An HVAC Engineer's Approach to Understanding Global Warming

Part 1 of 2

By R.V. Simha

Airtron Consulting Engineers Pvt. Ltd.

Bangalore

Introduction

The burning topic of the day is the complex of Global Warming, Climate Change and Sustainability. *Figure 1* depicts an integrated framework comprising the components involved in the phenomenon of Global Warming. It has been constructed by scientists, while this articles is written from the point of view of HVAC. Accordingly, amongst the components of the framework listed, the terms that catch the eye are Temperature, Concentrations, Emissions, Adaptation and Mitigation. This effort will therefore focus on these components. Attention will also be paid deliberatelly to provide a bridge between the science and HVAC engineering. Interests in other components will be limited to the extent required to position oneself with respect to other related topics and thus acquire better understanding of Global Warming.

The Sun, Atmosphere and the Earth

Solar Radiation from the Earth to the Sun

We all know that the solar radiation (E_o) that arrives at the upper reaches of the atmosphere is about 1378 w/sqm (same as solar constant E_o; see ASHRAE Handbook Fundamentals 2013) at normal incidence. During its passage down to the surface of the earth, this value suffers many reductions. First, radiation is scattered by nitrogen, oxygen and other constituents of the atmosphere i.e., aerosols, water droplets, dust and other particles. Second, reductions occur due to absorption by ozone (in the outer atmosphere); reduction also occurs in absorption bands of carbon dioxide, water vapour, methane – and ozone (again), all below the level of troposphere (see *Figure 3*). Third, there are fluctuations in the incidence of radiation itself from the sun. Fourth, we need to look at average values in our context rather than maximum values. Lastly, radiation is received only during day time; and it is not normal most

About the Author

R. V. Simha is a graduate in both electrical and mechanical engineering with over 40 years experience in HVAC. He is a past president of ISHRAE (1991-92), founder president of ASHRAE South India chapter (1999-2000) and an ASHRAE Fellow. Recently, he served as a corresponding member of several ASHRAE technical committees and his current interests are climate, comfort, room air movement, natural cooling and related topics. He can be contacted at *simha@airtron.in*

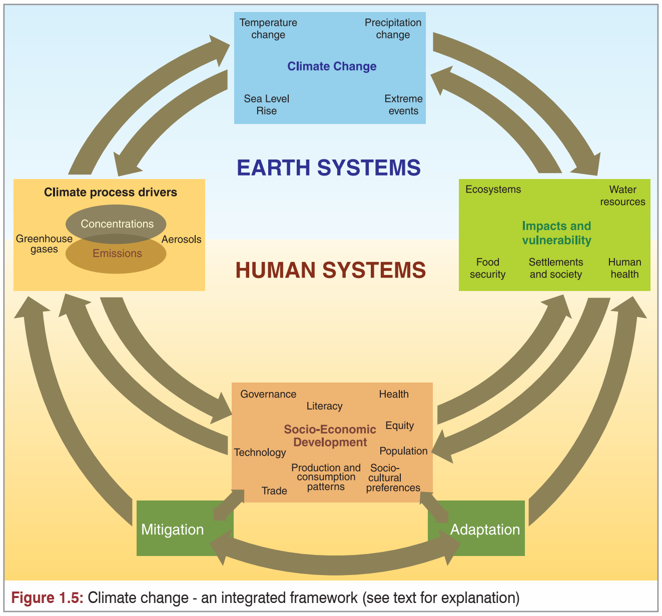

Figure 1: The global warming framework (Courtesy: IPCC AR-4 Assessment Report-2007)

of the time. Thus, starting with a radiation intensity of 1378 w/sqm at the upper reaches of the atmosphere, it has incurred heavy losses on its way to the earth, so that it dwindles to just about to 290 w/sqm at the surface of the earth.

In this kind of exchange, the energy received must be compensated by an equivalent quantity of energy which is lost (also) to maintain an energy balance. For simplicity, one may assume that in this case, the mode of heat exchange will be limited to radiation. The earth is a black body; and accordingly, it both absorbs and emits energy back (to space). The quantum of energy emitted depends on the temperature of the earth – the higher the temperature of the earth, the larger is the quantum of radiation or radiant energy emitted. This applies to absorption

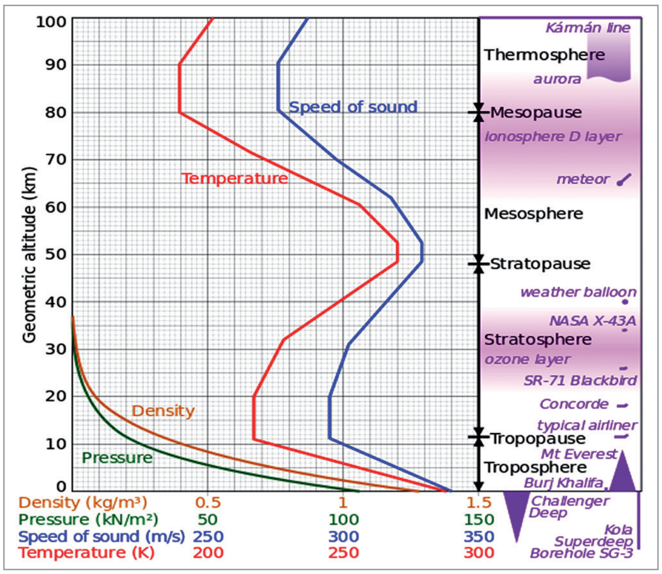

Figure 2: Variation of physical properties over altitude

also. Calculations made on the basis that radiation is the only mode of heat transfer in this case, show that an earth's surface temperature of -6°C is sufficient to radiate energy to space at 288 w/sqm. This model, however, as may be expected, turns out to be too simplistic because measurements of earth's temperature show that it is around 15°C in reality, i.e., over 20°C above the calculated figure of -6°C. To explain this difference, it is necessary to look at the atmosphere closely and observe what is happening in the atmosphere. There are two phenomena that come to our rescue: a) Greenhouse Effect, and b) Convection and Mixing.

Green House Effect

What is Green House Effect? The atmosphere, one would think, consists of 79% nitrogen and 21% oxygen. Neither of them have a role to play in this context. It is nitrous oxide, carbon dioxide, methane, water vapour and ozone that matter. These minor gases are the Green House Gases. (See *Figure 4* and *Table 1*.) What is a 'Green House' and what are 'Green House Gases'?

Table 1: Composition of Earth's atmosphere

Gas	Volume	GWP
Nitrogen (N_2)	780,840 ppmv (78.084%)	—
Oxygen (O_2)	209,460 ppmv (20.946%)	—
Carbon dioxide (CO_2)	397 ppmv (0.0397%)	1
Methane (CH_4)	1.79 ppmv (0.000179%)	25
Nitrous oxide (N_2O)	0.325 ppmv (0.0000325%)	298
Hydrofluorocarbons (HFCs)	—	From 12 to 12000
Perfluorocarbons (PFCs)	—	From 5000 to 12000
Sulphur hexafluoride	—	22200
Water vapor (H_2O)	~0.25% by mass over full atmosphere, locally 0.001%–5%	
GWPs for GHGs are for those covered by Kyoto Protocol relative to carbon dioxide and for a time horizon of 100 years		

How the Green House Works

Green Houses are built essentially in glass (see *Figure 5*). Glass passes virtually all incident radiation, which is short-wave (SW), to the Green House, i.e., glass is transparent to visible radiation. The heat passed thus, warms the plants and soil of the Green House. The heat absorbed warms them up – and subsequently, they emit radiation themselves also. But this is long-wave (LW) radiation. When it strikes the glass again, part of it is re-emitted back to the Green House, while the rest of it finds its way to the atmosphere. The characteristic feature of the Green House is that the heat it absorbs and re-emits to the Green House helps to warm up the plants and the environment. The 'Green' in the Green House is to convey the image of the plants they succeed in keeping warm – the warmth being essential for their growth. The absorption and re-emission of heat back in to the Green House to raise its temperature is the Green House Effect and it is also likened to a 'Radiation'.

Convection and Mixing

In the atmosphere, however, heat transfer is not just by radiation alone; mixing and convection are also taking place.

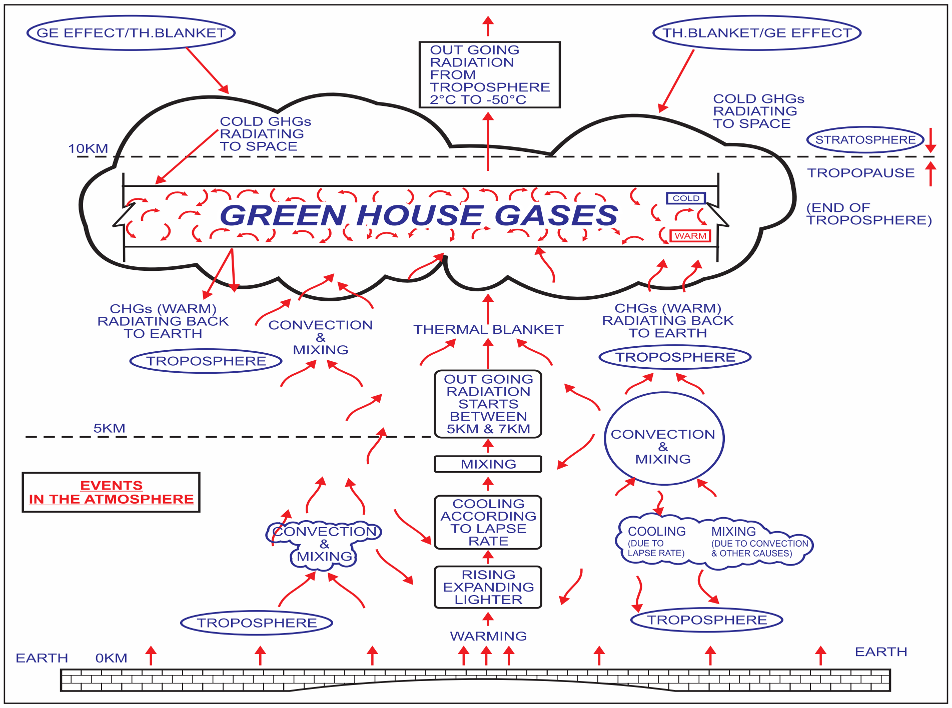

Figure 3: Radiation from the earth

The warm surface of the earth heats up the air and the lighter streams generated raise the air upwards. As the streams rise and expand (being lighter), the temperature falls. This expansion and fall of temperature is well known as 'Lapse Rate' in studies of weather and climate. There are two kinds of lapse rate – the dry and adiabatic processes. The latter occur in the atmosphere when streams of samples of the air mix at different temperature and moisture levels. The value of the dry lapse rate is about 10°C per km – and that of the adiabatic process is lower. The exact temperature is a kind of average as the air masses mix constantly. The value of 6.4°C will be therefore regarded as a figure that is conservative and safe. The same remark applies to moisture levels also. Both these parameters vary and influence the temperature of the air as it reaches the upper level of the troposphere i.e., at heights from 5 to 10 km above the ground level. One of the major points to be noted here is that the relatively low temperature achieved at the top of the 10 to 5 km band of the troposphere is what creates the cold radiation to the space, whereas the surface of the top is warmer and emits energy out into the space.

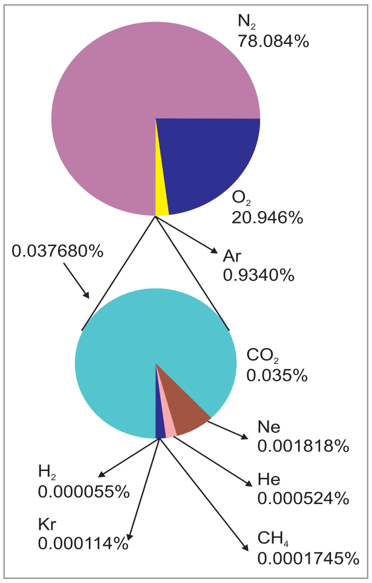

Figure 4: Composition of Earth's atmosphere by volume. The lower pie represents the trace gases which together compose 0.038% of the atmosphere. The numbers are from a variety of years (mainly 1987, with CO_2 and methane from 2009) and do not represent any single source.

All that has been described above started with the surface of the earth heated directly by solar radiation. The earth absorbs the heat and emits it back to the atmosphere; the radiation encounters the atmospheric layer, which includes the Green House Gases (GHGs). While most of the radiation interacts through to the space, some of it is absorbed by the GHGs (which are not transparent to LW radiation). The radiation absorbed by GHGs is emitted back to the earth.

In this picture, it will be noted that the GHGs absorb the LW radiation from the earth and emit it back to the earth; and in turn, it goes to warm the earth. It will be seen that the GHGs are discharging exactly the same function as glass did in the Green House, where it passed SW radiation from the sun to the plants in the Green House, which emitted some of it back to glass – and the glass again emitted it back to the plants to enhance the heating effect.

Events in the Atmosphere

A concept of what happens in the atmosphere can be formed by looking at pictures, observations and study of information obtained through instruments, cameras and satellite. At some wavelengths in the infra-red bands (window region: 8-14μm), the clear sky is largely transparent. At these wavelengths, the radiation from earth's surface leaves the atmosphere. At other wavelengths it is absorbed strongly by some of the gases, especially carbon dioxide, methane and water vapour, in other words, the Green House Gases. Absorbing gases in the atmosphere absorb some of the radiation emitted by the earth's

Figure 5: A green house

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surface and in turn emit radiation out to the space. The quantum emitted depends on their temperature. The level at which this occurs is between 5 and 10 km. The temperature at these levels – due to the lapse rate, convection and mixing – is much colder (about -30 to -50°C) than at the surface. The emission at lower temperatures is lower. The gases therefore absorb some of the radiation from the earth's surface but emit much less radiation out to space. This is similar to the radiation blanket in the Green House. The 5 to 10 km height band is playing the role of the glass. The outer surface is colder than the bottom surface (facing the earth) and helps to keep it warm.

The Concept of Energy Balance

No such complex phenomena in the atmosphere have been factored in the simple model envisaged. There are a number of streams of radiation entering the atmosphere and leaving the top of the atmosphere. The overall picture that emerges is that the radiation absorbed is 58 w/sqm, which is less than the 288 w/sqm that we started with. Clouds in the stratosphere are also involved in the energy balance. They also participate in the heat exchanges by reflection, absorption and emission. Clouds reflect some of the incident radiation from the sun back to space. However, they also absorb and emit thermal radiation and have a blanketing effect similar to that of the Green House Gases. These two effects work in opposite senses: one, the reflection of solar radiation has a cooling effect, and the other, the absorption of thermal radiation, has a warming effect instead. The net effect of clouds is a slight cooling of the earth's surface. This yields the energy balance we are looking for with 235 w/sqm on an average coming to the earth's surface and 235 w/sqm going out to the space.

In the pre-industrial era, the overall picture that emerges is that the radiation absorbed is 58 w/sqm which is less than 288 w/sqm that we started with.

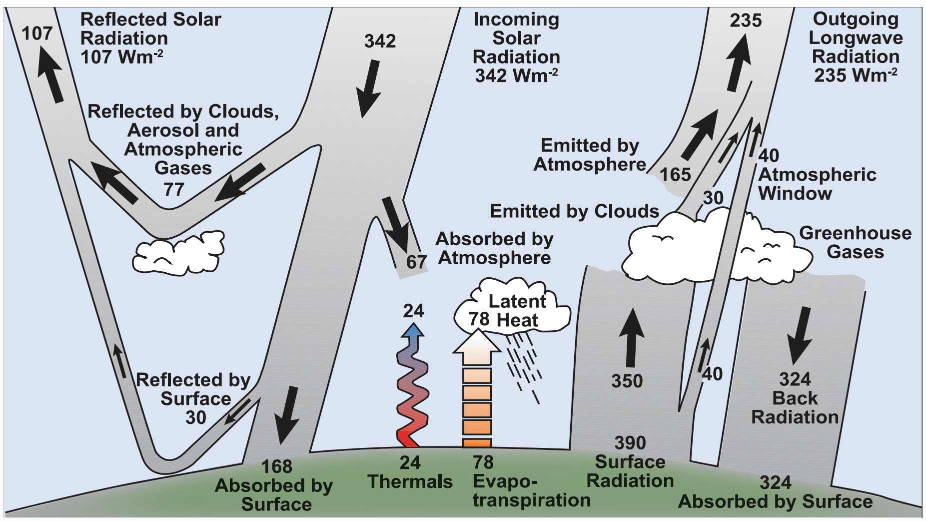

Figure 2.7: Components of the radiation (in watts per square metre) which on average enter and leave the Earth's atmosphere and make up the radiation budget for the atmosphere. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space.

Figure 6: The radiation balance for the atmosphere (Courtesy: IPCC AR-4 Assessment Report-2007)

Global Warming of Yore (pre 1750) and Global Warming of Today

Industrial Activities, Deforestation – Responsible for Global Warming of Today

The temperatures of the earth's surface and accordingly of the atmosphere above, adjust themselves to ensure that the balance is maintained. However, there will certainly be disturbances in the heat exchanges due to several reasons – the change in the solar radiation reaching the earth's surface, the change in the strengths of the GHGs in the atmosphere, changes in cloud related factors, changes in strength and characters of aerosols, etc. Whenever such disturbances take place, the temperature of the surface of the earth and the upper atmosphere adjust themselves so that the heat balance is maintained.

For thousands of years before 1750, the carbon dioxide level in the atmosphere was being maintained at a mean value of about 280 ppm within about ±20 ppm. The corresponding surface temperature of the earth was about 13°C. This may be compared with today's figure of 400 ppm reached from 280 ppm i.e., an increase of 120 ppm which has now occurred within a matter of 250 years. The temperature of 13°C noted here, compared with the theoretical figure of -6°C indicated earlier in the article, represents a difference of 19°C and this represents the Green House Effect. This is also Global Warming due to the Green House Effect. There were of course, at that time, no human activities (antropogic contribution). Global Warming is thus not new. It has been there for thousands of years. What has happened is that the 280 ppm carbon dioxide concentration and the earth temperature of 13°C were being maintained for thousands of years. But as we noted, it has gone up by about 2.5°C in the last 250 years. The increase in temperature of the earth since 1750 is due to human activities. It had been gradual but is much more rapid in the 20th century and continues to increase. The increase after 1750 and more particularly, rapid increase in the 19th and 20th centuries is what is generally meant and understood as Global Warming. Without the Green House Effect, the earth would have been much colder and life would have been significantly different.

It may be imagined that temperature rise of 2.5°C is trivial but it is not the air temperature we are talking about, it is the temperature of the earth instead. We are witnesses to this impact of the 2.5°C rise – like rise of sea level, melting of ice and snow, more violent and frequent occurrence of storms, cyclones and floods...post 1750.

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Global Warming and Radiative Force (RF)

It has been noted that the temperature of the earth adjusts itself in such a way to fluctuations that the heat balance is maintained at 235 w/sqm in and 235 w/sqm out. Question arises naturally as to the relation between the temperature rise of the outgoing radiation at the top of the troposphere for a given rise of concentration of GHGs like carbon dioxide, for example. Doubling the carbon dioxide content will result in an imbalance in the radiation budget of about 4 w/sqm. Incoming radiation will exceed the outgoing radiation by this value. The balance will be restored by an increased emission from the earth. This increased emission requires a higher earth temperature. The temperature rise required is about 1.2°C. This is on the assumption that nothing else changes i.e., clouds, water vapour, ice and snow cover . . . remain the same. Keeping this in view, the estimated global temperature rise (Global Warming) is expected to be about 3°C. The possibility of this doubling occurring is not remote either; in fact, it is the carbon dioxide level that the atmosphere is likely to see in 2030. In other words, the increase in temperature for doubling of a GHG like carbon dioxide is 1.2°C. This is the radiative force which is an index of this property of a gas and the calculations have been made for carbon dioxide, the most important of all GHGs (see *Figure 7*). A more formal definition of radiative force is: the change in average net radiation at the top of the troposphere which occurs because of a change in the concentration of a GHG or because of some other changes in the overall climate system. Cloud radiative forcing (which also happens) is the change in the net radiation on the top of the troposphere due to the presence of the cloud. Please see *Table 1* for properties of various GHGs.

Properties of Green House Gases

We shall now list the important and minor greenhouse gases and note their features and characteristics.

Carbon Dioxide

Respiration processes, photosynthesis of plants and trees and in the oceans are all part of the carbon cycle. It is well known that the atmosphere, forests and oceans are carbon reservoirs. Carbon dioxide is the medium that keeps moving carbon between the reservoirs. The movement of carbon occurs on huge time scales – from decades to millenniums. Carbon has a very long time scale. It stays in the atmosphere for large intervals of time. For example, about 50% of an increase in carbon dioxide will be removed within 30 years, a further 30% within a few centuries and the remaining 20% may stay put in the atmosphere for several thousands of years. This, incidentally, shows that GWP figures for carbon dioxide, listed on the basis of a life time of about 100 years, do not make any sense. They can indeed be very misleading.

Thus, the two chief characteristics of the presence of carbon dioxide in the atmosphere are that it is there in large quantities compared, of course, to other absorbing gases; and second, that it stays in the atmosphere over a period of time that varies from a few years to a few hundred years or even thousands of years. Carbon dioxide is the most important GHG and the only one that is spoken of as an 'important' GHG – so much so that the absorbing properties of other (minor) GHGs are also converted to an equivalent CO_2 value and designated as $CO_{2(e)}$.

The Role of Oceans

Oceans absorb plenty of carbon dioxide; this is familiar to us, because carbon dioxide is used in the manufacture of cold (carbonated) drinks. A great deal of carbon dioxide absorbed by the ocean is absorbed rapidly in the first few days. The rest of it takes several hundred years and up to a thousand years. In other words, the ocean does not provide an immediate sink when an increase in carbon dioxide in the atmosphere occurs. Animals and plants in the sea also participate in the carbon cycle by way of respiration and photosynthesis.

Methane

Methane is also known as 'natural gas' and 'marsh gas'. One can watch bubbles of this gas emerging from marshy (wet) soils in which material is decomposed. It is produced in farms, paddy and wheat fields and more generally from the agricultural sector. It can be destroyed by chemical action. The average lifetime of methane is about 12 years – much shorter than the life time of carbon dioxide. The presence of methane in the atmosphere is linked to population - although it does not originate from industrial activities of human beings.

Nitrous Oxide and Ozone

Emissions of nitrous oxide are associated with natural and agricultural eco systems, but it is a GHG. Ozone is again a minor GHG. However, its increase has been successfully restricted because its layer was getting depleted. In other words, the problem of ozone has been successfully tackled by introducing new refrigerants. While they worked for Ozone Depletion Potentials (ODPs), it was found that their Global Warming Potentials (GWPs) were too high. Refrigerants with low GWPs as well are already becoming available. Machines using low GWP refrigerants are also increasingly available. Research on finding refrigerants with lower GWP characteristics is an ongoing activity.

The formula relating Radiative Force RF for an atmospheric concentration of C ppm of CO_2 is

$RF = 5.3\ln(C/C_0)$ where C_0 is its pre-industrial concentration of 280 ppm.

Aerosols

Aerosols in the atmosphere scatter incoming radiation back to space. These particles originate from land surface, forest fires and sea-spray. One of the most important aerosols that arise from human activity are sulphate particles. They emanate from power stations – basically from combustion of coal and oil used for generation of power. The radiative force from aerosols can be positive or negative. Thus, they can reduce the carbon dioxide content in the atmosphere also sometimes. Aerosols also influence the emissions through indirect radiative forcing by their effect on cloud formation. The RF values of various GHGs and other sources of emission will be taken as carbon dioxide: 1.66 w/sqm, N_2O: 0.48 w/sqm, CH_4: 0.16 w/sqm, ozone: -0.05 w/sqm, water vapour: 0.07 w/sqm, aerosol: -1.2 w/sqm, exhaust from aircraft: 0.01 w/sqm, and total net human activities: 1.6 w/sqm. It will be seen that the carbon dioxide leads the pack amongst the contributors of positive

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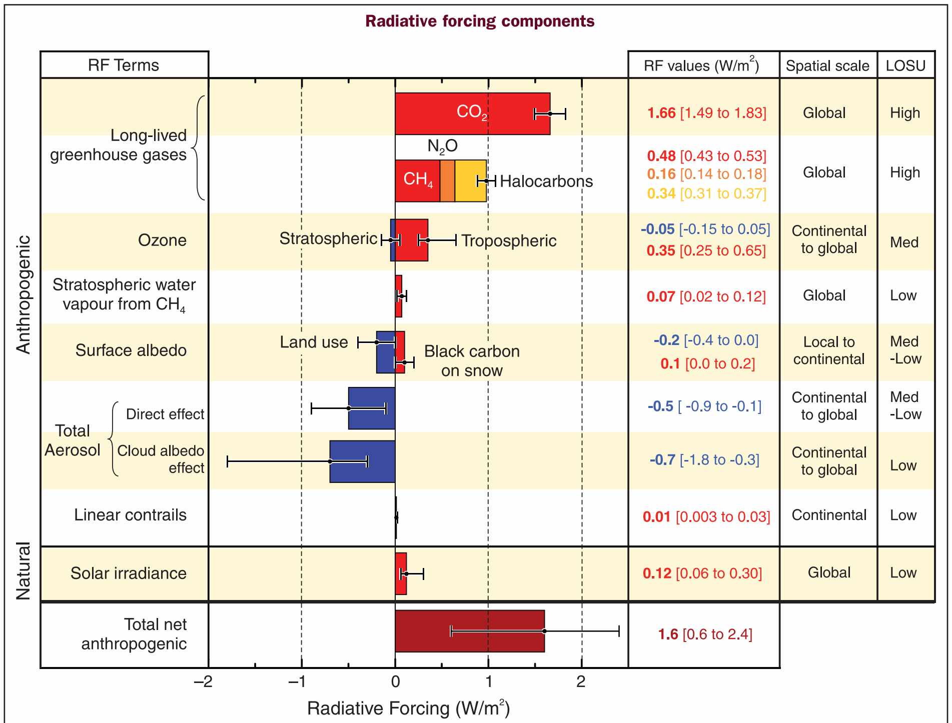

Figure 3.11: Global, annual mean radiative forcings (Wm-2) due to a number of agents for the period from pre-industrial (1750) to 2005. The size of the rectangular bar denotes a best estimate value; the horizontal lines indicate estimates of the uncertainly (90% confidence) ranges. To each forcing an indication is given of the geographical extent (spatial scale) and a 'level of scientific understanding' (LOSU) index is accorded. This latter represents a judgement about the reliability of the forcing estimate involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the machanisms determining the forcing and the uncertainties surrounding the quantitative estimate of the forcing.

Figure 7: Radiative forces (Courtesy: IPCC AR-4 Assessment Report-2007)

RF values, CH_4 being next; while negative RFs can be noted from ozone (together with positive RFs also), surface albedo (reflection) from land surface with positive RFs and total aerosols including both direct effect and cloud albedo effect (*Figure 7*).

Impacts on Climate, Health, Water...

Adverse impacts on fertile lands and people, loss of land, menace of tropical cyclones, flooding of river deltas (like Sundarbans), vulnerability to cyclones and storms, contamination of water used for agriculture and for drinking water as well, are already well known. Atmospheric pollution, restricted water supplies, deterioration of soil quality leading to poor crops and lower level of nutrition – are all negative factors from the point of view of human health.

All the factors mentioned above will get harsher as a result of climate change. Generally speaking, climate change will take the form of higher temperatures and higher humidities in tropical countries like ours. People do adapt themselves, but there will be limits. Difficulties will also be greater when changes occur too fast. Also, older people will find it harder to survive. Both questions of comfort and health are involved. Heat waves will be harsher and their occurrence will be more frequent. This results in increased deaths during that period with the maximum affected again being the more aged. Diseases also will be on the rise in hotter climate – malaria, dengue, yellow fever, viral encephalitis etc. Another major impact would be increasingly acute scarcity of water (for both industry and for drinking). Adaptation to change will depend on the mitigation systems. The poor will often not be able to afford the expenses for food even when available. Finding cures may be easier than finding the resources to apply them to the needy.

More generally speaking, the estimated cost for mitigation will be typically around 1% to 4% of GDP for developed countries and 5 to 10% or more for many developing countries.

Cyclones in River Delta and Coastal Areas – the Case of Sunderbans

Sundarbans (in Bangladesh and partly in our country) provides an example of a small region about 10% of which would be lost with half a meter of sea level rise and about 20% with a 1 m rise. Everybody recalls the disaster that struck this island and areas contiguous to it in the year 1999. The sea level rise is expected to keep increasing and reach about a meter by 2050. Increase in incidence of extensive flooding and loss of life should also be expected. Actions may be taken by way of mitigation – like relocation of the fishing industry. As for agriculture, cultivation could be moved deeper into the land but the quality of land may not be acceptable. Conditions may be so intolerable that there could be mass movements and migrations. Finding suitable land for migrants is not easy.

Feedbacks

Feedbacks are factors which tend to increase the rate of a process or decrease it, and are themselves affected in such a way as to continue the feedback process.

A positive feedback is a process in which an initial change will bring about an additional change in the same direction. An example of a simple positive feedback in everyday life is the growth of an interest-earning savings account.

There are also negative feedbacks, processes in which an initial change will bring about an additional change in the opposite direction. An example of a simple negative feedback is your body's cooling mechanism. When your body temperature rises, you begin to sweat. The evaporation of this sweat from your skin cools your body and your temperature returns to normal.

It is positive, rather than negative feedbacks that contribute to abrupt climate changes. In positive feedbacks, a small initial perturbation can yield a large change. Negative feedbacks, on the other hand, stabilize the system by bringing it back to its original state.

Carbon Dioxide

The role of carbon dioxide has been covered under the following heads/sub-heads.

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Water Vapour

Water vapour plays a crucial role as a feedback. Its content in the atmosphere fluctuates quite often, but generally speaking, as the global temperature gets warm, it will mean that moisture content in the atmosphere will keep going up over a period of several decades and centuries. It is found to provide an average positive feedback of a magnitude approximately double the increase in the global temperature than would arise with fixed water vapour.

Clouds

One of the more important feedbacks is Cloud Radiation Feedback, which is the source of the greatest single uncertainty associated with climate sensitivity i.e., change of the earth temperature for a given change in value or strength of the disturbing factor. Work on better observations, use of improved instruments and efforts to obtain better understanding and more accurate predictions of climate change is being done by the community of scientists.

As we have seen earlier, clouds reflect a part of solar radiation back to space. This reduces the inflow of total energy to the system (earth and atmosphere). They also provide a Green House effect. This way, by absorbing radiation from the earth's surface below and by emitting radiation, heat loss to the space is reduced. Thus the radiative forces due to the first effect and the Green House effect forces of the second effect have opposite signs. What sign the net radiation will have depends on the properties of the clouds at the time for which the calculations are being made. When all these are factored, the overall effect on the clouds can be either positive or negative.

Oceans

Oceans interact with the atmosphere. It is from them that the atmosphere gets its water vapour. At the same time, condensing water vapour provides the largest single heat source for the atmosphere. Oceans have large heat capacity compared to the atmosphere. Less than just 3 m depth of water (in the ocean) will equal the entire heat capacity of the atmosphere. With its large capacity, its diurnal variation of temperature is small. Seasonal variations occur over a long period of time. As a result, they have a large influence on the rate at which atmospheric changes occur. Circulation of water within the ocean helps to distribute heat throughout the climate system (for example, Gulf Stream and more generally, ocean currents).

Summarizing, the feedback values calculated are water vapour: -1.2 ±0.5, cloud: -0.6±0.7, ice albedo: -0.3±0.3, and total: -1.1±0.5. It is interesting to note that the total is negative.

In the second part of this article, which will appear in our September-October 2013 issue, we will have a look at modeling and simulation for accurate projection of future scenarios, earth temperature as proxy to assess impact of climate change vs. time, various scenarios, sharing the burden of emission cuts, the dilemma of whether we should stabilize the increase of earth temperature at 2°C or 3°C, and from science to engineering and enforcement. ❖