# The Earth's Changing Climate

## Man-Made Changes and Their Consequences

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**Various human activities have contributed to an increase in the levels of greenhouse gases. The contribution that these make to global warming requires further investigation, because there are several negative feedback mechanisms which inhibit the warming process.**

### Introduction

Many generations of scientists have been intrigued by the forces that change our climate. This is more so today because of the need for sustainable development. Sustainable development implies a growth strategy that will not harm the environment.

In this article we will be mainly concerned with anthropogenic, or man-made causes of climate change, because a review of the entire climate system is not possible within the ambit of a short article. We will focus on the atmosphere, although a brief reference will be made to the role of oceans. Global warming by anthropogenic emissions is referred to as the greenhouse effect because the atmosphere acts as a greenhouse. It allows solar radiation to pass through but traps the outgoing infrared radiation from the earth. Realizing the importance of global warming, the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP) have set up an Intergovernmental Panel on Climate Change (IPCC). We will refer to their assessment reports.

In 1861, Dr John Tyndall, the English physicist, was the first to draw our attention to the rapid absorption of heat by humid air in the atmosphere. A little later, in 1896, the Swedish chemist Arrhenius presented a paper on the sensitivity of the atmosphere to small changes in its composition. These perceptive papers were the earliest to stress the greenhouse effect.

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## The Earth's Radiation Budget

The average solar energy intercepted by a unit area of the earth's surface is S/4, where S is the solar constant. The factor of 1/4 allows for the radiation falling at an angle on large parts of the earth's surface. As S is around 1376 watts per square metre ($W/m^2$), S/4 is 344 $W/m^2$. About one-third of this is either back-scattered by air molecules or reflected back to space and this fraction is often called the planetary albedo. So the amount entering the top of the atmosphere is about 240 $W/m^2$. Solar radiation is in the short wavelength range between 0.2 and 4.0 microns ($\mu$m).

The earth, in turn, radiates as a black body. It obeys the Stefan-Boltzmann law and its emission is proportional to the fourth power of the earth's surface temperature. This infrared radiation from the earth is in the long wavelength range from 4.0 to 80 $\mu$m. Many atmospheric gases have a rotation as well as a vibration-rotation spectrum, so they are able to absorb and also emit radiation. This has two interesting consequences. First, the net upward emission by atmospheric constituents, clouds and a small part of the earth's emission adds up to 240 $W/m^2$. This represents a balance between incoming and outgoing radiation. Secondly, there is a downward counter radiation from the atmosphere towards the earth. This traps the earth's infrared radiation like a greenhouse. The radiation budget is shown in *Figure 1*.

It is interesting to note that in the absence of a greenhouse effect, the earth's mean temperature would have been 255°K, instead of the observed value of 288°K. Greenhouse warming is thus about 33°K. This is much more pronounced around the planet Venus, whose atmosphere contains over 90% carbon dioxide ($CO_2$), a prominent greenhouse gas. Without a greenhouse effect the mean surface temperature of Venus would have been 227°K, but greenhouse warming raises it to 750°K. This represents warming by 523°K!

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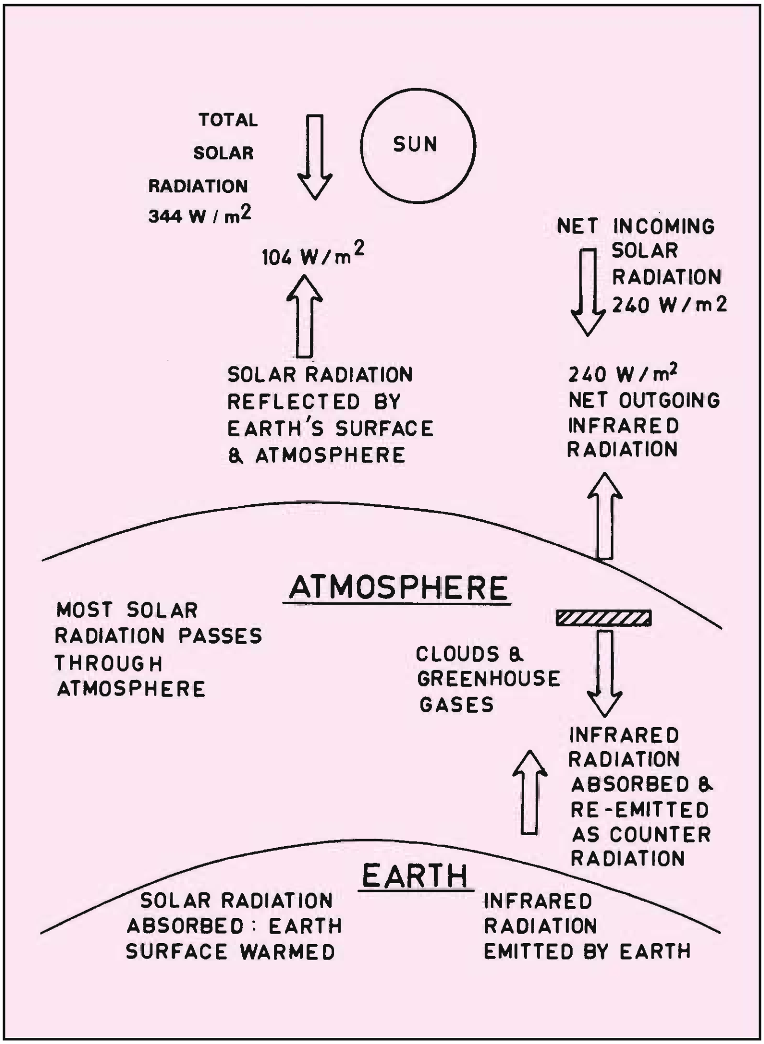


***Figure 1** The earth's radiation budget. Note that the net input of solar radiation (240 W/m²) is balanced by an equal output of infrared radiation.*

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The principal greenhouse gases in our atmosphere are: (i) Carbon dioxide ($CO_2$), (ii) Methane ($CH_4$), (iii) Nitrous oxide ($N_2O$), (iv) Ozone ($O_3$) and (v) halocarbons.

Halocarbons are compounds of carbon and halogens (chlorine, bromine and fluorine). Some refer to them as the chlorofluorocarbons, or the CFC's. Of late, another class of carbon compounds, the hydrogenated CFC's (HCFS) are also in the category of greenhouse gases. We will refer to them collectively as the halocarbons. Halocarbons are inert gases with a long life of 50 to 100 years. They are injected in the lower atmosphere, the troposphere, through refrigerants and aerosol sprays. The halocarbons destroy ozone in the lower stratosphere through chemical action, and as ozone protects us by absorbing harmful ultraviolet radiation from the sun, serious efforts are now in progress to replace halocarbons by other eco-friendly chemicals.

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Carbon dioxide, the principal greenhouse gas, is released into the atmosphere by burning fossil fuels, and by the cement manufacturing industry. But, it is removed from the atmosphere by the photosynthesis of plants. The largest reservoirs of carbon are in the deep oceans. Some of this reaches the atmosphere when waters from the deep ocean are brought up to the surface.

The main sources of methane ($CH_4$) are paddy fields and natural wetlands. Intestinal fermentation in animals also generates methane. Of the other greenhouse gases, nitrous oxide ($N_2O$) is obtained partly from the oceans and partly from fertilizers that are used in agriculture. The burning of biomass also generates $N_2O$.

Ozone ($O_3$) is a natural constituent of the atmosphere. Depending on the latitude, the ozone content in a vertical column of the atmosphere shows a peak concentration in the middle and lower stratosphere (15 to 35 km). This is known as the ozone layer. There is a gradual increase in ozone concentration from the equator and the tropics to higher latitudes. A matter of great concern is the recent discovery of a sharp decrease in ozone over Antarctica, especially during spring. The observations suggest a 50% decrease in 1987 when compared to values prevailing ten years ago.

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A disturbing feature is a gradually increasing trend for $CO_2$, $CH_4$, $N_2O$ and halocarbons. The rates of increase range from 0.25 to 0.9% per year for $CO_2$, $CH_4$ and $N_2O$, but it is as high as 4% for the halocarbons. There is some uncertainty about methane because it has shown a decreasing trend very recently. But, the overall need today is to decrease the emission rates of greenhouse gases. This is because of their adverse impact on climate. In this context, it is relevant to ascertain their contributions to global warming.

## Radiative Forcing and Global Warming Potential (GWP)

The change in radiation flux at the tropopause (*Figure 2b*) caused by the absorption of either solar or infrared radiation is defined as the 'radiative forcing'. Positive radiative forcing leads to warming, while a negative value cools the earth's surface. Radiative forcing could be either direct or indirect. Direct forcing occurs when the concerned gas is involved, but when the gas interacts with another gas by chemical interaction it leads to indirect forcing.

The hydroxyl (OH) radical plays an important role in indirect radiative forcing because it is a strong oxidizing agent. There are several reactions which lead to the formation of the OH radical. The OH radical is formed, for example, when solar ultraviolet radiation of wavelength less than 3 $\mu$m reacts with ozone. This gives rise to electronically excited oxygen atoms which react with water vapour to form hydroxyl radicals.

The IPCC assessments of radiative forcing are shown in *Figure 2*. The confidence for each assessment is shown in the bottom row

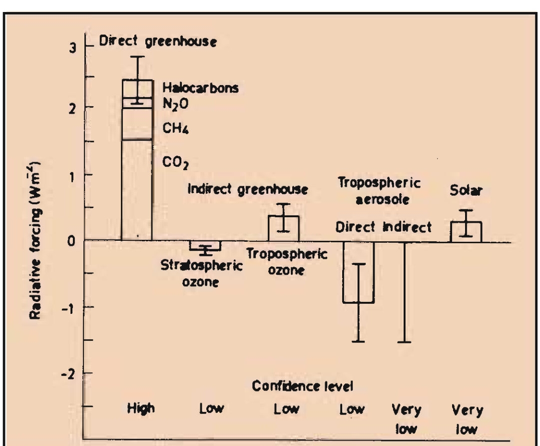


*Figure 2a (bottom left) Radiative forcing by different greenhouse gases. The error bars indicate the range of possible values. The confidence levels are indicated in the last row. (Source: Radiative forcing of climate change, 1994 Report of the Scientific Assessment Working Group of IPCC, WMO - UNEP, WMO Hq., Geneva)*

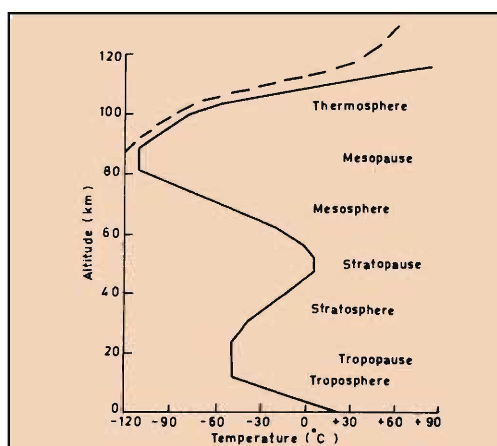


*Figure 2b (bottom right) Temperature variations with altitude. Dotted line indicates negative $CO_2$ feedback at high altitudes despite positive feedback at low altitudes. (Adopted from Cicerone,* Nature, *Vol.344, 1990).*

**Table 1 Global Warming Potential (GWP) for 100 years**

| Species | Life time (yr.) | GWP |
|---|---|---|
| $CO_2$ | - | 1 |
| $CH_4$ | 14.5 ± 2.5 | 24.5 |
| $N_2O$ | 120 | 320 |
| CFC-11 | 50 ± 5 | 4000 |
| CFC-12 | 102 | 8500 |

The uncertainty is around ±35% for each gas *[Source: Radiative forcing of climate change, report of the Scientific Assessment Group of IPCC, 1994].*

There is a larger warming potential of the halocarbons compared to the others.

of the figure. Of some interest are the low values given for solar variability. This suggests that variations in the solar constant, for example, are relatively unimportant.

The IPCC report also suggests Global Warming Potential (GWP) as an index for the greenhouse effect. It represents the cumulative effect of radiative forcing between now and a later time, say, a 100 years from now. For the purpose of calculating the GWP the forcing caused by a unit mass of gas is considered, and the index is expressed in terms of a reference gas, namely, $CO_2$. *Table 1* provides the GWP index for five principal greenhouse gases.

While the uncertainty factor is certainly large, the table indicates the very large warming potential of the halocarbons compared to the others.

## Negative Feedback Mechanisms

The IPCC estimates that the earth's mean temperature has risen by 0.3 to 0.6°K in the last 100 years. If no action is taken to restrict emissions, the warming rate is estimated to be 0.3°K for every ten years in the future, with an uncertainty range between 0.2° and 0.5°K.

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The large uncertainty range is due to negative feedbacks which we don't understand entirely. The four principal cooling mechanisms are: (i) ozone depletion in the lower stratosphere, (ii) back-scattering and reflection of short wave solar radiation by dust particles and aerosols, especially in the vicinity of sulphur emissions, (iii) clouds and (iv) $CO_2$ at high altitudes of the atmosphere. These feedbacks are briefly described in turn.

- *Stratospheric ozone depletion*

Ozone has a dual impact in the lower stratosphere (25 km). Firstly, the depletion of ozone by halocarbons implies less absorption of solar radiation by ozone, due to which more of it reaches the earth. This has a warming effect. But, less ozone also implies less absorption of outgoing infrared radiation. This cools the stratosphere. And, a cooler stratosphere emits less infrared radiation to the troposphere below. The net effect is one of cooling. Around 20-25 km, the cooling process usually dominates. We have already mentioned the ozone hole over Antarctica. The reasons for this are still unclear. Polar stratospheric clouds, which hold a wide variety of particulates and sulphate aerosols also contribute to ozone decline. In addition, chemical interactions release large amounts of chlorine that destroy ozone.

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- *Aerosols*

Aerosols also have a dual feedback. They scatter and reflect solar radiation, especially if they are covered with sulphates. This has a cooling effect. But, they also absorb both solar and infrared radiation. On many occasions the scattering features dominate, and this leads to cooling. Volcanic eruptions increase the dust load of the atmosphere and this increases negative feedback. The recent eruption of Mount Pinatubo was estimated to have decreased the temperature by a few tenths of a degree over many parts of the earth.

- *Clouds*

V Ramanathan, was the first to point out that clouds have a negative feedback. Clouds reflect solar radiation upwards to space. This cools the earth's surface, but they also absorb terrestrial infrared radiation which warms the earth. Cooling predominates in the thicker clouds, but the high altitude thin clouds generate more warming. Ramanathan's suggestion is that if global warming leads to warmer sea surface temperatures (SST) in the tropics, the ensuing convection could cause thick clouds. This will cool the atmosphere by a negative feedback of about 16 $W/m^2$. The clouds will thus act as a thermostat and set an upper limit to the sea surface temperature. This view has not found general agreement, because observations indicate that warm SSTs do not always generate thick clouds. The issue is still open.

- *High altitude* $CO_2$

In a recent communication to *Nature* (Vol.304, 8 March, 1990) Cicerone from UCLA in the USA suggests that increasing concentrations of $CO_2$ in the mesosphere (80 to 100 km above sea level) will cause stratospheric cooling because $CO_2$ molecules are efficient radiators of energy to space through infrared emissions. This negative feedback has not yet received much attention.

One of the difficult tasks that confront atmospheric scientists today is to ascertain if forcing mechanisms, such as global warming, generate responses that are larger than the natural variability of climate.

The negative feedbacks that we have mentioned above need further study and research. Unless this is done, future forecasts of global warming will remain uncertain.

## Natural Variability and Forced Oscillations

One of the difficult tasks that confront atmospheric scientists today is to ascertain if forcing mechanisms, such as global warming, generate responses that are larger than the natural variability of climate.

It is now recognized that on a regional scale global warming can alter the statistical mean or the variance of the distribution of a meteorological variable (See Rajeeva L Karandikar's article 'On Randomness and Probability' in ***Resonance*** Vol. 1 No. 2). This is shown in *Figures 3(a)* and *3(b)* and, as we can see, this will lead to

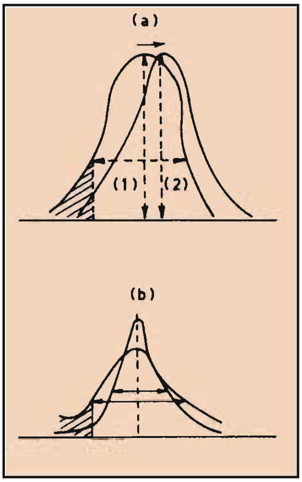


***Figure 3 Impact of a change in the mean and variance of a meteorological element due to global warming. Note the enlarged frequency of extreme events.***

a change in the frequency of extreme events. Let Figure 3(a) represent the rainfall distribution over a small region, such as a state in our country. The abscissa represents rainfall while the ordinate is the frequency. For simplicity, we will assume a symmetric bell-shaped (normal) distribution. Suppose now that as a result of global warming the median value is changed from (1) to (2), without any change in the shape of the distribution. As we can see from Figure 3(a) the frequency of low rainfall events (droughts) will decrease, while the frequency of high rainfall events will increase leading to more floods. The change in frequency of low rainfall is shown by the hatched area in Figure 3(a). Figure 3(b) shows the outcome of a decrease in the mean rainfall but an increase in the lateral spread or variance of the distribution. In this case there will be an increase in the frequencies of both low rainfall events (droughts) as well as high rainfall events or floods.

But, if we examine the time series of monsoon rainfall, for example, we will observe variations from year to year and decade to decade (*Figure 4*). Can we be sure that these variations are not due to natural causes?

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This interesting question was first raised by the late Professor Jule Charney of the Massachusetts Institute of Technology, USA and J Shukla, in the United States. Unfortunately, no clear answers have been found yet. One useful result that has emerged is an inverse relationship between equatorial Pacific SST's and monsoon rainfall. This result has been verified with the help of statistical techniques and mathematical models. The latter now simulate coupled ocean-atmosphere circulations.

In this context it is worth mentioning that a few promising signals of climatic change have been detected in the last decade. They are now attracting a good deal of research, especially for short term climate prediction. These signals are generated by the slow evolution of meteorological variables at the earth's surface. Examples of these variables are sea surface temperature (SST), snow cover and soil moisture.

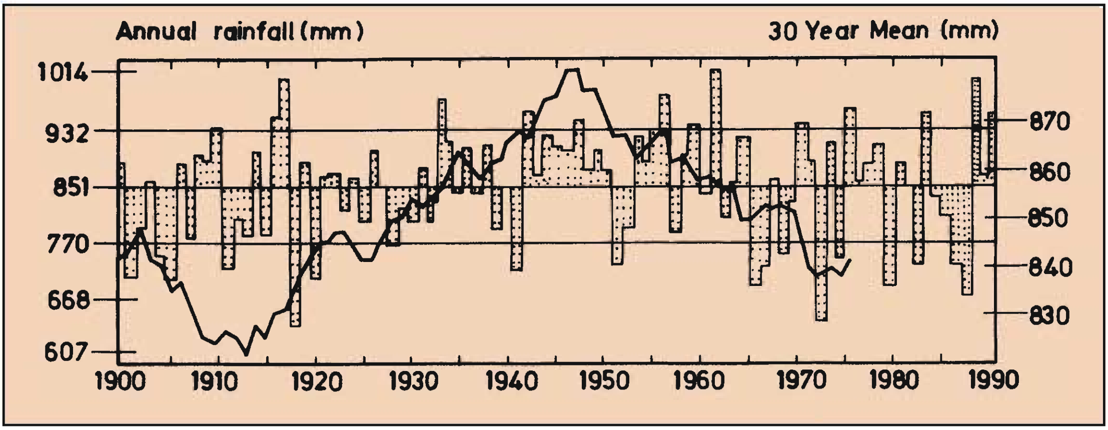


***Figure 4** Monsoon rainfall over India with 30 year running means (mm) indicated by solid lines. (Source: J. Shukla: Short term climate variations and predictions, Proc. Second World Climate Conference, 1991, WMO, Geneva).*

Perhaps the most interesting signal is an ENSO event in the equatorial Pacific. ENSO stands for an El Nino (EN) and the Southern Oscillation (SO). The former, which means 'a child' in Spanish, represents the sudden appearance of warm waters off the coast of Peru. It occurs once every two to seven years. As it occurs around Christmas many refer to it as the 'child Jesus'. It is accompanied by abnormally heavy rain in many parts of the tropics. The fishing industry of Peru suffers heavy damage due to the warm waters of an El Nino. The Southern Oscillation (SO) is the term used to define a see-saw pattern of pressure variations between the Pacific and the Indian Oceans. When pressures are low over the Pacific they tend to be high over the Indian Ocean and vice versa. A Southern Oscillation Index (SOI) measures the intensity and phase of this oscillation. It is the pressure difference between the island of Tahiti in the Pacific and Port Darwin (to represent the Indian Ocean). A negative value of SOI occurs concurrently with an El Nino which is why we refer to them, jointly, as an ENSO event. As an ENSO is associated with weak monsoon rains, its prediction is important for Indian agriculture.

El Nino represents the sudden appearance of warm waters off the coast of Peru. It occurs once every two to seven years.

Coupled air-sea models are now used to anticipate SST changes over the equatorial Pacific. Forecasts are being made with lead times ranging from a month to a year. The design of coupled models was pioneered by Zebiak and Cane of the United States in

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1987. To see how the model works, we consider an air-water interface between the atmosphere and the underlying ocean. The governing equations use the observed atmospheric winds to force ocean currents. This leads to variations in SST and they, in turn, determine the pattern of winds over the ocean. As the heat capacity of the ocean is much larger than that of the atmosphere the evolution of the SST variations is a very slow process. The oceans act as the memory of the atmosphere.

While encouraging results have been achieved, much more remains to be done. The performance of the model is very sensitive to the accuracy of the initial conditions. These conditions have to be specified before starting model integration. The Climate Research Centre (CRC) of the National Oceanic and Atmospheric Administration (NOAA) in the USA feels that the skill achieved so far is modest, but further research in this important area is being vigorously pursued.

Is the overall climate predictable? An answer to this intriguing question was the subject of an interesting paper by Professor E N Lorenz of MIT in USA (Tellus, 424, 378-389, 1990). Professor Lorenz has pioneered the modern theory of chaos. He considered a simple model climate consisting of an eastward moving wind current, which is disturbed by waves. Professor Lorenz suggests that short term climatic changes are essentially chaotic. He finds that if the external forcing during winter, for example, is very large then the circulation will become chaotic. And, it could remain chaotic until next spring, even though there might be a decrease in external forcing. This suggests that long range prediction of climate might not be possible. Professor Lorenz's model was a very simple one. It is possible that future models will contain stabilising factors that will improve the limit of predictability. An exciting field of research lies ahead.

## Summary and Conclusions

- Anthropogenic emissions of greenhouse gases indicate the possibility of an increase in global warming.

- There are several negative feedbacks which make future projections uncertain at present.
- Clouds often provide a large negative feedback, but they need not make the atmosphere a thermostat.
- It is difficult to separate forced climatic changes from the natural variability of climate.
- Short term climatic changes are mainly chaotic. This could make it difficult to make long range predictions. But, some success can be achieved in predicting variables which evolve slowly, such as, sea surface temperature (SST).

Is the overall climate predictable? Lorenz's experiment suggests that long range prediction of climate might not be possible.

## Suggested Reading


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**Hermann Hankel said...** "In most sciences one generation tears down what another has built, and what one has established another undoes. In mathematics alone each generation adds a new storey to the old structure".

**Bertrand Russell wrote...** "There was a footpath leading across fields to New Southgate, and I used to go there alone to watch the sunset and contemplate suicide. I did not, however, commit suicide, because I wished to know more of mathematics".