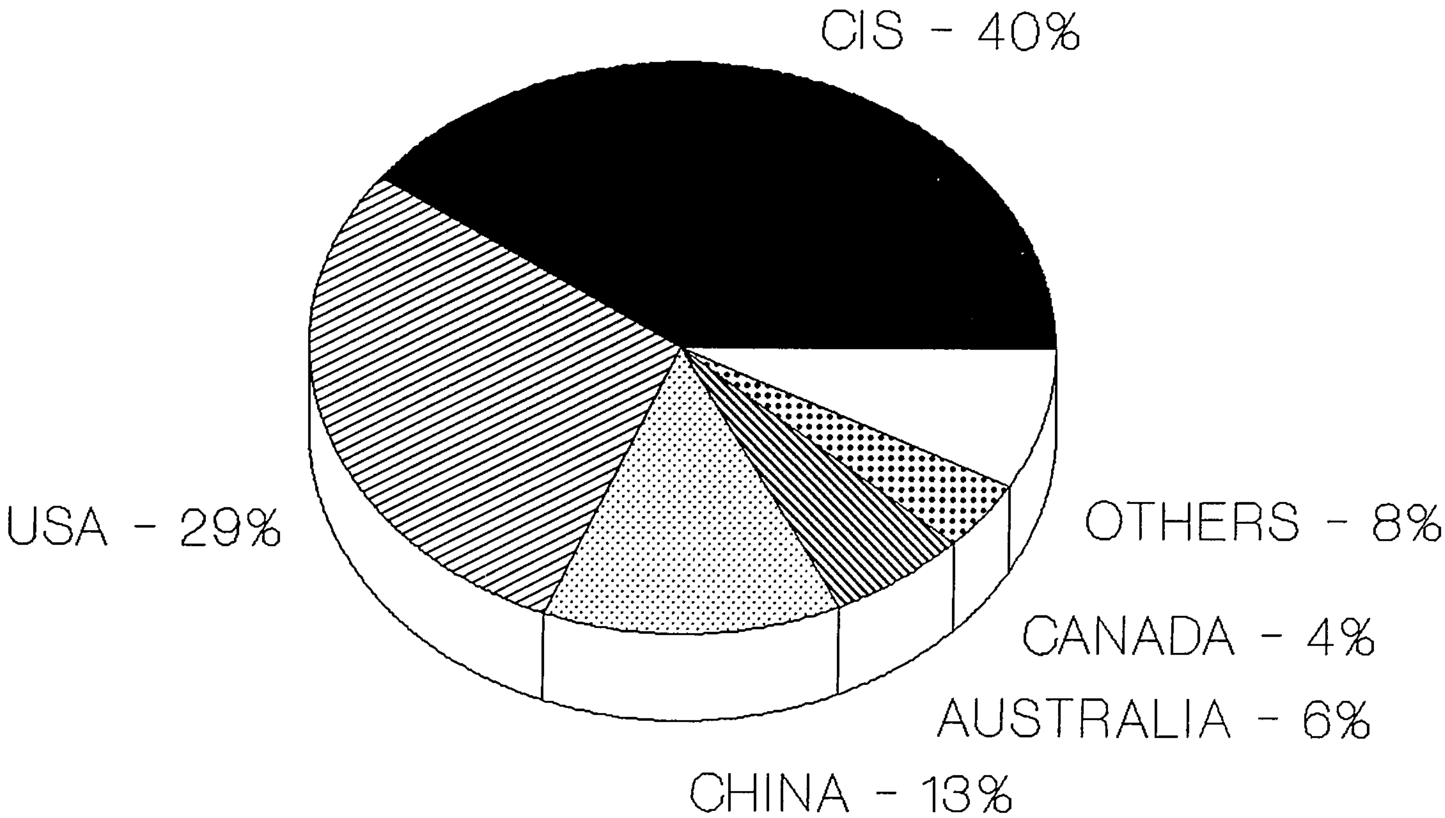


Fig. 10 - 1988 Canadian Carbon Emissions



Total approx. 15 trillion tonnes

Fig. 11 - World Coal Resources (Ultimate)

BIBLIOGRAPHY

1. Mason, J. "The Greenhouse Effect and Global Warming" BCVRA 1990 Robens Coal Science Lecture, Coal Research Establishment, Stoke Orchard, UK.

2. "The State of Canada's Environment - 1991", Cat. No. EN21-54/1991E, Environment Canada, Ottawa.

3. Smith, I.M., Thambimuthu, K.V. and Clarke, L.B. "Greenhouse Gases, Abatement and Control: The Role of Coal" IEA Coal Research, IEA CR/39, London, UK, June 1991.

4. Michaels, P.J. "Global Warming and Coal: The New Synthesis" Jour Coal Quality, Vol. 10, No. 1, Jan-Mar 1991.

5. Gruber, A. and Fujii, Y. "Intergenerational and Spatial Issues of Carbon Accounts" Energy, Pergamon Press, Vol. 16, No. 11/12, pp. 1404-1407.

6. Beckman, G. and Klopries, B. "CO_2 Increase: Questions Beyond Climatic Change" Energy, Permagon Press, Vol 16 No. 11/12, pp 1320-1329.

7. Cicarone, R.J. and Oremland, R.S. "Biogeochemical Aspects of Atmospheric Methane" Global Biogeochemical Cycles, Vol. 2, Dec. 1988, pp. 299-327.

8. Bolle, H.J., Seiler, W. and Bolin, B. "Other Greenhouse Gases and Aerosols: Assessing their Role for Atmospheric Radiative Exchange" The Greenhouse Effect, Climate Change and Ecosystems. John Wiley and Sons, UK, 1986, pp. 157-203.

9. Kits, G.H. "Slowing Global Warming and Sustaining Development: the Promise of Energy Efficiency" Energy Policy, Vol. 18, Jan-Feb. 1990, pp. 25-33.

10. Millard, V. "Equity between Regions and Economic Sectors" Conference on Global Warming: The Search for Cost Effective Action, Calgary, May 1991.

11. Schneider, S.H. "The Changing Climate" Scientific American, Vol. 261, No. 3, September 1989, pp. 38-47.

12. Hengeveld, H.G. "Greenhouse Gas Emissions Overview - Canada" Conference on Global Warming: The Search for Cost Effective Action, Calgary, May 1991.

13. Lee, G.K. and Hayden, A.C.S. "Greenhouse Mitigation through Clean Coal Utilization" CANMET Coal Seminar, Calgary, Nov. 1989.

14. Smelser, S.C. and Booras, G.S. "An Engineering and Economic Evaluation of CO_2 Removal from Fossil Fuel Fired Power Plants" Ninth Annual Conference on Gasification Power Plant, EPRI, Palo Alto, CA, October 1990.

15. Lipinsky, E.S. "R&D Status of Carbon Dioxide Separations, Disposal and Utilization Technologies" Battelle Columbus Report to Transalta Utilities Corp., April 1991.

16. "BP Statistical Review of World Energy" BP Corporate Communications Services, London, UK, July 1989.

17. Lee, G.K. "Canadian Coals, the Environment and New Coal Technologies" Proceedings Conference on Energy and Electricity, Canadian Energy Research Institute, Montreal, June 1990.

18. Walsh, J.H. "A Technology Strategy for Coal for a Reduction in Emissions of Carbon Dioxide" CIMM 92nd Annual General Meeting, Ottawa, May 1990.

19. "IEA Coal Information 1991" OECD, Paris, France, 1991, pp. 241.

20. Laver, E. "Coal in Canada" OERD - Industry Meeting on EMR Coal R&D Programs, Calgary, Feb. 25-27, 1991.

21. "Acid Mist Causing Global Cooling Trend" Ottawa Citizen, May 19, 1992.

22. Keepin, W. and Kats, G. "Greenhouse Warming - Comparative Analysis of Nuclear and Efficiency Abatement Strategies" Energy Policy, Butterworth and Co., Dec. 1988, pp. 538-561.

23. "Development of a Research Program for the Control of Greenhouse Gases from Coal Use" Sylpher-Mueller International Inc., Report to Environment Canada, March 1991.