RESEARCH ARTICLE

An evaluation of global warming and its impact

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Energy balance model has been calculated to assess the magnitude of the average global warming by the middle of the next century. It is shown that an increase in temperatures by about 4 K by the year 2050 as compared to the pre-industrial era (~ 1800 AD) could result from the projected growth of atmospheric concentrations of major greenhouse gases i.e. carbon dioxide, methane, nitrous oxide and chlorofluorocarbons (CFCs). The changes in global warming are considered for different scenarios including the proposed regulatory measures on the use of CFCs. It is shown that even though the adoption of the revised Montreal Protocol will reduce the global warming due to CFCs by almost 50%, the projected overall global rise in temperature will still be about 2.7 K by the year 2050. The possible climatic impacts of the global warming on a few biogeophysical parameters are found to be alarming. Unless prompt action is taken to control the emission fluxes of other major greenhouse gases on lines similar to CFCs, the consequences may be severe for life on earth.

Introduction

Increase in greenhouse gas concentrations and global warming

THE distinct possibility of continuous global warming in the coming decades and the climatic changes as a result of the drastic increase in the greenhouse gases of anthropogenic origin is now generally well accepted[1,2]. The perturbation in earth's radiative forcing caused by increasing tropospheric concentration of carbon dioxide (CO_2) due to fossil fuel burning and deforestation has been the main focus of attention. Long-period data collected over the Hawaiian station Mauna Loa since 1958 revealed[3] a systematic increasing trend of atmospheric fraction of CO_2. Over the past 20 years the annual rise in atmospheric fraction of CO_2 concentration has been particularly high, about 1.5 ppmv (parts per million by volume) due to accelerated rates of fossil

energy consumption and deforestation. If the artificially-induced CO_2 emission continues at the present rate, estimates show that the CO_2 concentration could double by the year 2050 compared to the pre-industrial era ($\sim$ 1800 AD).

Climatic models have been developed to derive the extent of global warming that may result from the entrapped infrared radiation of the earth by CO_2 and other greenhouse gases. Basic aspects of climatic modelling considered in the next section indicate that such doubling of CO_2 concentration could lead to a global rise in temperature between 1.5 and 4.5 K[4] depending on the sensitivity factors of various feedback mechanisms used in different models. The gap in the range of uncertainty is reduced ($\sim$ 3.5–4.5 K) when three-dimensional general circulation models (GCMs) are used to compute the magnitude of climatic change[5]. While the average equilibrium global temperature rise due to CO_2 doubling is indicative of the general problem, existence of significant latitudinal and seasonal anomalies and regional differences can lead to a much higher temperature increase at specific locations such as polar regions. Model simulations of likely time-dependent response of global temperature to the changing composition of the atmosphere since late 19th century, taking into account the thermal inertia of the ocean suggest that global warming between 0.4 and 1.1 K should have already occurred by the 1980s[6,7]. In addition to CO_2, the rapidly increasing emission of a number of other greenhouse gases such as methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) due to industrial and agricultural activities since 1960's are significantly adding to the greenhouse effect with magnitudes comparable to that of CO_2[8].

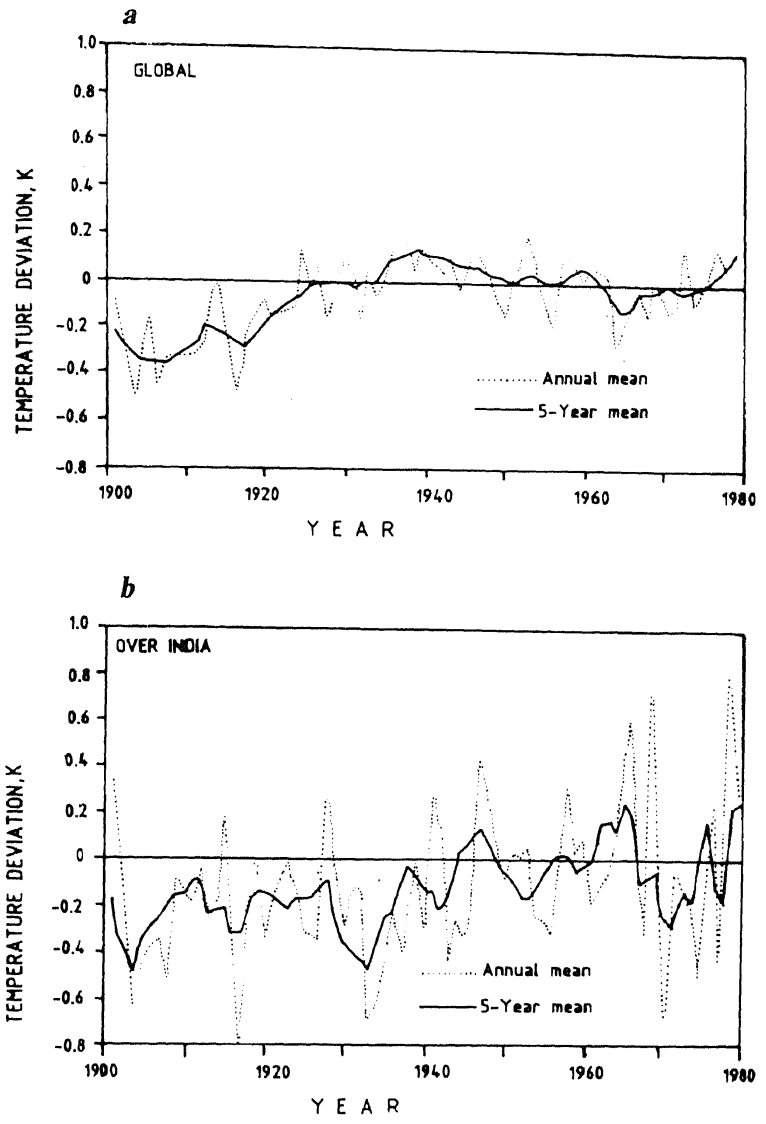

Figure 1. *a*, Global annual average surface-air temperature change with reference to average for the years 1951–80 (from Hansen and Lebedeff[11]); *b*, Annual average land-air temperature change over India with reference to average for the years 1951–80.

Evidence of global warming

The above scenario of predictable changes in global climate due to increasing proportions of greenhouse gas concentrations has led a number of scientific groups to search for observational evidence of global warming using both global surface air temperature data from meteorological stations and satellite passive microwave radiometric data. While on short time-scales of a decade or so, the ground as well as satellite-derived zonally averaged temperatures do not reveal a definite trend[9], hemispheric and globally-averaged temperatures derived from reliable meteorological data sets over the past 130 years show a global warming trend of about 0.5 K[10–12]. Figure 1,*a* shows the results obtained by Hansen and Lebedeff[11] on the departures of global annual surface air temperatures of individual years from a climatic average derived from the annual average temperatures during the years 1951–80. It can be seen that global temperature rose steadily up to the 1940s. Temperature thereafter remained relatively constant and since the mid-1960s even decreased slightly until the recent period of warming. Data analysis for southern hemisphere (not given in figure) showed a continuous increase also during the period 1940–65. The apparent break in the global temperature increase during 1940–65 has been attributed to a relatively colder period over the northern hemisphere even though normal conditions prevailed over the southern hemisphere.

An attempt has been made to check the existence or otherwise of such a global temperature trend on a regional scale by considering annual average land-air temperatures of 90 meteorological stations spread uniformly over the Indian subcontinent. After treating the data through several quality checks to ensure temporal and spatial homogeneity, the annual average temperature deviations with reference to a climatic mean calculated from the annual avaerage values during the years 1951–80 plotted for the time series

between 1901 and 1980 are shown in Figure 1, *b*. The five-year running means of these temperature deviations are also shown in the figure. It is interesting to note that despite rather large interannual variations as compared to the global pattern of Figure 1, *a*, a steady warming trend of about 0.5 K during the entire period 1901–80 over India is clearly demonstrated. The average increase of temperature by about 0.5 K seen both in the global and regional data sets, is in broad agreement with the predicted increase of 0.48 K in the global temperature derived from detailed calculations using the model developed by us and the measured increase in the concentrations of CO_2 and other greenhouse gases for the same period. It is clear from Figure 1 that apart from the slow and steady rise in global temperature over the long period of a century, there are fluctuations on shorter time scales of a decade or more. While it is considered outside the scope of this paper to discuss in detail the possible causes of these short-period modulations of global temperature deviations, these have been identified as mainly due to (a) changes in frequency of volcanic eruption, (b) El-Nino Southern Oscillation (ENSO) events and their morphological manifestations, (c) nonlinear feedback due to cloud physical and thermodynamic factors and (d) inherent climatic oscillations due to regional scale changes in radiative forcing of abnormal weather conditions.

Studies to determine the extent of global warming due to increase in atmospheric concentrations of greenhouse gases encounter three major difficulties: (a) accurate projection of future concentrations of trace gases, (b) three-fold uncertainty in the sensitivity of different climate models and (c) parameterization of the role of clouds and their overall feedback effect. In this paper we have attempted to synthesize the available information and make realistic future projection of the concentrations of trace gases taking into account the restrictions imposed on the production and usage of CFCs on account of adopting the Montreal Protocol, compute global warming due to these using an energy balance model and estimate the effect of the climatic impact on changes in sea-level, shore line dynamics, global food production and depletion in stratospheric ozone. Global warming is also likely to cause shifts in climatic zones and rainfall patterns, morphological variations of Arctic and Antarctic ice cover, disruption of major eco-system complexes and forest biomes, the estimates of which are not provided in this paper.

Climatic models and global warming

Energy balance (EB), radiative-convective (RC) and general circulation models (GCMs) have been developed earlier to simulate conditions of global warming[1,3]. The EB and RC models essentially utilize the radiative transfer equations and the criterion of ultimate balance of solar, terrestrial and atmospheric radiations. The atmospheric region is divided into a number of layers which are characterized by these radiative fluxes. The equations over appropriate time scales are integrated to determine the equilibrium surface temperatures and vertical temperature profiles in the troposphere with respect to different latitute zones and seasons. Sensitivity tests of these models are used to predict the effect of changing the input parameters of solar shortwave radiation, planetary albedo and atmospheric trace gas concentrations such as those of water vapour and CO_2 which are mainly responsible for trapping outgoing terrestrial radiation resulting in the greenhouse effect. GCMs involve calculations of the three-dimensional character of the climate. The equations involving conservation of mass, energy and momentum, the thermodynamic state and ideal gas law, are solved numerically for latitude–longitude grids with suitable spatial resolution. If various feedback effects due to changes in sea-ice albedo, cloud cover and water vapour are included then these solutions require supercomputing power of a higher order. The complex GCMs were developed a decade earlier than EB and RC models for computing greenhouse warming[1,3]. This is because these relatively simple models describe the state of climate fairly accurately at the same time executing the computer code economically. All these models have one limitation in that the aspects of interaction between photochemistry of trace gases and radiative transfer are not included in the formulation. Ideally the feedback due to all atmospheric chemical reactions affecting the radiative phenomenon should be included to make the simulation more realistic.

In a simple energy balance concept, the solar radiation flux received by the earth is equated to the blackbody radiation from earth which may be considered to escape into space instantly. The actual situation is different due to the presence of atmospheric gases such as water vapour, CO_2 etc, which absorb and re-emit terrestrial infrared radiation leading to a surface temperature (T_s) greater than the effective temperature (T_e) in the absence of earth's atmosphere and hence:

$$T_s = T_e + \Delta T. \quad (1)$$

If ΔT is constant, then earth's mean surface temperature will remain steady (presently around 288 K) assuming that solar incoming flux and planetary albedo do not change with time. The contribution to ΔT is made by a number of atmospheric constituents such as CO_2, CH_4, N_2O, chlorofluorocarbons (CFCs), ozone, water vapour, clouds and aerosols. Out of a long list of CFC gases only CCl_3F (CFC-11) and CCl_2F_2 (CFC-12) are of primary importance. Continuous global warming could

result through steady accumulation of any of these gas concentrations in the atmosphere due to activities of either natural or anthropogenic origin. The term symbol for this change in global warming state can be denoted as $\delta(\Delta T)$. The greenhouse components like water vapour, clouds and aerosols, although contribute substantially to ΔT, do not contribute to $\delta(\Delta T)$ in a period of tens of years. However, changes in water vapour concentrations and cloud cover due to global warming itself provide additional radiative forcing due to feedback processes.

In a time-dependent EB model the rate of change of temperature T with time t, caused by the difference between the net incoming (R↓) and net outgoing (R↑) radiative fluxes on top of the atmosphere is given by

$$c(\Delta T/\Delta t)=(R\downarrow - R\uparrow)A_e, \tag{2}$$

where c is the total heat capacity of the earth primarily governed by the first 70 m (mixed layer) of ocean waters, and A_e the area of the earth. $R\uparrow$ must include corrections for emissivity (ε) and infrared transmissivity of the atmosphere (τ_a) which is an integrated function of atmospheric concentration of greenhouse gases and can be determined using Planck's law. Thus we have the following expression:

$$\frac{\Delta T}{\Delta t}=\frac{1}{c}\{S(1-\alpha)/4-\varepsilon\tau_a\sigma T_s^4\}, \tag{3}$$

where S is the flux of solar incident radiation; α the planetary albedo (ratio of reflected to incident light) and σ the Stefan–Boltzmann constant. The equilibrium climatic state can be assessed by setting $\Delta T/\Delta t = 0$ and hence,

$$(1-\alpha)S/4 = \varepsilon\tau_a\sigma T_s^4. \tag{4}$$

Using the values of $\alpha(=0.3)$, $S(=1370\ \mathrm{Wm^{-2}})$, $\sigma(=5.67\times10^{-8}\ \mathrm{Wm^{-2}K^{-4}})$ and $\varepsilon\tau_a(=0.62)$, the surface temperature on the earth works out to be 287 K, in good agreement with globally-averaged surface temperature. A change in global surface temperature of 1 K will require only a very small change of $\varepsilon\tau_a$ $(=8.61\times10^{-3})$. The present model is based on the earlier work of Budyko and Sellers[14,15] which considers the balance of radiations between the incoming solar shortwave radiation, the outgoing terrestrial longwave radiation and transport of energy between latitude zones due to the equator-to-pole temperature gradient. In this case the energy balance of each latitude zone is considered independently as follows:

$$S_i\{1-\alpha(T_i)\} = R\uparrow(T_i) + F(T_i), \tag{5}$$

where i denotes a latitude zone and $F(T_i)$ refers to loss of energy by a latitude zone i to its colder neighbour(s). It is assumed that the contribution of any storage by the system can be neglected at climatic timescales. The surface albedo increase due to the formation of zonal sea-ice and snow cover is included in the model. The radiation emitted to space over the temperature range of interest (~250–300 K) can be expressed by a linear relation:

$$R(T_i) = A + BT_i. \tag{6}$$

The rate of transport of energy can be represented as being proportional to the difference between the zonal temperature and the global mean temperature ($\bar{T}$) by:

$$F(T_i) = K(T-\bar{T}). \tag{7}$$

Given a first approximate temperature distribution, successive applications of eqs. 5 to 7 eventually yield an equilibrium solution. The constant A represents the greenhouse effect of clouds, water vapour, carbon dioxide and other trace gases and constant B is representative of a climate sensitivity parameter which depends on feedback processes of changes in sea-ice albedo, water vapour and cloud cover due to change in global warming.

Global warming and the role of atmospheric chemistry

During the past 120–150 thousand years, there is evidence to believe that earth's temperature has changed by about 10 K between the glacial and interglacial periods. The present interglacial era provides for an average cooling rate of about 0.1 K/1000 years. The results of the analysis of deep ice cores extracted from the Arctic and Antarctic regions do subscribe to such slow temperature variations in the past[16]. From the analysis of air samples trapped in deep ice cores the concentrations of tropospheric CO_2 and CH_4 have been derived and the results show a very good correlation between variations of CO_2 and CH_4 with temperature. The reasons for such correlation are not clearly understood since it is difficult to envisage changes in the natural production and losses of these gases of such magnitude. CO_2 is a chemically inert gas but CH_4 takes part in a myriad of tropospheric photochemical reactions the rates of which are dependent on temperature. As shown in Appendix 1 about 20% decrease in CH_4 concentrations is possible due to surface temperature rise of 10 K. Also the concentration of CH_4 in the upper atmosphere depends critically on the concentration of the OH molecule which reacts with a number of other trace constituents.

The relationship between the emission fluxes of greenhouse gases and the actual increase in atmospheric concentrations depends in a very complex manner on a number of factors in which atmospheric chemistry plays a very important role[17]. The greenhouse gases particularly N_2O and CFCs react with stratospheric ozone and destroy the ozone layer which shields earth's

living organisms against exposure to harmful doses of solar UV-B radiation (λ = 280–320 nm). Any reduction in stratospheric ozone concentration would result in changing the earth's radiation budget which needs to be considered for improving the accuracies of calculations of global warming[18].

Model calculations of estimated growth of atmospheric concentrations and global warming

Basic data on greenhouse gases

For computing the growing concentrations of CO_2, CH_4, N_2O and CFCs (CFC-11 and CFC-12) and their impact on global warming during the next 60 years (i.e. up to 2050), the background information and data used are summarized in Table 1. Apart from their greenhouse warming effects, CH_4, N_2O and CFCs produce chemically active OH, NO and Cl gases which catalytically destroy ozone concentrations in the stratosphere. The lifetime of all gases (except CO_2) are calculated based on the rate constants of chemical reactions providing the sinks and the concentrations of the reacting gases responsible for the losses. This parameter is also defined as the ratio of total atmospheric content to the rate of removal. CO_2 has no real sinks as it is circulated between the three reservoirs of ocean, atmosphere and biota. On a short time scale it takes about 4 years for the atmosphere to attain a new CO_2 concentration value after 50% of the emission fluxes is removed by the mixed layer of the ocean and biota. Hence additional fluxes of CO_2 gas increase atmospheric concentrations as well as the amount dissolved in the oceanic mixed layer.

Projected anthropogenic emissions and growth of atmospheric concentrations of greenhouse gases

Based on the annual growth rates at current levels and lifetimes of trace gases, the total accumulated fluxes of trace gases in the atmosphere are shown in Table 2. The corresponding atmospheric concentrations of these gases are presented in Figure 2. Once the anthropogenic fluxes of trace gases are introduced into the atmosphere, the residence time of these gases in the atmosphere is mainly determined by the chemical loss processes in the atmosphere. The annual growth rates at present levels provide realistic estimates of the projected atmospheric concentrations of CO_2, CH_4 and N_2O up to the year 2050 taking into account the increased awareness to curb these artificially produced fluxes. For CFCs, however, realistic estimates need to be used based on the likely implementation of the revised Montreal Protocol which proposes to limit the growth of future emissions in a phased manner.

Table 3 presents the scenarios of per capita production and total cumulative additions of CFCs to the atmospheric reservoir as restricted by the two versions of Montreal Protocol in 1987 and 1990. A marked improvement is seen in the provisions of Montreal Protocol (1990) in checking the emission fluxes as compared to the earlier version of protocol. The increase in total cumulative atmospheric fraction has been computed using the perceived growth of global population separately for developed and developing countries[19]. As a result of these anthropogenic emissions, a comparison of the atmospheric concentrations of CFCs with respect to the normal growth (in the absence of any control measures) is shown in Figure 3.

Table 1. Salient data on the greenhouse potential and ozone depletion potential of trace gas constituents and their growth rate

Trace constituent	Greenhouse potential with respect to CO_2 per molecule	Ozone depletion factor	Pre-industrial atmospheric concentration (1750–1800) (ppmV)	Present atmospheric concentration (1990)	Present annual growth rate of atmospheric concentration(%)	Atmosphere lifetime (years)
CO_2	1	Affects O_3 through temperature feedback	270–280	353 ppmv	0.5	50–200
CH_4	25	Affects O_3 through complex chemical reactions in CH_4–CO–OH–O_3–NO_x system	0.8	1.72 ppmv	1	10
N_2O	250	Depletes O_3 in stratosphere through NO produced by photolysis of N_2O	0.285	0.31 ppmv	0.25	150
CFC-11 and CFC-12 (CCl_3F and CCl_2F_2)	20,000	Depletes O_3 in stratosphere through Cl produced by photo-dissociation of CFCs	Nil	0.8 ppbv	4	130

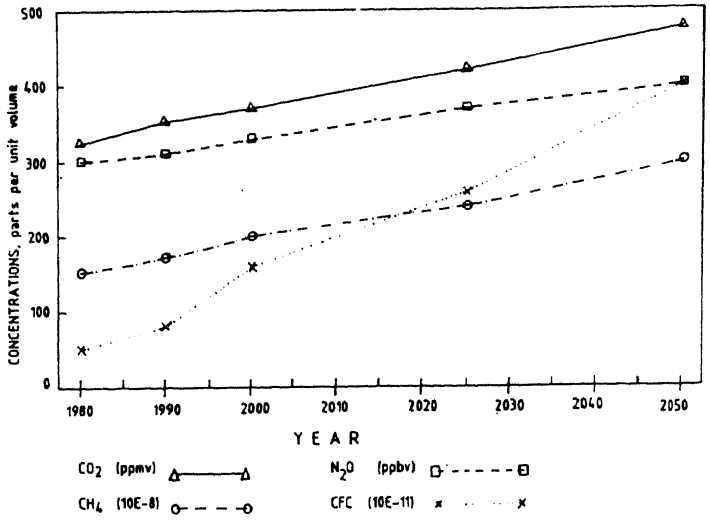

Figure 2. Growth of atmospheric concentrations of greenhouse gases based on linear extrapolation of the present rate of emission fluxes.

Table 2. Growth of atmospheric loading of trace gases due to anthropogenic causes. (a) Annual fluxes, (b) Total accumulation of trace gases in the atmosphere

Trace gas		1980	1990	2000	2025	2050
CO_2	a) Gt C/yr	5	7	8	9	10
	b) GtC	689	748	784	890	1009
CH_4	a) Mt/yr	40	50	60	85	110
	b) Mt	4450	4900	5390	6845	8685
N_2O	a) MtN/yr	12	12.3	12.6	13.5	14.1
	b) MtN	1370	1500	1770	2200	2810
CFCs*	a) Mt/yr	0.67	1.2	0.69	0	0
	b) Mt	—	9.35	26.5	30	20

*Fluxes and total accumulation of CFCs are calculated taking into consideration the control measures of Montreal Protocol (1990) and expected global growth in population separately for developing and developed countries.

GtC = Gega tonnes (10^{15}g) of carbon; Mt = Million tonnes (10^{12}g); MtN = Million tonnes (10^{12}g) of nitrogen

Table 3. Production/consumption of CFCs as regulated by the two versions of Montreal Protocol

			1980	1990	2000	2025	2050
(i)	Per capita consumption of CFC (kg)						
	(a) Developing countries	I	0.003	0.006	0.10	0.10	0.10
		II	0.003	0.006	0.10	0.00	0.00
	(b) Developed countries	I	0.8	1.1	0.6	0.5	0.5
		II	0.8	1.1	0.15	0.0	0.0
(ii)	Cumulative fluxes (Mt)						
	(a) Developing countries	I	—	0.2	4.5	15	38
		II	—	0.2	4.5	7	5
	(b) Developed countries	I	—	9.2	19.4	35	50
		II	—	9.2	22	23	15
	(c) Total	I	—	9.4	23.9	50	88
		II	—	9.4	26.5	30	20

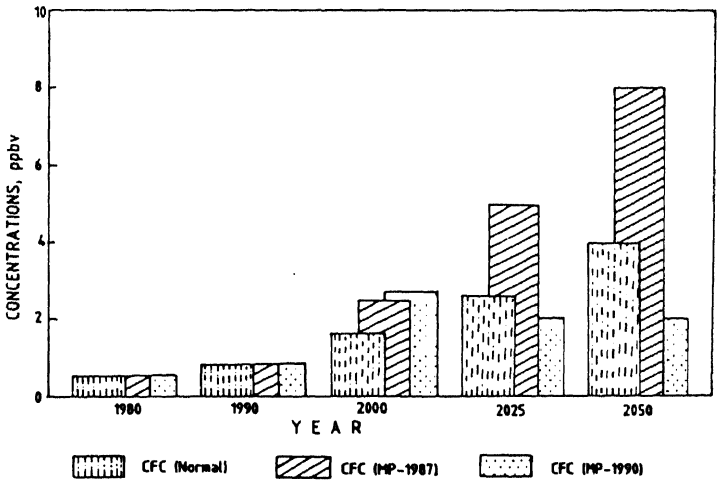

Figure 3. Comparison of future accumulation of chlorofluorocarbon concentrations in the atmosphere using three scenarios namely linear extrapolation of present rate of fluxes and the rates of emission as controlled by the provisions of Montreal Protocol, 1987 and its revised version of 1990.

It is clear that the control of future emissions of CFCs is linked with the overall technological development to find suitable CFC substitutes and ensuring the large-scale usage of such substitutes by developing countries, in particular. Noting that the developed countrties with less than 25% of the global population account for 98% of the present CFC emission, and if the large population in the developing countries in their anxiety to rapidly improve their standard of life increases their consumption of CFCs, the concentration of CFCs, would become unusually high. It is clear that CFC control measures can become practically effective only when the technologies of newly developed CFC substitutes are made available to developing countries at affordable costs.

Model calculations of global warming

Using the atmospheric concentrations of trace gases in the coming decades as derived in the previous section, the EB model mentioned earlier has been used to compute the change in global mean surface–air temperatures. The model calculations have been carried out mainly by assigning the changes in radiative contributions of trace gases in terms of their greenhouse potential to convert for equivalent CO_2 concentrations. The present-day mean global temperature and albedo values with zonally averaged latitudinal distribution, are used along with empirical values of constants A, B and K in eqs. (6) and (7). Before projecting the future scenarios of global warming, the sensitivity of the model

is checked for doubling of concentrations of CO_2 and other greenhouse gases from a reference value of these gases. The results of these sensitivity tests are compared with results of the RC model obtained by using the following empirical formula given by Kondratyev *et al*[20]:

$$\Delta T(K) = 0.57\,[CH_4]^{0.5} + 2.8\,[N_2O]^{0.6} - 0.057\,[CH_4]\,[N_2O] + 0.15\,[CCl_3F] + 0.18\,[CCl_2F_2] + 2.5 \ln\{1 + 0.005\,[\Delta CO_2] + 10^{-5}\,[\Delta CO_2]^2\}, \quad (8)$$

where the gas concentrations are in ppmv except for CCl_3F and CCl_2F_2 which are in ppbv, and the CO_2 is in ppmv above a reference value of 300 ppmv. The results of the increase in surface–air temperatures from the two models as shown in Table 4 compare quite well. Using our EB model, possible increases in the average global surface temperatures up to 2050 AD due to individual trace gases are shown in Table 5 and Figure 4. Major conclusions drawn from the above computations are summarized below.

Summary of results on global warming

(a) Our model calculations using the linear extrapolation of the present annual growth rates of the atmospheric concentration of CO_2, CH_4, N_2O, CCl_3F (CFC-11) and CCl_2F_2 (CFC-12), indicate a global warming of about 3 K by the year 2050 in broad agreement with the results of other authors.

(b) A striking result of the analysis is that if CFCs continue to be produced at the present rate then by the year 2050 their contribution to global warming will exceed the combined contribution due to CH_4 and N_2O. If the two scenarios of CFC concentrations based on the regulatory measures of Montreal Protocol (1987) and its revised version (1990) are considered then by the year 2050, the contributions to global warming due to CFCs alone will be 1.4°C and 0.34°C respectively. This indicates that the provision for per capita consumption of CFCs under Montreal Protocol (1987) was unrealistic and the situation would improve considerably if the

Table 4. Global warming due to doubling of concentration of greenhouse gases – comparison of results of Radiative Convective (RC) model of Hansen *et al.* (1981)[28] and simple radiative (R) model (present work).

Gas constituent	Base value of atmospheric concentration (ppmv)	Doubling of the base value of atmospheric concentration	Global warming (K)	
			RC-Model	R-Model (present work)
CO_2	300	600 ppmv	2.8	2.83
CH_4	1.6	3.2 ppmv	0.4	0.35
N_2O	0.28	0.56 ppmv	0.6	0.60
CFC-11 and CFC-12 (combined)	0	4 ppbv	0.5	0.65

Table 5. Model calculations of global warming using the projected growth of the atmospheric concentrations of greenhouse gases.

Gas constituent:	$\delta(\Delta T)$, K				
	1980	1990	2000	2025	2050
CO_2	0.40	0.70	0.85	1.27	1.75
CH_4	0.12	0.16	0.21	0.27	0.37
N_2O	0.04	0.06	0.10	0.18	0.25
CFC-11 & CFC-12					
(a) Montreal Protocol (1987)	0.09	0.13	0.42	1.0	1.4
(b) Montreal Protocol (1990)	0.09	0.13	0.46	0.34	0.34
(c) Normal growth (not controlled by Montreal Protocol)	0.09	0.13	0.27	0.44	0.68
Totals (a)	0.65	1.05	1.58	2.72	3.77
(b)	0.65	1.05	1.62	2.06	2.71
(c)	0.65	1.05	1.43	2.16	3.05

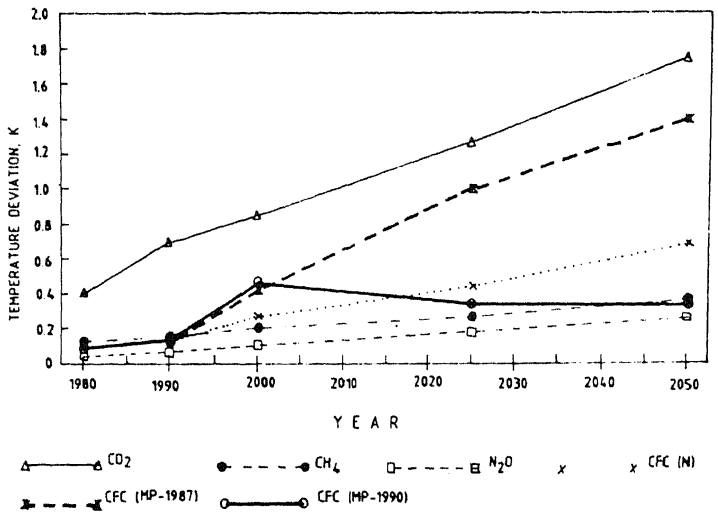

Figure 4. Global change in temperature calculated using the Energy Balance model for the projected atmospheric concentrations of greenhouse gases shown in Figure 2 and Figure 3.

revised Montreal Protocol was implemented. However even with the total ban of CFC usage by the year 2010 under the revised protocol, the overall global warming will still be around 2.7 K by the year 2050.

(c) The atmospheric concentration of CO_2 by the year 2050 has been estimated based on a moderate energy consumption scenario. Pessimistic projections[4] based on higher energy consumption rates some of which predict that the total earth reserve of technically recoverable fossil fuel (3084 Terra Watts) would be exhausted by the turn of the century would increase the rate of emission to about 20 GtC/year by the year 2050. If this scenario is used the global warming due to enhanced atmospheric CO_2 concentration of about 535 ppmv alone would be as much as 2 K resulting in a total global warming exceeding 4 K.

(d) While the present annual rate of methane fluxes is not likely to increase substantially, the actual rise in its atmospheric fraction would depend on a large number of chemical reactions initiated through the photochemically driven oxidation process of the polluted troposphere. As mentioned in Appendix 2, methane oxidation may lead to production of tropospheric ozone under certain conditions. The net impact of these nonlinear reactions on climatic change during the coming decades is very difficult to assess with the present inadequate understanding of such climate–atmospheric chemistry interactions.

(e) The present growth rate of nitrous oxide flux is not expected to change drastically in the coming decades. However climatic feedback may be provided due to its photochemical decomposition in the stratosphere producing nitric oxide $\{N_2O + O(^1D) \rightarrow 2NO\}$, which destroys stratospheric ozone catalytically ($O_3 + NO \rightarrow NO_2 + O_2$ and $NO_2 + O \rightarrow NO + O_2$). Similarly CFCs get photodissociated in the stratosphere and would provide a climatic feedback by destroying ozone catalytically $\{CFCl_3 + h\nu\ (\lambda < 226\ \text{nm}) \rightarrow CFCl_2 + Cl;\ O_3 + Cl \rightarrow ClO + O_2;\ ClO + O \rightarrow Cl + O_2\}$.

Impact of global warming

The major concern of global warming impact is the melting of snow caps and continental glaciers which will raise the sea level causing catastrophic inundation of land areas, particularly the littoral states and coastal regions. According to an estimate, if the whole of the present 25 million km^3 volume of continental ice were to melt this would produce a sea level rise of 65–70 m. A number of models have been developed to compute the magnitude of snow-melt causing the rise in sea level. Revelle[21] derived a sea level rise of about 70 cm for a global warming of 6 K. While there are uncertainties of the order of 25% in these estimates, realistic values can be obtained by assuming a moderate rise in sea level by 2 mm/year for every 1 K increase in global temperature[22].

A direct consequence of sea-level rise is the recession of shore-line due to flooding. The magnitude of this change depends on the topography of the affected region including beach profiles, coastal erosion characteristics etc. Hoffman *et al.*[23] suggested an empirical relation which predicts an average global shore-line recession of 1.5 m for every centimetre sea-level rise.

While rainfall is likely to increase by 5–15% at high and low latitudes, decreases in rainfall are likely to occur between middle latitudes (30°–45° N or S) if the global warming is of the order of 3–4 K[24]. Also the increase in potential evapotranspiration rates due to global warming will result in marked water stress. Then global warming will inevitably change the climate and affect food production, particularly in the tropical countries of Africa, South America and Asia, where the productivity is already poor[25]. A detailed analysis which has to be carried out regionwise is highly complex and beyond the scope of this paper. Notwithstanding, on a global basis, the studies indicate that yields of rice and wheat crops can get reduced by about 5% due to 1 K change in global temperature[26].

While increasing concentration of CFCs in the troposphere contributes substantially to global warming, these gases catalytically destroy ozone in the stratosphere through photochemical reactions. The magnitude of this ozone depletion due to CFCs has been estimated by Haigh and Pyle[27] using a 2D model incorporating the radiative, dynamical and photochemical interactive processes. A typical result of this study is that doubling of CO_2 and four-fold increase in CFC concentration produced an ozone depletion of 8%. The effect of CO_2 is to increase ozone concentrations through radiative cooling in the stratosphere providing a negative feedback to ozone loss process due to CFCs.

Using the above considerations and empirical relationships, the impact of global warming on rise in sea-level, shore-line shifts, global food production and ozone depletion (due to increase in stratospheric CFCs) has been computed for the scenario of temperature increase of 3 K due to projected growth of green house gases at the present rate up to the year 2050. The results of such computations shown in Table 6 reveal that the climatic impact of this global warming will result in a sea level rise of 18 cm, shoreline recession of 27 m, reduction of food production by 15% and ozone depletion of about 14% (without considering the possible reduction in CFC concentrations due to the implementation of Montreal Protocol, 1990).

Conclusions

Analysis of surface–air temperature data has shown that the average global temperature increased by about 0.5 K during the past hundred years. Similar warming trend has also been observed over India on a regional scale. The results of a variety of climatic models developed for the purpose indicate that continuous growth of anthropogenic emission fluxes of CO_2, CH_4, N_2O and CFCs may have been responsible for this global change. The existing radiative–convective and three-dimensional general circulation models are not adequate to tackle the problem in its entirety as these do not take into account all the climatic feedback effects and the important role played by atmospheric chemistry which govern the atmospheric lifetimes of the greenhouse trace constituents. It is shown that simple energy balance models can be used quite effectively to compute the magnitude of average warming of the earth's surface, the results of which are in broad agreement with other models and agree with the observed change in global temperatures. Realistic estimates of the increase in the total atmospheric reservoir and the atmospheric concentrations of greenhouse gases have been made up to the middle of the next century by assuming the realistic growth rates of these gases. For CFCs, two additional scenarios corresponding to the voluntary restrictions in the use of these chemicals under the provisions of Montreal Protocol, 1987 and its amended version in 1990, have been examined and it is found that the implementation of 1990 protocol could help contain the global warming by CFCs alone to about 0.3 K compared to 1.4 K if the 1987 protocol were to be exercised. However the overall global rise in temperature due to all greenhouse gases in the former case could still be about 2.7 K by the year 2050 and this calls for similar control measures in checking the growth of other trace gases due to fossil fuel burning, deforestation etc. Unless this is done, the climatic impact of this global rise in temperature by the year 2050 on sea level rise (18 cm), shoreline recession (27 m), reduction in food production (15%) and ozone depletion (14%) could become a major challenge to the survival of mankind.

Table 6. Climatic impacts of global warming

	1980	1990	2000	2050
$\delta(\Delta T),K$	0.65	1.05	1.43	3.05
Sea level rise (cm)	2.6	3.7	4.3	18
Shoreline recession (m)	4.0	5.6	6.5	27
Reduction in global food production (%)	—	2.6	4.3	16
Ozone* (%)	0.2	4.5	6.5	14

*Projection of ozone depletion based on increase of CFCs at the present level of growth rate and without considering the impact of implementation of Montreal Protocol.

Appendix 1. Temperature dependence of tropospheric concentrations of methane.

The concentrations of methane in the troposphere for a given flux depends on the photochemical reactions responsible for its removal as follows:

$$O_3 + h\nu(\lambda < 342\text{nm}) \rightarrow O(^1D) + O_2 \quad \text{(a)}$$
$$O(^1D) + H_2O \rightarrow 2OH \quad \text{(b)}$$
$$CH_4 + OH \rightarrow CH_3 + H_2O \quad \text{(c)}$$

The rate of reaction (c) is

$$\Delta[CH_4] = -k[CH_4]\,[OH]\,\Delta t, \quad \text{(d)}$$

where brackets represent gas concentrations
k = reaction rate constant $= 2.4 \times 10^{-12}\exp(-1710/T)$ (e)
Δt = increment in time; and T = surface–air temperature
Substituting k for two temperatures 288 and 298K in equation (d), it can be seen that this temperature change of 10K will lead to a decrease of methane concentration by about 22% as compared to an increase of 80–90% observed from ice core analysis. Present understanding of methane sources and sinks is not adequate to explain this large variation of CH_4 concentration during the glacial–deglacial period.

Appendix 2. Photochemistry of polluted atmosphere.

Methane is oxidized in the troposphere by reacting with OH and O_2 molecules. A chain reaction is initiated by this process leading to either production or destruction of tropospheric ozone. The production or loss of ozone critically depends on the concentrations of NO_x ($NO + NO_2$), CO and non-methane hydrocarbons (NMHC) molecules. Some of the photochemically governed reactions of the troposphere are given below:

$$CH_4 + OH \rightarrow CH_3 + H_2O$$
$$CH_3 + O_2 + M \rightarrow CH_3O_2 + M$$
$$CH_3O_2 + NO \rightarrow CH_3O + NO_2$$
$$CH_3O + O_2 \rightarrow HCHO + HO_2$$
$$HCHO + OH \rightarrow CO + HO_2$$
$$HCHO + h\nu \rightarrow H_2 + CO$$
$$HCHO + h\nu \rightarrow H + HCO$$
$$H + O_2 + M \rightarrow HO_2 + M$$
$$HCO + O_2 \rightarrow HO_2 + CO$$
$$OH + CO \rightarrow CO_2 + H$$

$$OH + H_2 \rightarrow H_2O + H$$
$$OH + NO_2 \rightarrow HNO_3$$
$$OH + O_3 \rightarrow HO_2 + O_2$$
$$HO_2 + NO \rightarrow NO_2 + OH$$
$$HO_2 + O_3 \rightarrow 2O_2 + OH$$
$$NO_2 + h\nu(\lambda < 420\ nm) \rightarrow NO + O(^3P)$$
$$O(^3P) + O_2 + M \rightarrow O_3 + M$$
$$O_3 + NO \rightarrow NO_2 + O_2$$

Presence of other NMHC molecules will remove NO_x through similar oxidation reactions, eg:

$$R.H + OH \rightarrow R. + H_2O$$

(where $R.$ is the alkane radical other than CH_3.)

$$R. + O_2 + M \rightarrow R.O_2 + M$$
$$R.O_2 + NO \rightarrow R.O. + NO_2$$
$$NO_2 + O_3 \rightarrow NO_3 + O_2$$
$$NO_3 + NO_2 \rightarrow N_2O_5$$
$$N_2O_5 + H_2O \rightarrow 2HNO_3$$

Hence production or destruction of ozone is the outcome of a complex set of chemical reactions. Ozone is produced due to oxidation of methane provided NO_x is present in right proportion. For low or very high values of NO_x, ozone in the troposphere will be lost.

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ACKNOWLEDGEMENTS. We thank Shri M. G. Chandrasekhar, Shri V. Jayaraman, Shri K. R. Sridhara Murthy, Dr B. Manikiam and Dr P. P. Nageswara Rao for useful support and discussions. Temperature data over Indian region received from the India Meteorological Department is thankfully acknowledged.

Received 13 August 1991; revised accepted 16 November 1991