Review Paper:

Global Warming, Impacts and Mitigation Measures: An Overview

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Abstract

Global warming is the rise in global average temperature near the surface of earth. It is primarily caused due to the emission of Green House Gases like water vapors, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbon (CFC) etc. in the atmosphere. These gases allow the incoming sunlight to pass through the atmosphere but absorb and reradiate the energy corresponding to longer wavelength (infra-red) reflected by the earth's surface. This process makes our earth warm and is called Green House Effect. However, it has been noticed and reported by numerous researchers that over the last century, the Green House Effect has enhanced due to the increased amount of Green House Gases especially CO_2 gas in the atmosphere. CO_2 alone produces roughly more than two-third of the enhanced Green House Effect. CO_2 is released in the atmosphere primarily from the burning of fossil fuels (coal, oil and gas), deforestation and other land use change activities.

According to recent Intergovernmental Panel on Climate Change (IPCC) report 2018, the earth's average temperature has raised ~1 ℃ over the past century (1850-2018) and it is further expected to temperature rise of 2.5 ℉ to 10 ℉ over the next century. The possible consequences of global warming include rising sea level due to the melting of the polar ice caps, increase the global mean rates of precipitation and evaporation, increase in lightning activity, forest fires, drought, longer spell of dry heat waves, changes in biosphere and other severe weather events. In this study, we will discuss the cause of global warming, the role of global warming in climate change and its various impacts on the planet earth.

Keywords: Global warming, Atmosphere, Climate Change, Geoengineering, Green House Effect, Green House Gases, Permafrost, Heat waves, Ocean Iron Fertilization.

Introduction

Global warming is the increase of global mean surface temperature of the earth and one of the most important challenges facing the modern world in 21st Century. Increase in the ocean heat content, decline in glaciers and snow cover and shrinkage in Arctic sea area etc. are all evidence of global warming[58]. When the sun's energy reaches the earth's atmosphere, some of this is reflected back to the space and rest of the energy comes to the earth. Again, some part of it is reflected by the surface of earth and partly is absorbed by the earth.

As earth's surface is heated, it radiates part of this energy back to space. The long wavelength radiation (infrared) are absorbed by the atmospheric Green House Gases (GHGs) and radiated towards the earth which produces steady heating of earth's atmosphere and surface and makes it habitable. This natural process is known as Green House Effect (GHE). The importance of GHE can be understood if we calculate the earth's surface temperature without assuming its atmosphere. The temperature of earth without considering its atmosphere is given by the Stefan-Boltzmann Law:

$$T = \left(\frac{(1-a)S}{4\sigma}\right)^{1/4} \tag{1}$$

where a=0.31 is called Albedo of Earth; S=1361 Wm^{-2} is called solar constant and $\sigma=5.6703\times10^{-8}\ Wm^{-2}K^{-4}$.

On putting above values, the temperature of the earth comes out to be around 253.7 K or –19.4℃. This is well below the freezing point of water. The earth's actual global mean surface temperature is around 14℃ i.e. ~34℃ warmer than the calculated value. This extra warming of Earth's surface is due to its atmosphere containing GHGs which produce GHE and maintain our earth as comfortable place for existence of life. Without the GHE, our earth would be a frozen ball of ice. The credit of discovery of GHE goes to French mathematician Josef Fourier and later it was experimentally verified by John Tyndall.

GHGs consist of three or more atoms. The type of molecular structure of these gases provides them ability to trap the heat and transfer it to earth's surface making it warm. The GHGs include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbon (CFC). Carbon dioxide, methane and nitrous oxide are anthropogenic GHGs which are released from burning of both fossil and biomass fuel as well as decomposition of organic matter above and below ground. It has been observed that during the last century the GHE has been enhanced due to the increase in the amount of GHGs especially CO_2 and consequently the average global temperature also has increased[41].

The concentration of CO_2 has increased from 277 parts per million (ppm) in 1750, the beginning of industrial era to 405±0.1 ppm in 2017 (46%)[76] and is projected to rise reaching up 970 ppm by the end of this century and 1900 ppm by the year 2300[15]. Hansen et al[31] reported that the global average surface temperature has risen around 0.6℃ since last three decades and 0.8℃ since last century. Stocker et al[93] reported the increase in temperature of 0.85℃ over the period 1880-2012.

Moreover, Hansen et al[31] described that global warming occurred before 1975 over the century which was slow with large fluctuations but after that it was rapid with a rate of ~0.2℃ per decade. This rate may accelerate if no efforts are made to mitigate the GHGs. According to IPCC report of 2018, the global warming is likely to reach 1.5℃ between 2030 and 2052. The main GHG concentrations that have been increased during the industrial period are carbon dioxide, methane, nitrous oxide and chlorofluoro carbons. The main gas responsible to heat the atmosphere is water vapor. The rise in temperature due to enhanced GHE will increase the amount of this gas which will cause the further enhancement of the global warming via positive feedback. Over 95% of the previous literature clearly shows that the global warming is happening due to the human induced activities.

According to Inter Governmental Penal on Climate Change (IPCC) Report-2001, most of the warmings of past 50 years are likely (>66%) to be attributable to human activities. IPCC report of 2007 concluded that warming is unequivocal, and most of the warming of the past 50 years is very likely (90%) due to increase of GHGs. Carbon dioxide, methane and other greenhouse gases (GHGs) have increased significantly since the industrial revolution because of the burning of fossil fuels for energy and from changes in land use such as deforestation for agriculture.

According to Solomon et al[92], carbon dioxide emissions from fossils fuels have long residence time (~100 years) in atmosphere and for large concentration of CO_2, our earth will take centuries to come in thermal equilibrium. Therefore, the effects of elevated GHGs on global climate and ecosystems will last for thousand of years. Researchers suggest that warming below 1.2℃ is permissible but more than 2℃ will be dangerous and we will have to face serious situations.

It should be noted that enhanced CO_2 is not the only GHG contributing to global warming, other gas CH_4 is also increasing in the atmosphere. Its atmospheric concentration has been tripled since pre-industrial level[29]. Molecules of methane trap approximately 28 times more heat than carbon dioxide. However, because methane is present in small amount as compared to carbon dioxide gas, so its aggregate effect is less. Methane is primarily emitted due to the anaerobic decomposition of organic matters.

The sources of global methane are both natural as well as anthropogenic. The natural sources are wetlands, termite activity, methane hydrates and oceans whereas anthropogenic sources are livestock, rice agriculture, landfills, burning of fossil fuels and biomass burning. However, 60% of the global emissions of methane gas are due to human activities.[11]

In fig. 1, we have shown that carbon dioxide gas has increased around ~100 ppm since1960 till now. Similarly, in fig. 2 we have shown the rising of methane. Methane is accumulating in our atmosphere at a rate of 1% per year. It has been elevated around 200 parts per billion (ppb) in our atmosphere since 1985 till date.

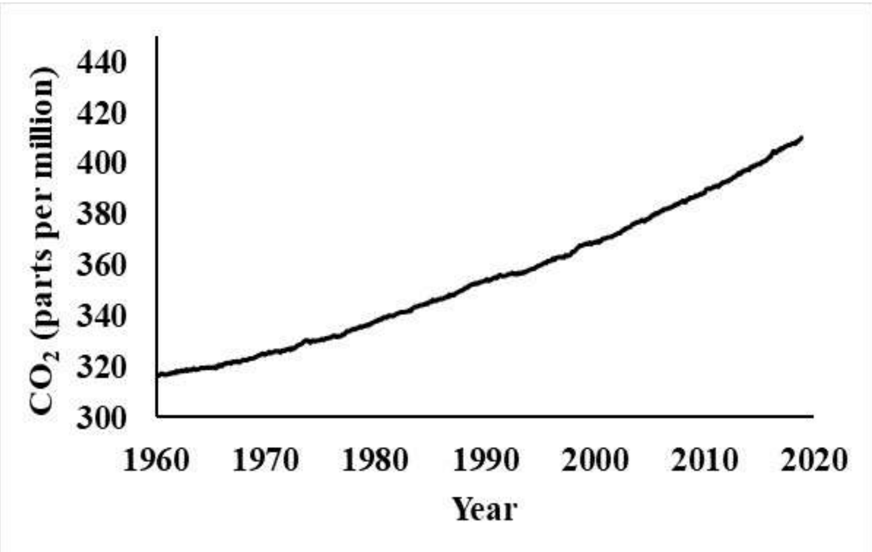

Figure 1: Graph showing the increase of CO_2 gas since 1960. The data has been taken from ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt

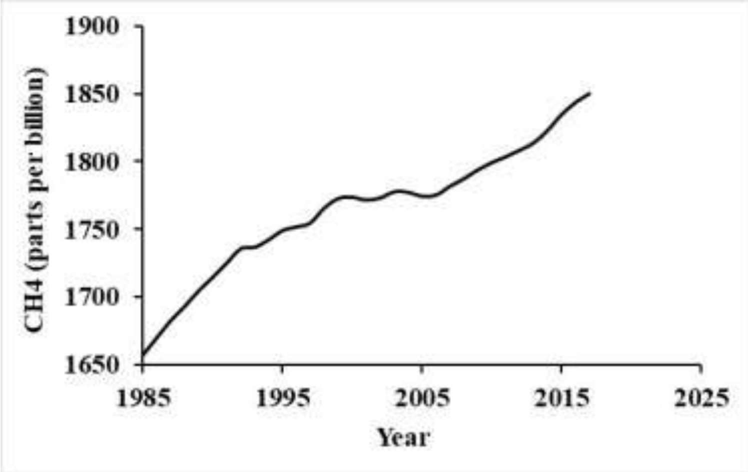

Figure 2: Graph showing the increase of CH_4 gas since 1985. The data has been taken from ftp://aftp.cmdl.noaa.gov/products/trends/ch4/ch4_annmean_gl.txt

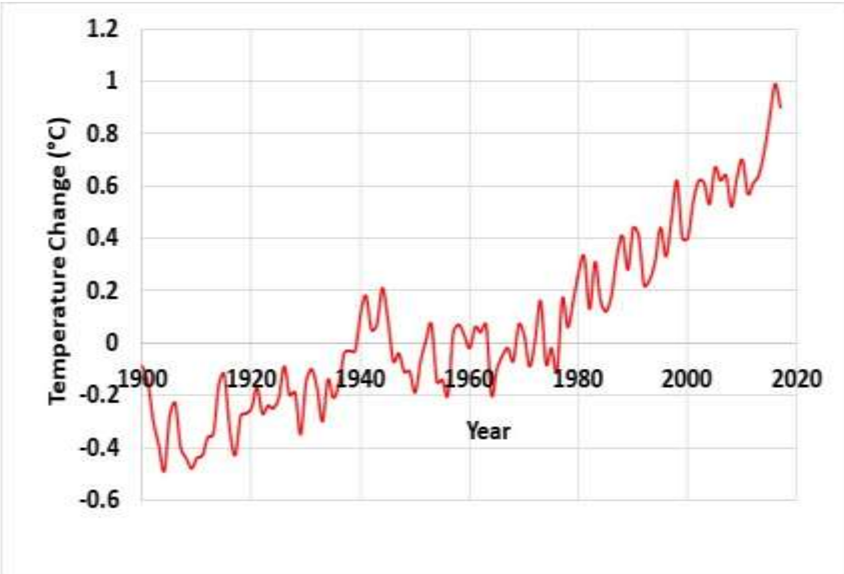

Figure 3: The graph shows the change in global surface temperature relative to 1951-1980 average temperatures. The data credits to https://climate.nasa.gov/system/internal_resources/details/original/647_Global_Temperature_Data_File.txt

However, it held steady since 2000 to 2007. Nisbet et al[71] reported that methane rise since 2007 is dominated by significant increases in biogenic methane emissions, particularly in the tropics, for example, from expansion of tropical wetlands in years with strongly positive rainfall anomalies or emissions from increased agricultural sources such as ruminants and rice paddies. The effect of increasing level of these gases i.e. rise in global mean surface temperature of earth has been shown in fig. 3. The rise in temperature is around 0.9°C relative to 1951-1980 average temperature.

Impacts of Global Warming

The global warming can impact in different ways on our quality of life. The foremost impact is on the climate, better known as climate change. Climate determines whether a plant will grow or a species will survive or not at a particular place. Small increase in global temperature may provide enough energy to our earth which is capable for changing the climate. Global warming may lead the following serious consequences via climate change.

Rise of sea level: Rise of sea level is becoming increasingly important as a hazard to humans worldwide due to global warming. Low-lying coastal plain regions, deltas, and most of islands are highly vulnerable. As we look back, sea level was fairly stable for the past 3,000 years until about the mid of 19^{th} century. During the 20^{th} century, sea level began rising at a global average rate of 1.7 mm/year[106] and during last two decades it rose at a rate of 3.2 mm/year. Rahmstorf[77] presented a semi-empirical relation that connects the rate of global sea-level rise (*H*) to global mean surface temperature (*T*). The relation is given by:

$$\frac{dH}{dt} = a(T - T_0) \quad (2)$$

where T_0 is the base temperature at which sea level is in equilibrium with climate and 'a' is another constant. Both T_0 and 'a' can be determined from data. Eq. (2) describes that the rate of sea-level rise is roughly proportional to the magnitude of warming above the temperatures of the pre-industrial age. He proposed the rate of sea level rise of 3.4 mm/year per 1°C and projected the rise in sea level of 0.5-1.4 m above the 1990 level in 2100.

Vermeer and Rahmstorf[102] extended the eq. (2) by adding one more term ($b\, dT/dt$) to its right hand side and projected the sea level rise ranging from 0.75-1.75 m for the period of 1990-2100. Later, Church and White[18] estimated the rate of sea level rise as 3.2 ± 0.4 mm/year from the satellite data and 2.8 ± 0.8 mm/year from the *in situ* data for 1993-2009. The global average sea-level rise from 1880 to 2009 is about 21 cm.

Using computer simulations, Jevrejeva et al[42] estimated sea level rise in a range of 0.57-1.10 m by 2100 and 1.84-5.48 m by 2500. More recently, using a 25 year time series of precision satellite altimeter data from TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3, it is estimated that global mean sea level has been rising at a rate of ~3±0.4 mm/year since 1993[70]. Moreover, they showed that this rate is accelerating at 0.084 ± 0.025 mm/year[2].

It is suggested that if the sea level continues to change at this rate and acceleration, sea-level rise by 2100 will be more than double the amount if the rate remains constant at 3 mm/year with respect to present sea level. Previous observations show the increase of carbon dioxide emissions since the industrial revolution has increased global mean temperature of the air and ocean due to global warming. Global warming raises sea level due to two different processes. First, increase in temperature causes sea level to rise due to thermal expansion. Secondly, it causes melting of glaciers, and loss of ice from the Greenland and Antarctica ice sheets which add this water to the oceans.

An immediate result of melting glaciers would be a rise in sea levels. Small rise in sea level can have large impacts along the coastal areas due to storms surges and exceptionally high tides. Even a modest rise in sea levels could cause flooding problems for low-lying coastal areas. However, if the West Antarctic ice sheet is melted and collapsed into the sea, it will increase sea level more than 32 feet, and many coastal areas will vanish. Other impacts of sea level rise may be loss of fragile land and population displacement, unemployment, salinization, reduction in freshwater availability, erosion of sandy beaches, hampering coastal tourism etc.

Heat waves and wildfires: The condition when the temperature of a place raises above normal maximum temperature is termed as heat wave. According to India Meteorological Department (IMD), if the normal maximum temperature of a station is less than or equal to 40°C, then a departure of 5 to 6°C from this is called 'heat wave' and increase of 7°C or more from normal is declared as severe heat wave. If the normal maximum temperature at a station is more than 40°C, then the rise of 4 to 5°C above normal maximum temperature is termed as a 'heat wave' and the variance over 6°C above this is classified as a 'severe heat wave'.

However, when actual maximum temperature remains 45°C or more for consecutive two days, irrespective of normal maximum temperature, heat wave is declared[10]. A study shows that an increase in heat-absorbing greenhouse gases i.e. global warming intensifies an unusual atmospheric circulation pattern which produces heat waves and these heat waves will be more intense, more frequent and longer lasting in Europe and North America during second half of 21st century[66]. Heat waves can kill more people in a shorter time than almost any other climate event. They are known as silent killer. The IMD has declared 2016 as the warmest year ever recorded since 1901.

During the last two to three decades, whole world has been affected by the heat waves. According to records, around 700 people died as a result of Chicago's mid-July1995 heat wave[105]. The havoc created by heat waves has been seen during August 2003 in which the citizens of France (~15000), Germany (~5000), Italy (~3000), Spain (6000), Holland (1500), Portugal (2000) and the United Kingdom (2000) are estimated to have died along with thousands of farm animals[27]. Robine et al[80] analyzed summer mortality for the reference period 1998-2002 and for 2003 in 16 European countries. They found that more than 70,000 additional deaths occurred in Europe during the summer of 2003 due to catastrophic European heat waves.

Climate projections indicate that such type of European heat wave could occur in Chicago also by mid of this century. Between mid and end of this century, there could be as many as five such events under lower, and twenty five under higher Green House Gas emissions[33].

India was also struck by the severe heat waves in 1998, 2003, 2012 and 2015. Recently in May 2015, it caused the deaths of more than 2500 people in multiple regions[84]. The South Indian States Andhra Pradesh and the neighbouring Telangana, where more than 1,735 and 585 people died respectively, were the areas most affected by the heat waves. Other casualties were from the eastern states of West Bangal and Odisha. Between 1992 and 2016, heat waves caused 25,716 deaths in India. The warming of the tropical Indian Ocean and more frequent El Nino events in future may further lead to more frequent and longer lasting heat waves over India[84].

Further, over central and north western parts of India, frequency, total duration and maximum duration of heat waves are increasing. According to Dosio et al[22] in a world of 1.5°C warmer than pre-industrial levels, 13.8% of the world population will be exposed to severe heat waves at least once every 5 years. This fraction becomes nearly three times larger (36.9%) under 2°C global warming, i.e. a difference of around 1.7 billion people. According to Im et al[39], a global temperature rise of 2.25°C by the end of the century could create dangerous heat conditions across South Asia including India. Under this scenario, the conditions of deadly heat wave could occur every two years in South Asia instead of 25 years at present and it may impact 55% of the region's population instead of 15% today.

Mishra et al[68] reported that the frequency of severe heat waves will rise by 30 times the current climate if the global mean temperature is increased to 2.0°C above pre-industrial conditions by the end of 21st century. Not only human beings but marine life is also in danger zone due to global warming. Like heat waves over land, the heat waves over oceans also happen during sunny days called "marine heat waves".

Marine heat waves are generated when the sea surface becomes quite warmer than normal temperature and persists for longer time periods (days to months) which can extend up to thousands of kilometres. Recent studies show that marine heat waves may harm the marine ecosystems and fisheries significantly[38,72,104]. Recently, Frolicher et al[24] detected double the number of marine heat wave days between 1982 and 2016, and this number is projected to further increase on average by a factor of 16 for global warming of 1.5°C relative to pre-industrial levels and by a factor of 23 for global warming of 2.0°C.

At present, 87% of the marine heat waves are attributable to human induced global warming and it will be 100% when temperature will exceed 2°C. It is also expected that super heat waves may create the conditions of wildfires also. The heat sucks moistures from the soil and produces the ripe conditions for wildfire to break out. In 2017, unusually high fire levels have been seen in many parts of the world like Chile, the Mediterranean, Russia, the US, Canada and Greenland.

Jolly et al[43] described that climate strongly affects global wildfire activity. They showed that fire weather seasons have lengthened across 29.6 million km^2 (25.3%) of the earth's vegetated surface resulting in an 18.7% increase in global mean fire weather season length. In addition, Abatzoglou and Williams[1] reported that anthropogenic warming and drying are increasing wildfire activity across wide swaths of forested land in the western United States. They also estimated that climate change/global warming has contributed to an additional 4.2 million ha of forest fire area during 1984-2015.

Drought and intense rainfall: Drought is defined as prolonged absence or marked deficiency of precipitation that results in water shortage in some regions. Global warming has a direct effect on precipitation. Increased heating leads to greater evaporation and thus surface becomes much dry, thereby increase in intensity and duration of drought happens in some regions. However, the water holding capacity of air with temperature increases by about 7% per 1°C warming which leads to increase of water vapor in the atmosphere and produces more intense precipitation events causing floods in other regions[98]. Thus, global warming produces non uniform distribution of precipitation i.e. dry areas will face drought and wet areas will experience floods in future. It is inferred that human-induced greenhouse gases have contributed to changes in heavy precipitation events at the global scale.

Lehmann et al[55] showed that over the last three decades the number of record-breaking heavy precipitation events have significantly increased in the global mean. In India, intense rainfall in Mumbai occurred in 2005 that caused the death of more than 1000 people. In Uttarakhand, torrential rain in June 2013 resulted in large flooding and associated landslide. In this disaster, around 15000 people were dead, 11000 missing including thousands buried in the debris and economic loss of 12000 crores rupees in the tourism industry alone[21]. In Gujrat, heavy rainfall occurred in 2015 and 2017 which caused more than 200 deaths.

More recently in August 2018, extreme precipitation and severe flooding in the State of Kerala (India) displaced hundreds of thousand people and killed at least 483[73]. This flood was declared the state's most damaging in 100 years. Numerous other studies also have shown that worldwide there are extensive increases in heavy precipitation and decreases in light and moderate rain also due to global warming[53,91,103]. On the other side, Mishra and Liu[67] reported that there are increases of $49\% \pm 21\%$ and $33\% \pm 17\%$ in prolonged dry spells and total dry days respectively over India for each degree Kelvin (K) increase in global mean temperature during six decades (1951-2012). The increases in prolonged dry spells in north-eastern and western India are even more i.e. $51.06 \pm 24.32\%$ and $39.22 \pm 15.43\%$ respectively. They suggested that there is an increased risk of drought over India due to global warming.

Storms: Tropical storm or tropical cyclone is one of the most dangerous and devastating natural phenomena originated over the sea surface. Recently, it has been reported that increase in sea surface temperature due to global warming will increase the globally averaged intensity of tropical cyclones from 2-11% by 2100, however, their frequency of occurrence will decrease from 6-34%[44,45]. A warmer sea surface provides more energy for storm development and favours higher intensification rates.

According to Kang and Elsner[44], global ocean warmth causes a convectively more unstable environment with more moisture in the lower troposphere, but a stronger high pressure aloft. This lowers the frequency of tropical cyclones occurrences but provokes bursting intensities. Several strong tropical storms like typhoon Megi in 2010, typhoon Haiyan in 2013, typhoon Mangkhut in 2018, Hurricane

Wilma in 2005, Hurricane Harvey in 2015, Hurricane Irma in 2017, Hurricane Mariya in 2017 have occurred during the recent years. Some of them may be influenced by global warming. These highly intensified tropical storms brought fatalities and widespread damages to many countries.

Ocean acidification: Ocean acidification occurs when CO_2 in the atmosphere reacts with water to create carbonic acid. In this process, the pH of ocean water decreases. It is well known that the oceans absorb almost 25% of the atmospheric CO_2, so ocean acidity has been already increased by 30 percent due to anthropogenic emissions of CO_2[23]. Depending on the extent of future CO_2 emissions and other factors, the IPCC-2007 report predicts that ocean acidity could increase by 150 percent by 2100 and may cause threat to life for a large number of marine organisms.

Thus, increasing the level of CO_2 will not only affect the human beings or the other creatures that are living on land through global warming but will also affect the aquatic animals in the oceans. For example, the coral reef organisms and the structures they build will be increasingly exposed in the coming decades to the impacts of ocean acidification. Previous studies show that ocean acidification linked to CO_2 gas emission is already slowing coral reef growth[28]. Global warming also plays an important role for coral bleaching[2]. In the year 2015-16 the hottest years on record, the increased sea surface temperature resulted in the worst mass bleaching event on record for the Great Barrier Reef (GBR) in Australia, with 93% of individual reefs experiencing some degree of bleaching and 67% of coral were dead in the northern section of the GBR[38].

Reef structures play an important role as natural breakwaters, which minimize wave impacts from storms such as cyclones, hurricanes or typhoons. Also, their beauty makes coral reefs a powerful attraction for tourism. The well managed tourism provides a sustainable means of earning foreign currency and employment for people around the world. Coral reefs provide food for people living nearby, especially on small islands. The animals or organisms living in coral reefs are used for medicines for the treatments of world's most prevalent and dangerous illnesses and diseases. Thus, a deep cut of the emission of GHGs along with protection from poor water quality is necessary for the survival of beautiful coral reefs.

Permafrost degradation: Permafrost is the ground or rock which covers around 15 million km^2 of the land surface and contains vast amount of carbon in the form of plants and animals that have died since last ice age and are frozen without decaying at or below the freezing point of water (0℃) for a minimum period of 2 years. Permafrost can be from 1 m to 1450 m thick[87]. These are most sensitive to warming.

Scientist have estimated that the world's permafrost contains around 1700 billion metric tonnes of carbon which is almost double the amount of carbon currently present into the atmosphere[59]. Most of the permafrost is found on higher latitude regions. It is clear that on increasing the temperature of Earth's surface permafrost melts and decomposition of organic materials will start. Decomposition will result in the emissions of CO_2 and CH_4 gases. The emission of these gases will enhance the GHE and more warming will take place, consequently more CO_2 and CH_4 will be released. This will provide an irreversible positive feedback to the global warming. Fig. 4 shows the positive carbon feedback.

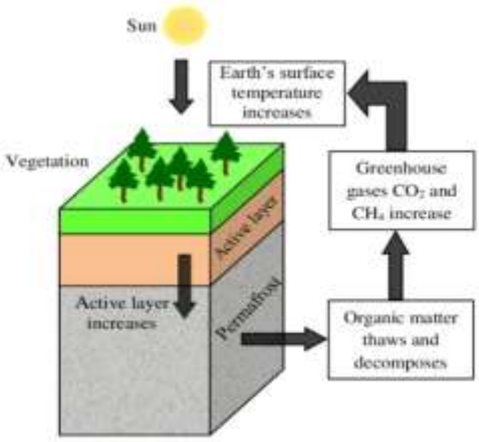

Figure 4: Schematic diagram of the permafrost carbon feedback. The organic matter present in the permafrost will decay due to global warming and produces CO_2 and CH_4 gases resulting in further increasing surface temperature i.e. global warming. The figure is partly adopted from Schaefer et al.[86]

According to Schuur et al[88], large quantities of organic carbon are stored in permafrost within Arctic and sub-Arctic regions. Global warming can induce environmental changes over there which can accelerate the microbial breakdown of that stored organic carbon resulting in the release of CO_2 and CH_4 gases. Computer simulations results show that permafrost soils will release between 68 and 508 Pg carbon by 2100[59].

Recently, Biskaborn et al[9] reported that the permafrost is warming and its global temperature has increased by 0.29 ± 0.12℃ during 2007 to 2016. According to a study if the global average temperature rises up to 2℃ above preindustrial level, the permafrost region would eventually be reduced by over 40% and if temperature stabilizes at 1.5℃ then it would save approximately 2 million km^2 of permafrost[17]. Roughly 35 million people live in permafrost zones. They all can face serious problems if permafrost decays. Additionally, increase in temperature in permafrost regions may cause the release of disease-causing bacteria and viruses frozen in the dead bodies which can take life of people.

Measures to reduce Global Warming

Various approaches or technology have been proposed to prevent the increase of the earth's surface temperature i.e.

global warming. However, geoengineering is the best way to mitigate future's severe global warming. Geoengineering is divided broadly into two categories: carbon dioxide capturing and removal (CDCR) technology and solar geoengineering or solar radiation management (SRM) technology[16]. CDCR technology aims to capture and remove carbon dioxide and other GHGs from the atmosphere whereas SRM technology involves reflecting more and more sunlight back to space which would otherwise warm the earth. The term "geoengineering" was first introduced by Victor Marchetti[60].

Carbon dioxide capturing and removal technology: According to Paris climate agreement in 2015, the rise in global temperature well below 2℃ above pre-industrial levels is extremely necessary to avoid the worst impacts of global warming. In order to holding the temperature up to this level (below 1.5℃), global emissions of CO_2 will need to decline by 45% from 2010 levels by 2030, and reach net zero by 2050 (IPCC, 2018). Carbon dioxide capturing and removal technologies aim to limit or remove the excess CO_2 emissions from the atmosphere and store the carbon in the land biosphere, ocean, or deep geological reservoirs. There are various methods under this technology given below.

Carbon dioxide capture and storage from fossil energy (F-CCS) and Bioenergy with Carbon Capture and Storage (BECCS) strategies: In order to fulfill energy demand for rapid economic growth, fossil fuels i.e. coal, oil and natural gas are the dominant sources of the global primary energy supply at present time, and will likely to remain for the rest of the century. It is estimated that global GHGs emission in 2030 will increase by 25-90% as compared to the year 2000 level without climate change mitigation policies, and CO_2 concentration in the atmosphere will grow as much as 600-1550 ppm[69].

It is necessary to keep the temperature rise less than 2℃ relative to pre-industrial levels by 2100 for staying in safe zone. Therefore, carbon dioxide capture and storage from fossil energy (F-CCS) strategy may be used extensively for the reduction of CO_2 emission in the atmosphere in near future. F-CCS can reduce the CO_2 emission from coal and gas-fired power plants and large industrial sources. This approach is a three-step process given below:[57]

(i) Capture: The chimney smoke from the power plant contains various gases along with 10-12% of CO_2. The first step of F-CCS process is to capture CO_2 from the flue gases. This process is known as carbon capture and it can be done by three different techniques namely post combustion capture, oxy-combustion capture and pre-combustion capture. This step is the most difficult step in the entire F-CCS process. After capturing CO_2, it is compressed to liquid.

(ii) Transport: Compressed CO_2 gas is transported from its source to the storage reservoir through pipelines. However, CO_2 can be transported by truck, trains or ship but it would be expensive as compared to pipelines when done on large scale. Pipelines should be made of good quality of materials so that it may not lead to CO_2 leak.

(iii) Injection: After transporting of CO_2 to the potential site, it needs to be stored. The best way to store CO_2 is by geological method i.e. it may be injected in deep saline aquifers, unmineable coal seams and depleted hydrocarbon reservoirs in the deep underground where it stays permanently[99].

Once the CO_2 is underground (0.7 to 5 km), it must be monitored to ensure that almost all the CO_2 stays out of the atmosphere for hundreds of years or longer. There should not be any leakages otherwise it will not only damage the environment but also lots of money invested in the process. F-CCS can capture around 90% of the CO_2 gas produced from the combustion of fossil fuels for electricity generation so it may be a good technology and can lead to slow the pace of global warming.

The other approach or strategy gaining more popularity in recent years is generating bioenergy along with carbon capture and storage (BECCS). In BECCS technique, the feedstock is biomass instead of fossil fuels. BECCS involves growing plant material, burning that material for energy, capturing the CO_2 emitted during combustion, and storing it underground[101]. In this way, BECCS is truly a negative emission technology that offers a net removal of CO_2 from the atmosphere.

However, availability of large amount of biomass is the critical factor for the use of BECCS. Biomass from cellulosic bioenergy crops such as perennial grasses (switchgrass) and short rotation woody crops is expected to play a substantial role in future energy systems because of their toleration in diverse growing conditions and less maintenance but their large scale cultivation can also have significant impacts on global food prices, food crop land, water crisis and biodiversity[75]. Also, BECCS systems are fairly expensive to operate. It costs $100 to capture a ton of CO_2 for a biomass plant and for a comparable fossil fuel plant, capturing carbon costs just $ 60 a ton[101]. It is estimated that the potential of global bioenergy when environmental and agricultural constraints are taken into account ranges from 130-270 EJ (1 EJ=10^{18} J) per year in 2050, equivalent to 15-25% of the world's future energy demand[8].

Currently, there are only a few BECCS projects which are in working condition mainly in Europe and USA. It is suggested that BECCS must be implemented worldwide on a large scale but in a sustainable way in order to mitigate global warming.

Carbon dioxide can also be directly captured from the atmosphere. This approach is known as direct air capture (DAC). DAC was first introduced by Lackner et al[46] in 1999. In this process, ambient air is passed through a chemical sorbent (liquid or solid) that absorbs/adsorbs the CO_2. The CO_2 is then released as a concentrated stream for disposal or reuse, while the sorbent is regenerated and the CO_2 depleted air is returned to the atmosphere[64]. The solution sorbents are calcium hydroxide $Ca(OH)_2$, sodium hydroxide NaOH and potassium hydroxide KOH. However, solid organic-inorganic hybrid materials based on amines are highly suitable for DAC. DAC actually reduces the atmospheric CO_2 concentrations unlike F-CCS which only limits the excessive emissions; hence it is also a negative emission technology. DAC processes are not location specific i.e. capture facilities can be installed anywhere. The disadvantage of this technology is that it is very expensive (\$1000 per ton of CO_2)[37]. Currently, the DAC is in its infant stage and needs much more research and development.

Biochar technology: Production of biochar and its storage in soil can be used as a tool to mitigate global warming and climate change. Biochar is the carbon rich solid material produced by the heating of biomass (agriculture residues, biomass crops, agroforestry, wood, leaves) under complete or partial exclusion of oxygen at moderate temperature 300-500°C[5]. This process is known as pyrolysis. Biochar is highly aromatic organic material with carbon concentration of about 70-80% and can endure in soil for thousands of years[54]. It is generally applied into soils for carbon sequestration or for improving soil fertility. It is also a source of renewable bio energy.

The carbon bonds in biochar are very strong and do not break down easily. It is highly stable as compared to biomass against microbial decomposition and hence reduces GHG emissions. It is estimated that global implementation of biochar can potentially offset a maximum of 12% of the current CO_2-C equivalent emissions [that is 1.8 Petagram (Pg) CO_2-C equivalent per year of the 15.4 Pg CO_2-C equivalent emitted annually] and that over the course of a century, the total net offset from biochar would be 130 Pg CO_2-C equivalent[107]. Lenton and Vaughan[56] calculated a reduction in atmospheric carbon of up to 22 GT (equivalent to a reduction of 10 ppm CO_2) using biochar technology by 2050.

Lal[47] estimated that in India about 309 million ton of biochar could be produced annually by using the plant residues and it can offset the 50% of carbon emission (292 Teragrams C $year^{-1}$) from fossil fuels. Additionally, heat and gases produced during pyrolysis can be used to produce energy carriers such as electricity, bio oil and hydrogen for household use or powering cars. In this way, biochar technology will not only slow the rate of warming, it will enhance soil fertility too.

Prevent deforestation and increase afforestation and reforestation: Trees hold large amount of terrestrial carbon in their biomass. They capture atmospheric CO_2 as they grow. Therefore, preventing deforestation and increasing afforestation and reforestation are much better ways to mitigate global warming. The terms deforestation means cutting of trees in forests and afforestation is generally defined as the establishment or planting of forests in areas where there have not been forests (e.g. grasslands) or where forests have not been present for some time (usually more than 20 years)[65]. However, reforestation implies re-establishment of forest formations that have been destroyed or damaged for the benefits of mankind.

McKinley et al[65] estimated that forests and forest products currently offset 12-19% of fossil fuel emissions for the USA. Houghton et al[36] estimated that re-forestation of 500 million hectares could sequester at least 1 Pg C $year^{-1}$ for decades and it will help in stabilizing and then reducing the atmospheric CO_2 concentration. Trees take in carbon dioxide and give oxygen during the process of photosynthesis. In this way, they store carbon dioxide within them. When trees are logged and burnt, they release all the carbon stored within them and increase the GHGs in the atmosphere which accelerate the rate of global warming.

It has been observed that a decrease in the rate of deforestation will give more reduction in CO_2 emissions than forest establishment. Deforestation may cause species extinction and loss of biodiversity via global warming. Global warming resulting in climate change is the biggest problem for the world and preventing our forests is one of the key solutions.

Ocean iron fertilization: Ocean iron fertilization (OIF) means adding of iron ($FeSO_4.H_2O$) in the ocean as a fertilizer to help the growth of phytoplankton which helps in sequestering the atmospheric CO_2 via photosynthesis process[19,61] and deposit much of the carbon in the deep ocean when they die. Phytoplankton are microscopic single celled plants that live mostly near the surface of ocean. It is found that the phytoplanktons suffer from iron deficiency and are not able to use the luxuriant supply of major nutrients in most of the regions of Southern Ocean and northern and equatorial Pacific which prevent them from blooming[61]. These regions of ocean are known as high nitrate low chlorophyll (HNLC) regions.

Langmann et al[48] produced strong evidence that a natural iron fertilization induced by volcanic eruption of Kasatochi volcano in August 2008 created the favourable conditions to generate a massive phytoplankton bloom in iron limited oceanic area of NE Pacific. Therefore, it is thought that adding of iron in the oceans especially in the HNLC regions artificially will sequester the CO_2 from the atmosphere. In order to see the effect, a total of 13 artificial OIF experiments namely Iron-Ex1, Iron-Ex2, SOIREE, EisenEx, SOFeX-N, SOFeX-S, EIFEX, SAGE, LOHAFEX, SEEDS-1, SERIES, SEEDS-2 and FeeP have been conducted in HNLC regions of the oceans till now[108] and found large increase of chlorophyll and a strong decrease of surface CO_2. It is estimated that about 2×10^8 tons carbon could be sequestered per year by fertilizing 10^8 km^2 of ocean[14]. According to

Aumont and Bopp[6], iron fertilization should be done continuously to mitigate global warming, as when stopped, a large part of the sequestered carbon will be reexposed to the atmosphere quite rapidly.

Enhanced weathering of rocks: Weathering is the breakdown of rocks into minute pieces due to the slightly acidic rain (mixture of water and atmospheric CO_2) and forms bicarbonate. The atmospheric CO_2 in the form of bicarbonate washes into the ocean and locked up on the sea floor for millions of years. The natural chemical weathering of rocks is a very slow process and currently absorbs about 1.1 Gt CO_2 annually in the ocean as bicarbonates.

However, enhancing of this process can remove substantial amount of CO_2 from the atmosphere which ultimately reduces the rate of global warming. This natural process can be enhanced by grinding selected types of rocks into small grain sizes and spreading them over the forests and cropland areas.

The rock material is dissolved in the presence of CO_2 and water (H_2O) and dissolved products are transported towards ocean via rivers where they are stored for millions of years[25]. The best suited locations for enhanced weathering are warm and humid areas, particularly in India, Brazil, South-East Asia and China where almost 75% of the global potential can be realized[94].

According to previous studies, dunite rock is found best suited in terms of weathering efficiency but it carries harmful elements such as Ni and Cr which can be released in the environment during dissolution[97], so besalt is used as an alternative material in this process because it contains less harmful elements (Phosphorous, Magnesium and Calcium) compared to dunite rock and it also can act as a fertilizer[32]. This process if done at global scale can also help to reduce the ocean acidification to protect coral reefs and marine fisheries. According to a recent study, idealized enhanced weathering scenarios over less than a third of tropical land could cause significant drawdown of atmospheric CO_2 by 30-300 ppm and ameliorate ocean acidification by 2100[96].

The approaches under CDCR technology are slow process and thus these methods typically require a long duration to impact on the global warming. Thus, another technology given below is quite fast and should be implemented along with CDCR technology in parallel.

Solar engineering or Solar Radiation Management (SRM) technology

Solar geoengineering or Solar Radiation Management (SRM) aims to decrease the global warming by artificially reducing the amount of sunlight absorbed by earth[16]. This can be achieved in two ways: (1) reducing the amount of solar radiation reaching the earth and (2) increasing the reflectivity of earth[7]. This technology will be preferred when the consequences of global warming are more severe than expected. This is relatively fast acting option for quickly reversing the effects of global warming. The various approaches of SRM are given below:

Space based approaches: Space based approaches aim to reduce the incoming solar radiation to earth by reflecting it back to space using certain types of reflectors and sunshades in space. Global warming of 2-5°C can be prevented by reflecting 3-7% respectively of the incident solar radiation[63]. In order to partial block of solar radiation, Early proposed constructing a thin glass shield from lunar materials and placing it near the first Lagrange point (L_1) of the Earth-Sun system. The first Lagrange point (L_1) is a neutrally stable point where an object experiences the equal forces from both Earth and Sun.

Pearson et al[74] suggested to create an artificial ring of space dust/trillions of controlled space crafts with extended parasols about the earth to shade it and reduce global warming. The ring would have a radius of 1.2-1.6 R_e and shade mainly the tropics. It would have an estimated cost of $6-200 trillion. Mautner[63] also proposed to design a belt of reflective film in an orbit above the earth. The required cost for such type of belt based on lunar materials would be $100 billion.

Injection of sulphur in the stratosphere: Injection of sulphur in the stratosphere is another method to deliberately mitigate the global warming and has been suggested as a cost effective method. Stratospheric injection of sulphur was first suggested by Budyko in 1977[13] and later by Crutzen in 2006[20]. This method was inspired by the volcanic eruptions such as 1991 eruption of Mount Pinatubo in the Philippines which deposited the large amount of particulate matter and sulphur dioxide (SO_2) into the atmosphere. This aerosol layer reduced the average temperature around the world by 0.55°C over the following more than two years[81].

The precursor of sulfide gases such as H_2SO_4, SO_2 and H_2S can be delivered to the stratosphere by artillery, aircrafts and balloons. The most interesting thing about this method is that it can be reversed at any time. In this project, deployment of 3 to 5 million tons/year of sulphur would be needed to mitigate the effects of doubling of CO_2. The amount of cooling will depend on the amount of sulphate aerosols in the stratosphere as well as how the sulphur cloud is maintained there. Thus, a continuous supply of large amount of sulphur is required to fight with the global warming. The balloon option would cost $21 billion per year in 2008 dollars[82]. However, this approach may cause the significant reduction of ozone layer if implemented at global scale[34].

Land albedo enhancement: Increasing the albedo of earth at different places can also be useful to mitigate the global warming. This method will reflect more of the incoming solar radiation and reduce the fraction of short-wave radiation absorbed by the earth's surface. There are some principal albedo enhancement schemes given below:

First one is urban albedo enhancement. This scheme involves enhancing the albedo of urban areas by replacing standard building materials for roofs and paving etc. with alternative more reflective (higher-albedo) materials or by adding a more reflective coating[40]. Using reflective materials, both roof and pavement albedos can be increased by about 0.25 and 0.15 respectively resulting in a net albedo increase for urban areas of about 0.1[3]. The simulation results indicate a long-term global cooling effect of 3×10^{-15} K for each 1 m^2 of a surface with an albedo increase of 0.01[4]. This temperature reduction corresponds to an equivalent CO_2 emission reduction of about 7 kg.

On global scale, increasing the world-wide albedo of urban areas (roofs and pavements) will induce a negative radiative forcing on the earth equivalent to offsetting about 44 Gigatonnes of CO_2 emissions[3]. Sailor[85] showed that increasing the albedo in downtown Los Angeles by 0.14 and over the entire basin by an average of 0.08 decreased peak summertime temperatures by as much as 1.5℃. Previous simulation study showed that large scale increase in surface albedo and vegetation can reduce the temperature of most of the urban regions by about 0.5-1.5℃ which decreases the peak electricity demand up to 10% in summer days[95].

Recently, Sharma et al[90] reported that by using white paint on the rooftops in urban areas of India, the albedo can be increased by 0.52 (from 0.28 to 0.80). They analyzed that this increase in the albedo of urban areas will lead to an increase of outgoing terrestrial radiation by 1.314 W/m^2 and corresponding reduction in temperature was estimated to be 0.63±0.004 K.

Second scheme is crop albedo enhancement. It involves growing of crop plant varieties with higher albedo which may help to cool the planet. Hamwey[30] suggests that all grassland (cropland, pasture, and wild grassland) could be modified and that the albedo could be increased by 25% (+0.0425). It has been observed that switching from potential biofuel crop such as corn (albedo: 0.20-0.23) or soybean (albedo: 0.21) to a higher albedo biofuel crop such as sunflower (albedo: 0.24-0.30) can increase surface albedo by 0.06[12]. It is estimated that regionally up to ∼1℃ of surface warming could potentially be mitigated by careful selection among existing crop varieties. However, warming mitigation with crops is mostly localized to a band stretching from central North America through midlatitude Eurasia. Parts of Africa and South America have little potential for achieving significant mitigation of warming[79].

Third scheme is desert albedo enhancement. It involves the laying of highly reflective material across the extensive desert areas of the world to increase the average planetary albedo[26].

Fourth scheme is ocean albedo enhancement. This method involves to create microbubbles in the body of water such as oceans which reflect the sunlight and less energy is absorbed by oceans[89]. Increasing water albedo in this way can reduce solar energy absorption by as much as 100 Wm^{-2} resulting reduction of temperature by several Kelvin. It has been proposed that ships can be used to pump tiny microbubbles about 2 µm in diameter into the sea as they travel[89]. Small bubbles will act as the small mirrors and backscatter light more efficiently than large ones. These bubbles can be created by boats, by using devices mixing water with compressed air into swirling jets of water. The computer simulation resulted that the tiny bubbles injected this way would cool the planet by up to 3℃.

Marine cloud brightening (MCB): Marine Cloud Brightening (MRB) is another SRM scheme proposed to mitigate global warming[49,50,52]. The basic principal behind this scheme is to seed marine stratocumulus clouds with seawater aerosol produced at or near the ocean surface. This will increase the cloud condensation nuclei (CCN**)** into the remote marine atmospheric boundary layer. More CCN will increase the number of droplets while reducing their size. This will increase the total droplet surface area of the cloud and thus the cloud albedo (and possibly longevity): thereby producing a cooling. Previous calculations indicate that a doubling of the natural droplet concentrations in all marine stratiform clouds would produce sufficient cooling roughly to balance the warming associated with CO_2 doubling[51].

The advantages of this scheme over other SRM schemes are that (i) the amount of cooling could be controlled by measuring cloud albedo using satellites, (ii) The entire system can be switched off instantaneously if any adverse effect occurs, (iii) It is relatively simple, the only raw materials required are wind and seawater, (iv) Flexibility in choosing the place for cooling[51]. It is also reported that MCB scheme will reduce the intensity of hurricanes.

Use of renewable energy sources

As we know, fossil fuels are non-renewable and eventually will be exhausted. This is the time we need to install facilities to use alternative energy sources. The term 'alternative energy' refers any form of energy other than the conventional sources of energy. The use of fossil fuels to meet our demands is producing enormous amount of CO_2 and other GHGs which are producing global warming. To minimize this effect, we should go for nuclear and renewable energy resources like hydro, solar, wind, geothermal, and biomass which are sustainable with the current global energy supply and demand.

However, there are high risks in case of nuclear power generation where highly radioactive wastes are produced which require proper management. Other source of renewable energy is ocean energy i.e. ocean wave energy and tidal current energy[100]. Since oceans cover two-thirds of the earth's surface, they are renewable source of energy with extreme potential. All we need to develop technology which is capable to exploit its huge potential of energy. Renewable energy resources are environmental friendly and thus save our environment for future generations. These sources are clean energy with minimum emissions and improve air quality too.

Although renewable energy systems produce much less carbon, their installation is quite expensive, for example the average price per watt for solar energy was $3.05 in the USA in early 2019. Thus, in order to make it cost effective, the government and private sectors must be involved together and invest in renewable energy systems as much as possible.

Discussion

Global warming is one of the greatest challenges human society is facing today. According to IPCC-2018 report, human activities have already increased the global mean surface temperature to around 1.0°C above the pre-industrial level. It is expected that this increase will likely to reach 1.5°C between 2030 and 2052 if the global warming continues to increase at the current rate (0.2°C per decade). It is clear that the future emission pathways will decide how high sea level may rise this century, how severe the draught and rainfall will occur, and how much time we will have to protect our people.

According to IPCC-2018 report, sea level will continue to rise well beyond 2100 but rising of sea level will be 0.1 m lower with global warming of 1.5°C as compared to 2°C. It is reported that 10 to 20% of mangroves will be lost if sea level rises by 1 m above today[35].

Mangroves are critical important costal habitat for numerous coastal species and reduce coastal erosion. Global warming will also lead to decrease in the availability of fresh water and the yield of basic crops like wheat and maize. It has been reported that the increase in global temperature is forcing the terrestrial and aquatic animals to migrate towards more adequate climate, but many of them will not be able to do so quickly enough during the 21st century.

In this way, global warming may lead to extinction of some species and so it is highly needed to reduce the concentration of CO_2 gas from human activities to avoid substantial damage to ocean ecosystems and marine life. Excess heat due to global warming is increasing threat to health of human beings also and it will be greatly aggravated if greenhouse gases are not considerably reduced.

Conclusion

It is suggested that there is no alternative to emissions reductions. Cutting global Green House Gas emissions must remain our highest priority. Now, this is the time we need to explore non-conventional energy resources such as solar energy, wind energy, bio-mass and bio-gas, hydrogen, bio-diesel which may help for the sustainable fossil fuel reserves and reduce emission like CO_2, CH_4, NO_x etc. and other pollutants. It is further suggested that limitation and adaptation strategies need to be developed and implemented. However, geo engineering is the option to mitigate the global warming but it is needed to analyse both the positive and negative effects before applying any geo engineering methods. For example OIF method can remove up to billions of tonnes of carbon from the atmosphere per year but its effects on marine ecosystem and biodiversity are highly uncertain. BECCS is another promising negative emission technology which offers reasonable CO_2 offset, but it requires large amount of land for its operation. For example, sequestering 1 Gt of CO_2 annually via this route will require more than 200000 square miles of land[78].

Similarly, the use of SRM techniques would reduce the GHGs induced effects rather than the root cause of global warming, and thus it will have some side effects; for example, the reduction of incoming solar radiation at earth's surface reduces evaporation which in turn will reduce precipitation mostly in tropics. It will deplete the ozone layer, produce less sunlight for solar power and will do nothing to stop ocean acidification. Furthermore, it would hamper the earth based optical astronomy. Injection of sulfur in the stratosphere has been discussed more among the scientific community.

A complete list of benefits and side effects of injection of sulphur in the stratosphere is given by various authors[82,83]. Similarly, Mathur and Roy[62] have reported all the benefits and associated risks of all the geoengineering schemes. We would like to suggest that the geoengineering schemes must be applied in parallel for the mitigation of adverse effects of global warming but their side effects must be taken into account and a thorough research and development is needed before their implementation on global level. Finally, we suggest that all the world's governments should realize the long-term benefits of renewable energy sources and mark it as top priority in their economic growth plans.

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