Climate Change, Greenhouse Gases and Aerosols

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The surface temperature of the earth is controlled by the balance between the absorbed solar radiation and the emitted infrared radiation. During the past 150 years the amount of carbon dioxide in the earth's atmosphere has increased from 280 parts per million to more than 380 parts per million on account of burning of fossil fuels. The higher absorption of infrared radiation by the atmosphere (on account of higher carbon dioxide) has resulted in an increase in the surface temperature of the earth. The burning of fossil fuels has also caused an increase in sulphate and soot aerosols in the atmosphere. Both these aerosols reduce the solar radiation incident at the earth surface. Hence the surface of the earth has cooled on account of increase in aerosols. The sulphate aerosols have also cooled the atmosphere but the soot aerosols, which absorb solar radiation, have heated the atmosphere. The net impact of increase in carbon dioxide and aerosols has been an increase in the surface temperature of the earth by 0.7 degrees centigrade in the past 100 years.

Introduction

The Nobel Peace Prize for 2007 was awarded jointly to Al Gore, the former Vice President of USA and the Intergovernmental Panel for Climate Change (IPCC) for their efforts to build up and disseminate knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change. The Nobel Committee states categorically that "Action is necessary now, before climate change moves beyond man's control". Will the problem of global climate change be a really serious issue in the 21st century? In 1988, the United Nations constituted IPCC to examine the scientific evidence on climate change. This panel has published several monographs

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that highlight our present understanding of the impact of human activities on the climate. We know now that most of the warming that has been observed during the past 100 years is mainly on account of human activities like burning of fossil fuels and biomass that release CO_2, SO_2 and soot into the atmosphere. How do these gases influence the Earth's climate?

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Climate and Greenhouse Gases

Nitrogen, oxygen and argon that constitute 99.93% of the Earth's atmosphere hardly absorb either the incident solar radiation or the radiation emitted by the Earth's surface. Earth's climate is strongly influenced by the presence of a few minor gases: water vapor, CO_2, ozone and methane. These minor gases account for less than 0.1% of the Earth's atmosphere but have a profound influence on the Earth's climate. They are called greenhouse gases because their radiative properties are similar to the glass used in a greenhouse. Greenhouse gases in the Earth's atmosphere absorb 90% of the radiation emitted by the Earth but absorb only 15% of the solar radiation. The presence of these gases in the Earth's atmosphere has made the surface temperature of the Earth warmer by about 33 ^{o}C and hence more habitable for human beings.

During the past two hundred years the amount of CO_2 has increased from around 280 parts per million (ppm) in 1850 to 380 ppm in 2005 (see *Figure* 1). During the same period the global mean surface temperature of the Earth has increased by about 0.7 ^{o}C (see *Figure* 1). This increase in the temperature during the past 100 years is primarily on account of the increase in CO_2 (see *Figure* 1). Human activities, such as fossil fuel and biomass burning, release about 7 GtC (in giga tons of carbon) of CO_2 per year. A part of the CO_2 released is absorbed by the ocean and the biosphere while the remainder increases the concentration of CO_2 in the atmosphere by around 1 to 1.5 ppm per year. The per capita emission of CO_2 in developed countries is about 8 times more than the per capita emission in developing countries. Hence the major responsibility to arrest global warming due to CO_2 emission lies with the developed countries. The Kyoto Protocol

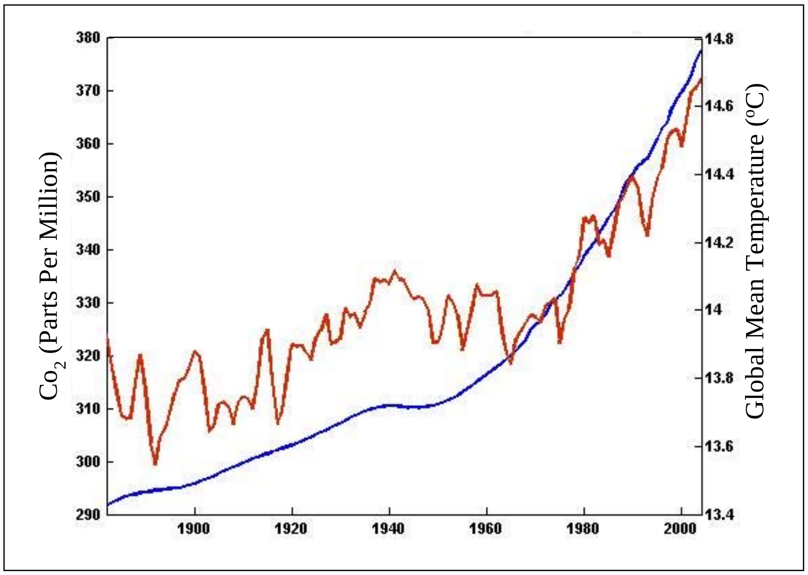

Figure 1. Variation of CO_2 (blue line) and temperature (red line) during the past 122 years.

adopted in 1997 resolved that developed countries would reduce by 2008–2012 the emission of greenhouse gases by 5.2%. The United States of America decided not to follow the protocol unless developing countries also did so. This has caused a stalemate in negotiations.

The Earth's climate is also strongly influenced by the spatial extent of the polar ice caps. The temperature has not remained invariant during the past 4 billion years. During the ice ages the global mean temperature was about 5 °C below the present value and the amount of CO_2 and methane was much lower than the present[1]. This demonstrates clearly that there is a correlation between the amount of CO_2 or methane in the atmosphere and the global mean temperature. In addition to these the Earth's climate is also influenced by aerosols.

[1]See article by J Srinivasan in *Resonance*, Vol.4, No.8, pp.25–35, 1999.

Aerosols and Sulfate

Aerosols are tiny liquid or solid particles suspended in the atmosphere. They are created naturally or by human activities such as burning of fossil fuels. Natural aerosols are dust, sea salt or sulfate. These influence the climate of the Earth by altering the radiation fluxes[2] in the atmosphere.Volcanic eruptions release a large amount of aerosols into the troposphere and their residence time is of the order of years. These aerosols increase the reflectivity (also called *albedo*) of the Earth-atmosphere system and hence lead to the cooling of the atmosphere and the surface of the Earth. The aerosols released by human activities, such as sulfate and soot, are confined to the lower troposphere and their residence time is usually less than a week because they sink rapidly or are washed out by rain. The impact of aerosols on human health has been investigated for a long time but their impact on climate has been examined only recently.

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The global emission of SO_2 on account of human activities has increased from around 10 tera-gram of sulfur per year in the beginning of the 20th century to more than 60 tera-gram per year at the end of the 20th century (see *Figure* 2). The amount of SO_2 emissions from India is about one sixth of the emissions from North America, Europe or China. The present global emission of SO_2 by human activities is almost four times larger than the natural flux of SO_2. Hence there is a new concern about the impact of anthropogenic aerosols on climate. The changes in radiative flux (at the top of the atmosphere) due to an increase in greenhouse gases or aerosols is called *radiative forcing*[2]. The

[2]For more details see the article by P K Das, *Resonance*, Vol.1, No.3, pp.54–65, 1996.

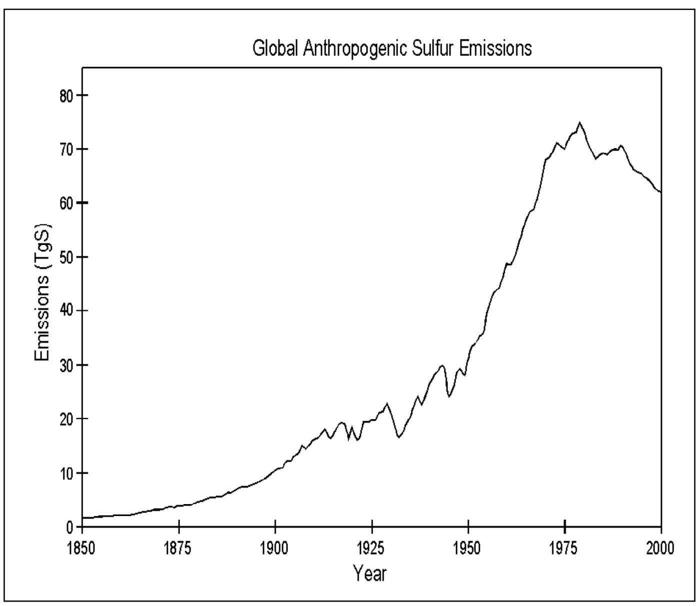

Figure 2. Global anthropogenic sulfur emissions. Adapted from *Historical Sulfur Dioxide Emissions 1850–2000*: *Methods and Results,* S J Smith, E Conception, R Andres and J Lurz, Joint Global Change Research Institute, 2004.

The increase in CO_2 in the atmosphere increases the surface temperature of the Earth on account of greenhouse effect. An increase in SO_2 increases sulfate aerosols which reflect solar radiation back to space and hence reduces the surface temperature of the Earth.

human activities which increase tropospheric aerosols can alter the *radiative forcing* directly as well as indirectly. The direct radiative forcing occurs on account of the changes in reflectivity (i.e., albedo) and absorptivity of the atmosphere that occur because of the presence of these aerosols. Indirect radiative forcing by aerosols occurs on account of the modification of the lifetime of clouds and their radiative properties.

Burning of fossil fuels increases the amount of CO_2 and SO_2 in the atmosphere. The increase in CO_2 in the atmosphere increases the surface temperature of the Earth on account of greenhouse effect. On the other hand, an increase in SO_2 increases sulfate aerosols which reflect solar radiation back to space and hence reduce the surface temperature of the Earth. Hence burning of fossil fuels has caused both heating and cooling of the surface of the Earth. The warming (due to increase in CO_2) has dominated the cooling (due to increase in sulfate aerosols). When the effect of aerosols is included in climate models we are able to simulate more accurately the variation of global mean temperature during the past 100 years. The residence time of CO_2 in the atmosphere is of the order of a hundred years while the residence time of sulfate aerosols is of the order of weeks. Hence the emission of CO_2 during burning of fossil fuels has long-term impact while the impact of increase in SO_2 has a short-term impact.

The global mean radiative forcing by greenhouse gases and aerosols from pre-industrial times to the present have been estimated by IPCC. The greenhouse gases contribute 2.5 W/m^2 with the dominant contribution being from CO_2 (1.5 W/m^2). The next important greenhouse gas is methane (0.5 W/m^2). Chlorofluorocarbons such as freons (used in refrigerators) contribute less than 0.5 W/m^2. Their contribution will decline in the 21st century since their emissions will reduce on account of the Montreal protocol signed in 1988 after it became clear that chlorofluorocarbons caused the reduction of ozone over Antarctica.

The amount of CO_2 in the Earth's atmosphere increased by 30% during the 20th century. This increase cannot explain the increase of 0.7°C in the global mean temperature. It can explain an increase of only about 0.2°C. This 0.2°C change would have triggered an increase in water vapor content of the atmosphere by about 10%. Since water vapor is a powerful greenhouse gas, it would have amplified the increase in global mean temperature caused by CO_2

Climate Models

In order to understand the impact of aerosols and greenhouse gases on future climate, we need climate models. These models are called General Circulation Models (GCM). The entire atmosphere of the Earth is divided into a large number of small boxes. The typical size of each box is 200 km in longitude, 200 km in latitude and 1 km in height. The temperature and wind speed and direction in each box is calculated using the physical laws governing the conservation of mass, momentum, and energy. The moisture content is calculated by ensuring the conservation of water in all phases (liquid, solid and vapor) in each box. The representation of clouds in climate models is crude because the typical size of the cloud is much smaller than the size of the box. The clouds are represented in these models based on certain assumptions. Different modeling groups have represented clouds and their impact on climate in different ways. The presence of aerosols and green house gases alters the radiative heating and cooling rates in these models and also the amount of clouds. In most of the models the representation of the biosphere (i.e., vegetation) is rather poor. The vegetation types prescribed in each of the boxes do not change when the climate changes. The oceans are also represented by a large number of small boxes. The temperature and winds in each box are calculated using the physical laws governing the conservation of mass, momentum, and energy. The salinity content of the ocean is calculated by ensuring the conservation of salt. The oceans have large thermal inertia and hence change much more slowly than the atmosphere and hence coupled ocean-atmosphere models must take into account the different response times of ocean and atmosphere. Most predictions about the evolution of the climate in the 20th

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and 21st centuries have been based on simulations with coupled ocean-atmosphere models. The simulations of the global mean temperature of the 20th century by the climate models show that the large increase in global mean temperature during the past 40 years is primarily on account of the increase in greenhouse gases.

Soot and Climate

In the past few years a new concern has been expressed about the impact of soot aerosols on climate. Soot is present in the atmosphere in many regions of the world where there is burning of fossil fuel or biomass (see *Figure* 3). In the Arabian Sea and Indian Ocean regions, soot aerosols were found during the period January to April during the Indian Ocean experiment [3]. In this season the soot aerosols generated by fossil fuel and biomass burning in the Indian sub-continent reaches the Arabian Sea and the Indian Ocean on account of the prevailing north-easterly winds. The prevailing winds change direction from north-east to south-west in May. As the wind speed increases in May and June, natural aerosols become more important in the Arabian Sea and

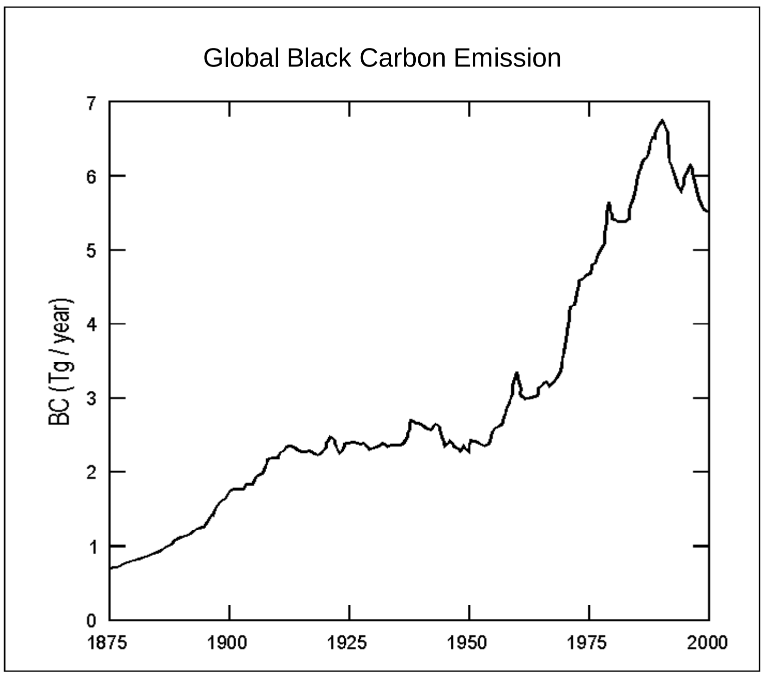

Figure 3. Total black carbon emissions from fossil fuel burning.
Adapted from Novakov *et al*, *Geophysical Research Letters*, Vol.30, No.6, p.1324,2003. doi:10.1029/2002GL016345, ,

the Indian Ocean. The amount of natural aerosols (such as sea salt and dust) that is generated depends on the wind speed. During the south-west monsoon season the winds are large and hence natural aerosols become more important than the aerosols generated by human activities. Aerosols such as sulfate and sea salt reflect radiation and hence cool the atmosphere and the surface of the Earth, whereas aerosols such as soot and dust absorb solar radiation and hence heat the atmosphere and cool the surface. Hence the presence of soot will tend to heat the atmosphere while sulfate aerosol will tend to cool the atmosphere. The impact of soot aerosol on climate is complex. When both soot and sulfate aerosols are present, the atmosphere may be cooled or heated depending upon their relative amounts.

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The impact of absorbing aerosols on global climate may not be as large as that on regional climate. Most climate models used by IPCC have not incorporated the effect of aerosols on radiation budget. Hence the understanding of the impact of aerosols on regional climate is still in its infancy. In the past few years some studies have examined the impact of soot emission from India and China on regional climate. The amount of data available regarding the seasonal variation of soot in India is limited and hence these models have assumed that the amount of soot in the atmosphere is independent of season. This assumption is not realistic since natural aerosols are more abundant during the monsoon period from May to October. Moreover the impact of aerosols on climate depends upon how clouds are represented in these models. Since the representation of clouds in General Circulation Models (GCM) is still very primitive, the prediction of the impact of aerosols on regional climate by these models will not be reliable [3].

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Future Climate

The amount of CO_2 in the atmosphere is expected to increase further during the 21st century. This depends upon the rate of increase of global population and the pace of industrialization in

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the developing countries. The IPCC has estimated that the amount of CO_2 in the atmosphere will be in the range of 500–900 ppm at the end of the 21st century. The amount of methane in the atmosphere then is expected to be in the range of 2–4 ppm. Although the amount of methane in the atmosphere is much less than the amount of CO_2, it has a greater impact on climate. This is because the amount of terrestrial radiation absorbed by a molecule of methane is 21 times more than that absorbed by a molecule of CO_2. Predictions by climate models indicate that the global mean temperature may be 1.5–5.5 °C higher than the present at the end of the 21st century. Why is the range of predicted temperatures so large? There are two reasons. The first is on account of the uncertainty regarding the level of CO_2 and methane that will prevail in the atmosphere at the end of the 21st century. This uncertainty is related to the variations in the projections as regards population and the level of industrialization at the end of the 21st century. The second is on account of differences between different climate models regarding the way they incorporate clouds, vegetation and oceanic processes. If the temperature rise at the end of the 21st century is less than 2 °C then human beings may be able to adapt to this warming. If the temperature change is around 5 °C then it may have a catastrophic impact on weather, agriculture and health. In a warmer Earth, the hydrological cycle will be more vigorous and hence floods and cyclones will be more intense. The direct impact of increase in global mean temperature will be an increase in global mean sea level on account of thermal expansion of sea water and melting of ice and glaciers over land. By the end of the 21st century the global mean sea level may increase between 10 cm and 80 cm. Many low-lying areas in countries such as Maldives, Egypt and Bangladesh will be uninhabitable if the mean sea level rises by more than 50 cm.

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Conclusion

The climate of the Earth will change in the 21st century on account of emission of greenhouse gases and aerosols by human beings. Gases such as CO_2 will remain in the atmosphere for more than 100 years and thus can cause an irreversible change. In contrast the aerosols released by human activities will remain in the atmosphere for a few weeks. Hence the impact of reduction in aerosols will be seen almost immediately while the impact of reduction in CO_2 will not be been seen immediately. CO_2 is an invisible pollutant that does not have any direct adverse impact on our health. Hence most countries have no legislation to reduce the emission of CO_2. The impact of CO_2 on human beings will be indirect and complex. For example, an increase in CO_2 alone will increase the yield of crops through better photosynthesis. An increase in CO_2 will increase the surface temperature and hence can increase the moisture stress. If the impact of moisture stress is dominant then there will be a decrease in yield of the crop even though more CO_2 is available for photosynthesis. The impact of aerosols on climate and agriculture is even more complex. Our understanding of the impact of aerosols on climate and agriculture is very primitive and hence we cannot provide a reliable estimate of the impact of aerosols at this time.

As more and more human beings in developing countries demand cleaner air, the problem associated with aerosols should subside. An attempt to reduce CO_2 emission will not be so simple because it is intimately linked to our modern energy-intensive lifestyle. People in developed countries will not give up their lifestyle unless they are convinced that there is an immediate threat to their health or climate. The impact of increase in CO_2 on climate or health will not be seen immediately but will begin to emerge in 50 to 100 years. Hence the governments in developed countries will be reluctant to bring legislation to reduce the emission of CO_2 until the adverse impacts are discernable. If the governments wait that long, then they may be unable to prevent an adverse irreversible change in the climate of the Earth.

Suggested Reading

[1] **Climate Change 2007, *Scientific Basis, Inter-governmental Panel on Climate Change*, Cambridge University Press, 2007.**

[2] **F Drake, *Global Warming*, Oxford University Press, 2000.**

[3] **J Srinivasan, and S Gadgil, *Current Science*, Vol.83, pp.586–592, 2002.**

[4] **Discussion on issues related to climate change can be found in www.realclimate.org**

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