ATMOSPHERIC MODELLING

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The possible consequences of global warming have raised so much concern that United Nations has sponsored an effort to develop cooperative mitigation strategies for greenhouse phenomenon. The global temperatures and precipitation with increased levels of carbon dioxide and other greenhouse gases have become a subject matter of deep concern. While actual measurements enable the temperature profile existing at any particular time, modelling has become necessary to predict global warming effects. Even if such predictions are prone to large margin of errors, they are required for the development of mitigation strategies for global warming and risk is too large not to look for means of mitigation.

The various atmospheric modellers employ one-, two- or three dimensional models with varying levels of sophistications and demand on computer time. One dimensional models compute the composition of atmosphere as a global average varying only with the altitude. The two dimer.sional models calculate changes with both latitude and altitude. In the three dimensional models, Earth's surface is divided into 800-11000 grid points and atmosphere over each grid point is divided into five to fifteen layers. Projections far into the future using three dimensional models are prohibitively expensive due to the time required on super computers. Although spacial resolution in the global climate is often inadequate, such models do produce accurate simulation of some phenomena. Comparisons of simulated data with the total ozone mapping made on Nimbus 7 satellite has raised significant issues in the predictability of atmospheric models in general. Most of these models contain about 160 chemical reactions and more than 40 reactive species. Each time a reaction rate is remeasured, a new species or reaction discovered or a new product for a known reaction identified, the models need further refinement, especially if prediction far into the future is required. However, for short term applications such as the regulation of traffic in a crowded city, simpler models with the required level of reliability do exist. Since the species with long lifetimes such as $CFCl_3$ or CF_2Cl_2 with 73 and 110 years respectively seem to hold more threat to global climate, it has become essential to examine the lifetimes of relevant chemical species and even some airborne dust and inorganic materials. In this presentation, the Status of Art in atmospheric modelling and its possible role in policy making would be highlighted.

HUMAN INFLUENCE ON ATMOSPHERIC CONSTITUENTS : TODAY'S CONCERN

Atmospheric temperature has played a key role in the evolution of intelligent life on the Earth. A remarkable feature is that minor constituents present in parts per million or billion levels dominate the atmospheric properties. Especially, the atmospheric temperature is sensitive to levels and nature of trace gases in the environment. In the evolution of atmosphere, supernova explosions are known to have altered the concentrations of such minor atmospheric constituents. Climatic changes are believed to have led even to the extinction of several life species in the past and the climate is known to be influenced by trace gases as discussed by Mitra (1980).

The human activities have attained such proportions that their influence on the atmospheric constituents has now become apparent. Therefore, the response of the atmosphere to human influences has not only become relevant but also necessarily a matter of deep concern. Human impact on climate can arise out of alterations in the biosphere as well as atmospheric constituents. There are now increasing emissions of pollutants which persist in the atmosphere for long periods and can give rise to global problems. There are also steady discharges of pollutants with shorter atmospheric residence times which can contribute to an imbalance of the environment in the region.

Gaseous pollutants listed in Table 1 with longer atmospheric lifetimes are capable of diffusion into various atmospheric layers extending from 10-50 km above the Earth's surface (Hileman, 1989). The gases listed in Table 1 are now known to perturb the global thermal environment. The oxides of sulphur and nitrogen formed from the combustion of fossil fuel possess shorter atmospheric lifetimes and contribute

TABLE 1: Concentrations, Lifetimes of Greenhouse Gases

	Atmospheric concentration, ppm (volume)	Atmospheric lifetime
Carbon dioxide	350	~500 years[a]
Ozone	0.02-10	less than a few hours[b]
Methane	1.7	7-10 years
Nitrous oxide	0.31	150 years
CFC-11 ($CFCl_3$)	2.3×10^{-4}	75 years
CFC-12 (CF_2Cl_2)	3.8×10^{-4}	110 years

[a] Combined lifetime for atmosphere, biosphere, and upper ocean.

[b] Although lifetime of ozone itself is less than a few hours, lifetime of O_2 (ozone + oxygen atoms) depends strongly on location, varying from about an hour in the upper stratosphere to months in the lower stratosphere to hours to days in the troposphere.

Source : Department of Energy.

to acid rain. A summary of the levels of annual transfer rates of various elements into the environment resulting from human activities is included in Table 2. There is discharge of both solid and liquid wastes and gaseous emissions.

TABLE 2: Elemental Composition of Aerosols and the Annual Transfer Rates of Elements

Elements	Aerosol composition[a,b]	Annual transfer combustion	Rate mining[c]
Al	54-8000	2800	134000
As	0.5-80	1.5	47
Be	0.3-8	0.28	1.1
Ca	600-20000	420	~83000
Cd	1-47	0.065	7.7
Cr	4-180	2.8	~2500
Cu	8-1100	4.6	6190
Fe	100-14000	2200	680000
Hg	1-14	8.4	8.4
Mn	2-380	14	24600
Mo	0.2-12	0.8	76
Ni	0.4-230	5.6	560
Pb	30-7700	183	3340
Sb	0.2-91	0.28	75
Se	1-9	3	1.04
Si	120-18000	8400	380000
Sn	0.3-160	0.54	178
Ti	4-580	140	~1000
Zn	9-2500	22	4040

[a] typical composition at London.
[b] in mg/kg dust.
[c] 106 kg/year.

ATMOSPHERIC MODELS FOR ASSESSMENT OF HUMAN IMPACT

There is little that humans could do to alter the influence of the Sun on the Earth. However, there are now indications that additions to atmospheric constituents resulting from human activities may have an impact on climatic cycles as well as the biosphere around a specific region in the globe. Therefore, there are attempts being made to assess:

(i) The trends in the climatic changes occurring over centuries to delineate any superimposed effects of human activities and

(ii) The dangers of industrial activities to regional atmospheric conditions and life population.

An attempt has now been made to selectively review the atmospheric modelling approaches to both global and regional scenarios. Although basic principles involved

in the two types of model systems are similar, the dimensions of the problem vary markedly. Whereas regional models deal with emissions from point and continuous sources, the human impact on climatic changes is expected as a result of steady discharges of constituents exhibiting long atmospheric residence time over extended periods.

GLOBAL WARMING : A CAUSE FOR ALARM

The greenhouse effects of trace gases in the environment participate in the thermal regulation of the atmosphere. The thermal radiation environment of the Earth is undergoing a perturbation due to variations in greenhouse effects. Minor variations in temperature of the Earth can well lead to significant changes in the biosphere and geobiochemical cycle of the planet.

A simplistic model representing the energy transfers based on radiative-convective modes along one dimension namely vertical distance from the Earth and the importance of trace gases is depicted in Figure 1.

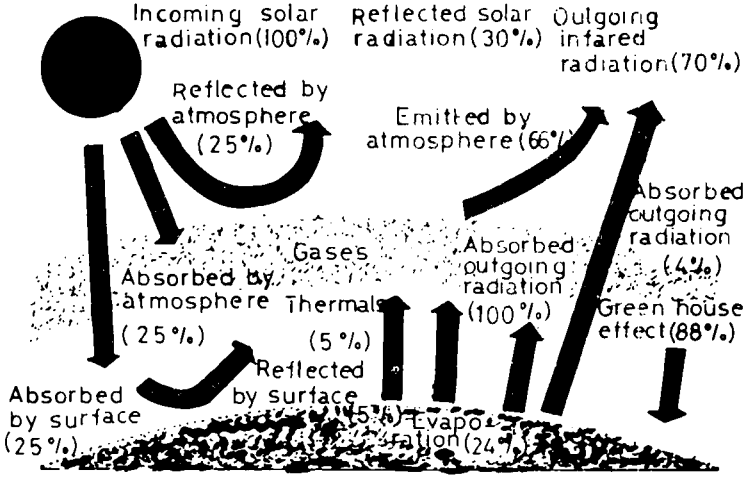

Fig. 1. Heat budget of atmosphere.

Several independent analyses of the Earth's surface temperature over the past century have shown that the past 10 years have been the warmest decade on record (Hileman, 1989). Although there are controversies on the possible consequences of the greenhouse effect, alarming consequences to global warming have been predicted (Global Change Report No. 4, 1988). A warming rate of 3.5° to 4.5° C over the next century has been predicted. Although the magnitude of the increase may seem small, even a change of 1°C can be severe and a global increase of 2°C is unprecedented in the era of human civilization.

Direct effect of global warming will be on ocean levels. Climatologists have generated various scenarios of temperature dependent ocean level increases and one such analysis is depicted in Figure 2 (Hileman, 1989; Ember *et al.*, 1986). With one-third of world's population living in coastal zones ocean level increases can endanger a vast section of human population. Therefore there is now a need to model the consequences of greenhouse warming effects which predict a slow but steady and alarming change. On the other hand, release of a toxic gas can impact the life system in the vicinity. The risk of such gas releases to the local environment needs also to be assessed, especially in view of a number of major industrial accidents in recent times.

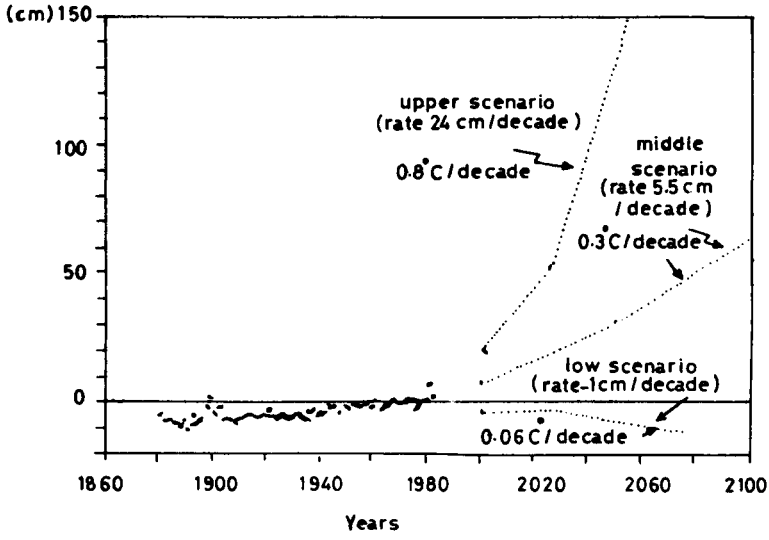

Fig. 2. Global sea-level change (cm).

MODELLING FOR RISK ASSESSMENT

A newer dimension has now become evident from recent industrial accidents such as those at Bhopal and Mexico city. Potential dangers of acutely toxic or combustible gas clouds to life systems are now obvious. The need for suitable safety/risk assessment is increasingly felt. Therefore mathematical models for atmospheric dispersion of toxic gas releases are attaining importance.

The basic difference between the two sets of risk assessment models namely those dealing with climatic changes on one hand and the immediate atmosphere on the other arises from the spatial and time frame considerations. Generally the mathematical models dealing with risk assessment of industrial gas releases deal with altitudes of 1-2 km and much higher concentrations of gases (Pasquill, 1980), whereas climate models need to deal with such greater heights as 10-40 km from the Earth's

surface and concentration levels of ppm and ppb. There are very few problems concerning the action of pollutants on the environment that do not at some stage involve a consideration of how materials are mixed and dispersed in fluid. In other words, atmospheric modelling deals with the influence of various factors on dispersion and mass transfer (Pasquill, 1980).

SOME GENERAL CONSIDERATIONS IN RISK ASSESSMENT MODELS

Mathematical models to describe the dispersion of heavy gases (heavier than air) have been developed and extensive reviews have appeared (Griffiths, 1984; Havans, 1987). There are a number of mathematical models, but commonly they are used to estimate the concentration downwind of a pollutant source located in a mixing layer. Mixing layer is believed to extend upto 0.5-1.0 km above the Earth's surface. Meteorological conditions, undoubtedly would influence the mixing layer significantly. The flow of gases is affected by the frictional drag of the Earth's surface within the mixing layer. A progressive reduction wind-speed is expected as the altitude decreases from the top of the mixing layer. Another important factor contributing to mixing is the heating of air in contact with the ground, which is warmed by the Sun.

Consideration of the spatial distribution of an airborne material necessarily needs to take into account (i) the shape of the distribution of concentration at any given time and downward position, (ii) the dimensions of the diffusing cloud, and (iii) whether the material is lost by deposition or decomposition. Dispersion models for two idealized cases of discharges namely instantaneous and continuous can be represented as in Figure 3. In a homogeneous air stream, diffusion along the x-axis (the mean wind), y-axis (crosswind) and z-axis (vertical) directions needs to be

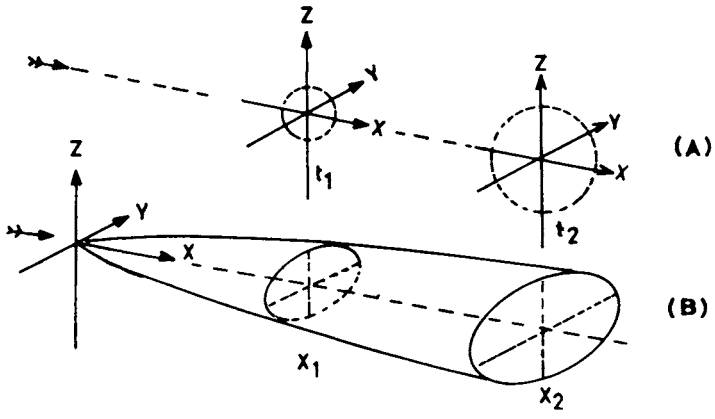

Fig. 3. Idealized representation of instantaneous (A) and continuous (B) sources.

considered (Pasquill, 1980). In case of an instantaneous point source, an equation of the general form as follows can be considered assuming exponential functions.

$$X\ (x, y, z, t) = A_1\ [\exp - (a|\ x\ |^p + b\ |y\ |^r + c\ |z\ |^s)]$$

where X is the concentration of the airborne material (unit of matter per unit volume), x,y,z are measured from a moving origin situated at the centre of the mass cloud. The quantities, p,r and s have positive values (Pasquill, 1980). In case of a continuous point source, applying continuity condition, equation of diffusion can be written as below:

$$X\ (x, y, z) = A_2 \exp\ [\ -\ (b|\ y\ |^r + c\ |z\ |^s\ )]$$

The above two equations define that zero concentration of the gas is observed only at infinity values of x, y and z. Therefore, these equations may be conveniently redefined as follows:

$$\int {}^{\infty}\!\int_{-\infty} \int xdxdydz = Q$$
$$\int {}^{\infty}\!\int_{-\infty} uXdydz = Q$$

An idealized formula recommended for the estimation of concentration at short range from a ground level continuous point source in neutral conditions can be written as below:

$$X\ (x, y, z) = \frac{Q_1}{2\Pi\ \sigma_y \sigma_z u} \exp\left|\frac{-y^2}{2\sigma_y^2}\right| \exp\left|\frac{-z^2}{2\sigma_z^2}\right|$$

where Q is the rate release of material and the quantities and σ_z are root mean square displacements (i.e. the standard deviations of the crosswind concentration distributions horizontally (y) and vertically (z) and u friction velocity. The values of σ_y and σ_z are evaluated on the basis of a correlation of data obtained from field experiments and needs to be categorized according to meteorological conditions including atmospheric stability (Pasquill, 1980; Havans, 1987).

Number of similarity and three dimensional models for estimating the assessment of risk from release of industrial gases have been reported already and many of them are being successfully used (Pasquill, 1980; Griffiths, 1984; Havans, 1987; Anita *et al.*, 1988). Essentially the gas dispersions to an altitude of say 0.5-1.0 km have been computed.

Changes occurring in the concentrations of gases beyond an altitude of 10 km are relatively minor. The concentrations of gases at such altitudes are so low that in three dimensional models used for industrial risk assessment the numerical diffusion errors in calculations cannot be easily overcome. However, even minor changes in the concentrations of trace gases present at such altitudes are known to influence the temperature of the planet significantly. Therefore, more elaborate models are necessary. Global changes due to greenhouse warming have become a matter of intensive study and search for suitable atmospheric models has become necessary.

GLOBAL CHANGES : ROLE OF GREENHOUSE GASES

The air, clouds, soils, vegetation and any form of material in the planet either reflect or absorb and re-emit a portion of the Sun's energy incident upon them. The bodies which absorb the energy radiate in the infrared region of the electromagnetic spectrum. Such an emitted energy is absorbed by some trace gases in the atmosphere, thus trapping a great proportion of the Sun's energy providing a greenhouse effect and a thermal radiation environment suitable to mankind.

The amounts of naturally occurring atmospheric trace gases such as carbon dioxide, methane and nitrous oxide and new radiatively important gases such as chlorofluorocarbons and other halocarbons are on the increase. The observed increases in the concentrations of carbon dioxide, methane, nitrous oxide and atmospheric halocarbons are as shown in Figure 4 (Ember *et al.*, 1986). It is now feared that such increases in greenhouse gases can aggravate the global warming effect.

Since the first systematic measurement of atmospheric carbon dioxide in 1958, its level has increased from 315 to 350 ppm. From the analysis of the air trapped in the ice cores of Antarctica, the preindustrial level has also been estimated to be 280 ppm. The current level of carbon dioxide appears to be the highest for the last 160,000 years (Hileman, 1989). Burning of fossil fuel and massive deforestation are the main reasons attributed for the changes in carbon dioxide levels.

Although the concentrations of the other trace gases such as methane, nitrous oxide, tropospheric ozone are much less relative to carbon dioxide, it is now estimated that they trap as much as 60 % of the energy trapped by carbon dioxide. Further, each molecule of other trace gases absorbs more infrared light than a carbon dioxide molecule. The combined greenhouse warming effect of other trace gases is believed to be equal to that of carbon dioxide. The role of methane, for instance, in greenhouse warming has received much attention in recent years, particularly because each molecule of methane is 15-30 times more effective than carbon dioxide molecule.

The possible interactions of some trace gases like nitrous oxide of halocarbons with tropospheric ozone raise further alarms. The Total Ozone Mapping Spectrometer housed in Nimbus 7 satellite has given valuable information on the trends of ozone levels in the atmosphere (Heath *et al.*, 1985; Ember *et al.*, 1986). The data based on tropospheric ozone levels is not complete and its effect on surface warming is complex. In upper troposphere it contributes more to surface warming than it does in the mid- or upper stratosphere.

Ozone depletion in the lower troposphere, in contrast, induces some surface cooling. Therefore, it becomes necessary in the case of ozone to examine the overall effects on surface warming by assessing the variations of the concentrations of the gas at various heights. Since there is an overall increase in global temperature, the possible roles of all the greenhouse gases have aroused much interest and concern. There is an attempt to estimate or predict the concentrations of greenhouse gases at different altitudes and latitudes. Particularly the ozone depletion in Antarctica has become a puzzle and the scientific opinion that the industrial activity in one part of the globe can influence markedly the ozone layer in another has made it necessary to take into account all relevant factors.

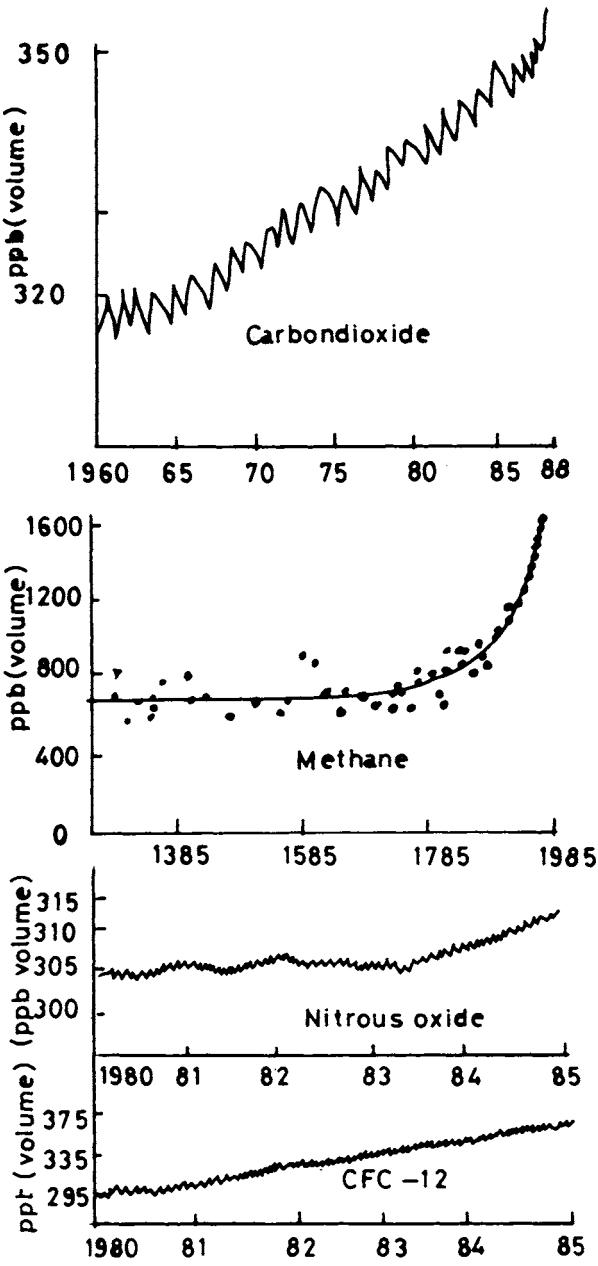

Fig. 4. Atmospheric concentrations of trace gases.

It is not surprising that in the last two years, the theory about greenhouse warming has been elevated to a matter of serious concern. Especially there is a growing concern on the level of ozone around 40 km above the Earth's surface. This is significant because the type of species involved in the depletion of ozone may vary depending on the altitude. Chlorine is thought to be destroying ozone at 40 km whereas nitrogen radicals are believed to be important at the altitudes of 12-30 km. The ozone depletion in the stratosphere is considered an early warning of the further climatic changes to come. There is now a sufficient evidence by way of direct measurements for the depletion of ozone layer over Antarctica.

ANTARCTIC OZONE PUZZLE

Data collected from Solar Backscatter Ultra Violet and Total Ozone Mapping Spectrometer (TOMS) aboard Nimbus 7 satellite showed unambiguously the more rapid depletion of ozone at the rates of 2.5 % over Antarctica, 1.5 % over the tropics and negligible over other areas. The seasonal variations in the ozone hole levels over the Antarctica have caused much discussion (Zurer, 1987; Hileman, 1989).

The observed variations in ozone levels over Antarctica have been analysed in terms of natural phenomena taking into account hydrodynamic and air current characteristics. Theories have been proposed that Antarctic ozone hole is a natural phenomenon. However, some environmentalists argue that the hole is a consequence of chlorofluorocarbons (Hills *et al.*, 1987; De Zafre *et al.*, 1987; Solomon *et al.*, 1987). In order to explain the loss of ozone at the altitudes of 12-20 km above Antarctica, where chlorine is expected to be in the inactive form for ozone depletion, a complex series of heterogeneous reactions has also been proposed (Rowland *et al.*, 1987). A photochemical process involving HOCl has been invoked as shown in the Table 3.

TABLE 3: Ozone Depletion Pathways Resulting from HOCl Photochemistry

$H_2O + ClONO_2$	⟶	$HOCl + HNO_3$	(1)
$HOCl + h\upsilon$	⟶	$Cl + OH$	(2)
$Cl + O_3$	⟶	$ClO + O_2$	(3)
$HO + O_3$	⟶	$HO_2 + O_2$	(4)
$ClO + HO_2$	⟶	$HOCl + O_2$	(5)

While the real causes for the ozone depletion over the Antarctica remain a puzzle, the need to examine the possible effects of such depletions on the global climate is being increasingly recognized. Climate modelling has aroused both scientific and public interest.

CLIMATE CHANGE : WHY TO MODEL ?

Modelling of the climate change has attained importance in recent years for several reasons. These are:

(i) Difficulties in explaining the observed statistical trend of global warming on the basis of chance and meteorological perturbations;

(ii) The discovery of a stratospheric ozone hole over Antarctica;

(iii) Possibilities that the ozone hole over Antarctica may have been caused by the release of chlorofluorocarbons and other man-made alterations to the environment;

(iv) The unprecedented increase in concentrations of the greenhouse gases; and

(v) The hope that with better understanding of the climate changes, a suitable mitigation strategy can be evolved if the models can give rise to reliable predictions.

There has been an increase in the remote sensing capability and substantial improvement in the range of devices for monitoring the atmospheric changes. There are controversies on the capabilities of the currently used climate models to discern man-made alterations from natural variations in climate but not on the need for modelling.

CURRENT CLIMATE MODELS : VARIOUS TYPES

Various factors in atmospheric models

The regions 35 km above the Earth's surface are considered to be photochemically controlled and the dynamical processes seem to be relevant in case of lower stratosphere. Factors such as the movement of air from the equator towards the poles or the upward transport of trace gases from the troposphere lying upto about 12 km above the Earth's surface are of prime importance in atmospheric modelling.

The most realistic computer models of the atmosphere need to consider photochemistry, radiation and transport of mass and heat as well as the coupling among the above three processes. Photochemistry is influenced by the nature of chemical species present in the atmosphere. The type and amount of photochemically relevant atmospheric constituents are now known to vary with the altitude and the location. The radiation incident upon the Earth from the Sun is also subject to major variations. The intensity and the wavelength of light incident upon the Earth's environment vary with time of the day, season, latitude and presence of greenhouse gases including ozone. The amount of solar radiation reaching Earth and Earth's changing orientation to the Sun have been important causes for climatic changes in the history of the planet throughout.

Changes in the Sun's irradiance are important. No scientific theory seems to exist to predict the future changes in the solar output. It is, however, recognised that the Earth's disposition with respect to the Sun varies cyclically over time. A periodicity of 41,000 years has been estimated in the tilting of the Earth towards the Sun from 22 to 24.5° and back again. The month when Earth is closest to the Sun varies over

the cycles of 19,000-24,000 years and currently January is believed to be the month when the Earth is in its closest position with respect to the Sun.

Variations in the shape of the Earth's orbit from being nearly circular to being elliptical with a periodicity of 100,000 years have been reported (Hileman, 1989). The climatic cycles caused by such orbital factors and inconsistency of the Sun as a radiation source are superimposed over any atmospheric perturbations resulting from human interventions. It is now believed that orbital changes alone would not cause vast climate shifts (Hileman, 1989). Feedbacks such as changes in Earth's reflectivity, dustiness of the atmosphere, the carbon dioxide and methane contents in the environment act together with orbtial changes to enhance global warming and cooling. Although some of the increase in carbon dioxide content in recent years has been attributed to human activities, the possible effects on the carbon dioxide levels of the atmosphere due to the striking of an extinction bolide onto a shallow marine carbonate rich sedimentary section have been assessed (O'Keffe and Aherms, 1989). It has been predicted that the impact of such a bolide (~KM in radius) onto a carbonate rich terrain would increase the carbon dioxide content by a factor of two to ten, which in turn could give rise to increase of global temperature by 2 to 10K and for periods of 104 to 105 years. In other words, natural processes of such large magnitudes are superimposed over the perturbations due to human impacts. In addition, most atmospheric models need to consider as many as 160 chemical reactions and the participation of more than 40 chemical species. With such complexities, atmospheric modelers are forced to rely on simplifications and make approximations.

Different climate models and their approaches

Most of currently used atmospheric models can be categorised as one-, two-and three dimensional types. One dimensional models compute the composition of the atmosphere as a global average varying only with altitude. The two dimensional models calculate changes with both altitude and latitude giving a longitudinal average. Three dimensional models are more realistic although they need considerable computer capability. The number of parameters and spatial resolution attempted in three dimensional models are large.

Future predictions using three dimensional values over extended periods of time are hence prohibitively expensive. However, such models are often used to calculate the global temperatures and the precipitation levels. In these models, the Earth's surface is divided into 800 to 11000 rectangles or grid points. The atmosphere over each grid point is divided into different layers ranging from a total of 5 to 15. The flow and mixing of atmospheric gases from each of these cells into adjacent cells is calculated using the basic laws of thermodynamics and hydrodynamics.

The laws of conservation of mass, energy and momentum are applied and the gas laws are taken into account. The transfer of electromagnetic radiation through a heterogeneous gaseous medium is related to incoming solar radiation and changes in the contents of each cell. The reflectivity of various surfaces such as ice, snow,

oceans, clouds and vegetated lands is included. Equations are solved to estimate winds, temperature, sunlight, relative humidity and precipitation for each point on the globe. In order to predict the effect of doubling of carbon dioxide and other trace gases on the atmosphere, the amounts of such gases are deliberately doubled and various scenarios are developed using three dimensional models. Variations in surface temperatures and alterations in cloud cover, wind and precipitation patterns are calculated.

In view of the increase of global mean tropospheric concentration of CFC-11 and CFC-12, respectively ~230 parts per and ~395 parts per 10^{12} by volume, there is now an effort to model the release and consequences of such gaseous emissions (Hammitt *et al.*, 1987; Wigley, 1988). A simple two-box model comprising an atmosphere box and delayed release box has been developed. The model equations are:

$$\frac{dM}{dt} = P_a + P_{na} + P - \frac{M}{\tau}$$

$$\frac{dD}{dt} = (1 - \alpha)\, P_{na} - D$$

where P_a/P_{na} are the aerosol/non-aerosol production rates, M and D are the masses in the atmosphere and delay boxes is the fraction of non-aerosols released directly to the atmosphere, alpha is the annual fraction of the delay box that leaks into the atmosphere and τ is the lifetime. Substituting rates of 0.25 and 0.15 for CFC-11 and 0.15 and 0.25 for CFC-12, various scenarios could be developed. The values of τ have been estimated as 75 and 111 yr. for CFC-11 and CFC-12 respectively. Different scenarios have been developed assuming that future concentration of CFC-12 and CFC-11 continue to increase asymptotically. A case where a cut-back in the production level of 1986 by 20 % was also assumed and the CFC levels computed. Production limits of ~19 % (CFC-11) and 15 % (CFC-12) of the 1986 values have been predicted to be required to stabilize the CFC concentration at the current levels. The greenhouse effect implications of various scenarios of CFC levels in the atmosphere have been analysed using radiative transfer models. The linear dependence of the direct radiative forcing perturbations (Q) on the concentration of C as in equations CFC-11; $\Delta Q = 0.00027C$ and CFC-12; $\Delta Q = 0.00031C$ has been assumed. For various values of α, β and τ, contribution of CFC-12 expected upto 2050 have been computed using mathematical models (Hammitt *et al.*, 1987; Wigley, 1988). The importance of the compliance of Montreal protocol on substances that deplete the ozone layer has been emphasised (Wigley, 1988).

Success of climate models and authentication

The currently used atmospheric models enable the prediction of summer and winter temperature extremes for large areas on the Earth. Calculated temperatures for various levels of the atmosphere of Mars and Venus, where coupling to well

developed biosphere is not relevant, are in close agreement with the values observed. Furthermore, the models have been able to simulate the temperature conditions that prevailed during Mesozoic Era and glacial/interglacial cycles. Experimental evidence for the temperatures of the past have been obtained from studies on ocean sediments and ice cores in Antarctica.

Some general limitations of climate models

All the atmospheric models developed so far have some basic limitations and one of them is the lack of required spatial resolution. A variety of atmospheric chemistry and physics occurs within the atmosphere over each grid point. For instance, storm fronts, mountainous ranges, urban/industrial pollution, atmospheric chemical reactions, changes in cloud type vary on spatial scales which are smaller than the sizes of the grid cells used by atmospheric modelers.

Accurate predictions of greenhouse warming involves understanding interactions among inconstant Sun and the highly complex systems of the atmosphere, biosphere and geosphere. Changes in one system such as the growth of phytoplankton or trees can produce a variety of effects on the atmosphere, some of which would produce warming and the others cooling. In other words, it is difficult to allow for feedback systems in climate modelling. Especially, the most important feedback system is the ocean and the understanding of its dynamics in light of greenhouse effects is crucial to assess the extent of global warming due to greenhouse perturbations. The analysis of the temperature conditions during "Younger dryers" cold event between 11-10 Kyr has led to a belief that heat budget of the high altitude North Atlantic produced changes over land. General Circulation Model (GCM) results support the dominant role of sea-surface temperature fluctuations in forcing high altitude climate change (Broecker *et al.*, 1985; Overpeck *et al.*, 1989). The importance of sea-surface interactions and their possible role in season changes in tropics have been much realised. Upwelling of nutrient rich water along the coasts of Arabian sea due to seasonal reversals in the surface circulation has been analysed. The role of particle flux pattern and the atmospheric dust fall out on the biological productivity along the coastal lines is now recognized (Nair, 1989). In this context, the particulate emission of many trace metal ions due to human activities and the resulting atmospheric fall out needs careful investigation and a modelling effort.

Changes of tropical sea-air interaction processes over a period of 30 years during 1949-1979 have been assessed using experimental measurements of sea-surface temperature, sea-air temperature differential, scalar wind speed, saturation defect etc. (Flohn and Kapala, 1989). Tropical circulation changes have been predicted on the basis of this study. A warming of the tropical troposphere by 1°C has been predicted to be associated with more frequent deep convections in oceans with sea-surface temperatures >27.5° . This is expected to cause the release of more latent heat into the atmosphere. The physical role of water vapour due to phase changes has been attributed to be more important than even its greenhouse effect. A positive feedback resulting from additional energy inputs may lead to the acceleration of delayed ocean

warming in lone altitudes (Flohn and Kapala, 1989). Thus the mathematical models need to necessarily take into account the complex processes resulting from sea-air interactions and the associated feedback responses. Currently used models need to take into account more fully the effects of ocean dynamics.

The prediction of the effect of global warming on the ecosystem, water supplies, agriculture and sea level changes is acutely more difficult at the global level. However, regional impacts can be assessed, although only with difficulty.

MITIGATION STRATEGIES

Global warming is now a phenomenon of much concern. Measurement of atmospheric trace gas levels gives valuable clues regarding trends in atmospheric and climatic changes. Modelling is perhaps a means to seek forewarnings of any catastrophe to come. It is possible to argue that the climatic models require further refinements, at least when the global changes are to be considered and the level of spatial resolution required is higher. The predictions made by the currently used models may be subject to large margin of errors. However, the risk of not acting on the possible alternatives to contain the global warming is too large to permit any complacency.

There is perhaps little that human kind could do to alter the weather cycle of the globe arising from natural phenomena. However, when the fear of the human impact on the weather cycle has arisen, it is necessary to evolve appropriate mitigation strategies against man-made global warming. There are still controversies on the beginning of the human impact on climatic change, but not on the potential danger resulting from some of the pollutants emitted by the industrialized world. Climate models may be prone to errors, but a blind and passive waiting is unacceptably foolish. There is now a need to discuss possible strategies to:

(i) Enhance capability to predict more accurately;

(ii) Measure and quantify the climatic perturbations; and

(iii) Evolve a global action plan for arresting the rapid increases in greenhouse gases.

Any discussion without support from a well conceived action plan and commitment could serve no purpose. There is an increasing recognition for the need to contain the global change. This is obvious from the jump in the federal funds for research on global change in USA by 42 % over the 1989 level. It is an area calling for interdisciplinary research inputs and committed political will of Nations to preserve the planet from impending adverse climatic changes.

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