UNIT 3 RADIATIVE FORCING

Structure

3.1 INTRODUCTION

Earth's climate is not static. Since its formation, earth's climate was changing due to natural drivers of climate change. However, the human activities in the post-industrialization era resulted in increases of radiatively active gases in the atmosphere leading to increase in global mean surface air temperature. Anthropogenic induced climate change is a cause of great concern due its potential impacts on environment. At any given time, the earth's climate is subjected to a number of influences. These influences are called forcings or "drivers". Some of them are natural and some caused by humans. Natural drivers such as solar activity, are part of an overall repeated cycle and impact climate over very long periods, tens of thousands to millions of years. Some events, like volcanic eruptions and impacts from celestial bodies, like asteroids, have immediate effect, but are one-time events and do not influence the global climate for more than a few years. The human "drivers" differ from their natural counterparts in fundamental ways. This human influence is happening very rapidly, is not cyclical, and pushes the climate continually and relentlessly in the single direction of warming. In the previous units, we have discussed the difference between weather and climate; composition and vertical structure of the atmosphere; the concept of greenhouse effect; and about the trends in the atmospheric concentration of major greenhouse gases. Through this unit, we will be discussing the drivers of climate change and the concept of radiative forcing.

3.2 OBJECTIVES

After studying this unit, you should be able to:

- explain the drivers' of climate change; and
- discuss the concept of radiative forcing.

3.3 DRIVERS' OF CLIMATE CHANGE

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen". Further, the "human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" (IPCC 2014). It is essential to attribute the changes in climate to either natural causes or human influence. However, it is a great challenge to attribute the causes of climate change because the climate system is highly complex. Further, the natural causes of climate change prevail over a long time periods, and the natural causes are overlaid by the human induced causes. The climate system is influenced by factors either internal or external to the system. The factors external to the system are called external radiative forcing which includes "solar variability", "astronomical effects", "tectonic processes" and "volcanic eruptions". The drivers' of climate change are both of natural origin and anthropogenic activity. Nevertheless, in the industrial era, human activities are more responsible for causing climate change. The important natural drivers of climate change in the industrial era are changes in solar irradiance, volcanic eruptions, and the ENSO. However, there are other known natural drivers of climate change which operate on longer geological time scales (example: Milankovitch cycles). Anthropogenic drivers include changes in GHGs concentration, changes in land-use, changes in aerosol concentration, etc. Let us discuss the drivers' of climate change.

3.3.1 Natural Drivers' of Climate Change

3.3.1.1 Solar Variability

The sun's energy appears constant but undergoes small changes over an extended time period. There are different types of solar activities, such as solar flares and sunspots. Sunspots are the relatively cool, dark spots appearing periodically in groups on the surface of the sun while solar flares are storms or eruptions of hot gases from the surface of the sun, accompanied by a burst of ultraviolet radiation. The sun goes through roughly 11-year-long periodic variations in the frequency of sunspots, solar flares, and other solar activity. During this period, the sun goes through a solar maximum and a solar minimum. During a solar maximum, the sun has the maximum number of sunspots and solar flares and gives off more energy. The inverse is true of a solar minimum, the sun has fewer sunspots and solar flares. It gives off less energy. Solar activity affects climate on earth. The "Little Ice Age" between 1650 and 1850 is believed to have been triggered off due to decreased solar activity. Further, it was reported that about three billion years ago, the solar radiance was only about 80 per cent of the present value. Nevertheless, then the atmosphere was rich in carbon

dioxide. Hence, there is variability in solar activity. We have discussed in the unit 2 of this course about the importance of solar radiation and its role in the global energy budget. As discussed in the unit 2, the solar constant exhibits small periodic variations of about 1 Wm^{-2} due to the sunspot activity. In other words, the solar output vary with respect to the number of sunspots. Further, it is reported that solar variability caused the change of climate in the past, before the era of industrialization (Barry and Chorley 2010). "Satellite observations of total solar irradiance (TSI) changes from 1978 to 2011 show that the most recent solar cycle minimum was lower than the prior two" (IPCC 2013).

3.3.1.2 Orbital Variations

Way back in 1930, the relation between the orbital variations and climate of the earth was proposed by Milutin Milankovitch. In fact, orbital variations influence the amount of solar radiation reaching the earth surface; and also distribution of sunlight vis-a-vis regions and seasons. Milankovitch oscillations are important from the perspective of understanding the past climate including the ice ages and interglacial periods. The shape of the earth's orbit oscillates from elliptical to circular orbit with a period of about 1,00,000. This is called as eccentricity of the orbit. As discussed in the unit 2, "the varying distance of the earth from the sun causes variations in solar energy received by the earth. Due to the eccentricity of the earth's orbit around the sun, the solar energy received on the earth surface varies between perihelion and aphelion. Nevertheless, this differential receipt of solar energy is masked by the atmospheric circulation and also due to the continentality. Further, about 11,000 years ago, the aphelion occurred in the northern hemisphere winter. Presently, the aphelion occurs in the northern hemisphere summer". The earth's tilt angle also varies between 21.5 degrees and 24.5 degrees with a period of about 41,000 years, which is called as the obliquity. Precession or wobble of earth's spin axis involves 23,000 year period.

3.3.1.3 Tectonic Processes

When you look at the events on the earth's surfaces on geological time scale, you can find that the positions of continents and oceans have changed due to the earth processes. The theory explaining the movement of continents and oceans is popularly called plate tectonics. These movements of lithospheric plates have caused formation of mountains; and changed the size and location of mountain ranges and plateaus. This has indeed influenced the atmospheric circulation pattern, and also the ocean circulation. It was reported that the ice age episodes such as the Permo-Carboniferous glaciation of Gondwanaland were due to the changes in continental location. Further, the desert conditions observed in the western part of China and Central Asia was attributed to the uplift of the Himalayan ranges and also the Tibetan Plateau. (Barry and Chorley 2010).

3.3.1.4 Volcanic Eruptions

Due to volcanic eruptions, large amounts of sulphur dioxide, water vapour, ash and dust particles are thrown up into the atmosphere. The tiny ash and dust particles form aerosols in the atmosphere which reflect solar energy back into space and have a cooling effect on the planet. "Equatorial eruption plumes spread into both hemispheres, whereas plumes from eruptions in mid- to high latitudes are confined to that hemisphere. Records of such eruptions are preserved in the Antarctic and Greenland ice sheets for at least the last 150,000 years.

Observational evidence from the last 100 years demonstrates that major eruptions cause a hemisphere/global cooling of 0.5 to 1.0°C in the year following the event, but there is strong regional variability" (Barry and Chorley 2010). The 1992-1994 cool spell is attributed to the increased reflection of the solar radiation, caused mainly by the eruption of Mt. Pinatubo. Mt. Pinatubo in fact erupted in the month of June, 1991 in Philippines. "The radiative forcing of volcanic aerosols is reported to be greatest for a short period (~2 years) following volcanic eruptions" (IPCC 2013).

3.3.2 Anthropogenic Drivers' of Climate Change

Anthropogenic influence on the environmental change particularly climate change is being increasingly recognized. Changes in atmospheric composition, land-use/ land cover changes, and changes in aerosol loading in the atmosphere are few striking variables that are influenced by the human activities, and these changes are responsible for bringing in a change in the climate system. The increase in GHGs concentration, and other changes in terrestrial ecosystem endeavour to increase radiative forcing and global temperatures.

3.3.2.1 Atmospheric Composition

In the unit 2, we have discussed about the importance of radiatively active gases, trends in the atmospheric concentration of GHGs, and their role in human-induced climate change. We have studied the role played by the water vapour and other naturally occurring greenhouse gases in causing the natural greenhouse effect. Further, the post-industrialization increase in the concentration of GHGs are mainly due to the human activities. The extent to which each GHG perturbs the climate system over a particular time period depends on the concentration of the gas in the atmosphere and its radiative forcing. The largest contribution comes from the burning of fossil fuels, mainly for transportation, heating and cooling of buildings, and industrial applications. There has been a remarkable increase in the combined radiative forcing of carbon dioxide, methane, and nitrous oxide over the last few centuries. Their increase during the past four decades has been at least six times faster than that observed over the last two millennia. "*Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C* (IPCC 2018).

3.3.2.2 Changes in Land-use

Land use may be changed for various reasons including but not limited to urbanization, agriculture, and industrialization. These changes bring about changes in land cover, the most visible and important of them being deforestation. It impacts rainfall pattern, soil pattern and land degradation. Deforestation influence the climate through changing the atmospheric composition and influencing the water cycle. "The anthropogenic land-use change has increased the land surface albedo, which leads to an RF of -0.15 ± 0.10 W m^{-2}" (IPCC 2013).

3.3.2.3 Changes in Aerosol Level

Atmospheric aerosols are very fine particles suspended in air. They are formed by the dispersal of material at the earth's surface (primary aerosols), or by reaction of gases in the atmosphere (secondary aerosols). They include sulphate and nitrates from the oxidation, respectively of sulphur dioxide and nitric oxide, during the burning of fossil fuels; organic materials from the oxidation of VOCs

(Volatile Organic Compounds); soot from fires; and mineral dust from wind-blown processes. Aerosols affect the climate through various ways viz. increasing the scattering of solar radiation, interaction with atmospheric gases, and indirect effect of cloud condensation nuclei on cloud albedo.

3.4 WHAT IS "RADIATIVE FORCING"?

Let us now study about radiative forcing as it is related to global warming. Figuring out how various drivers contribute to climate change and quantifying their effects is a great challenge. Nevertheless, quite number of metrics are available to provide estimates of the climate impact of individual factors or drivers of climate change.As defined by the Intergovernmental Panel on Climate Change (IPCC), radiative forcing is a measure of the influence a given climatic factor has on the amount of downward-directed radiant energy impinging upon earth's surface. In other words, radiative forcing is the "change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun. Sometimes internal drivers are still treated as forcings even though they result from the alteration in climate, for example aerosol or greenhouse gas changes in paleoclimates". It is an important tool used to determine the effects that greenhouse gases, aerosols, and clouds have on climate change. Further, "Effective Radiative Forcing" is the "change in net TOA downward radiative flux after allowing for atmospheric temperatures, water vapour and clouds to adjust, but with surface temperature or a portion of surface conditions unchanged". "The total anthropogenic ERF over the Industrial Era is 2.3 (1.1 to 3.3) W m^{-2} (IPCC 2013). As regards the forcing, changes that cause a warming effect are called "positive" forcing, while the changes that result in a cooling effect are called "negative" forcing. The imbalance between the positive and negative forces result in a change in the earth's average surface temperature. It is reported that "the net natural forcing which includes solar plus stratospheric aerosols from volcanic eruptions has been negative over the past two and possibly even the past four decades". On the other hand, "the positive forcing by well-mixed greenhouse gases has increased rapidly over the past four decades". As studied in the earlier unit, an average of about 342 watts of solar radiation strikes each square meter of the earth's surface per year. Any change in the distribution of radiation within the atmosphere will cause a corresponding rise or fall in the earth's surface temperature.

Kindred to the concept of radiative forcing is grouping forcing compounds by common properties. Grouping Forcing Compounds aid us in furthering our understanding of radiative forcing. Primarily, the forcing compounds are grouped into "well-mixed greenhouse gases" (WMGHGs) and "near-term climate forcers" (NTCFs). Well mixed GHGs are mixed throughout the troposphere such that few remote observation would suffice to gauge the atmospheric load of the forcing. Consequently, "global forcing per unit emission and emission metrics for these well-mixed greenhouse gases do not depend on the spatial or geographic location of the emission". Well-mixed greenhouse gases include CO_2, N_2O, CH_4, SF_6, etc. "The anthropogenic increases in the well-mixed greenhouse gases (WMGHGs) have substantially enhanced the greenhouse effect, and the resulting forcing continues to increase" (IPCC 2013). Near-term climate forcers or short-lived climate forcers or short-lived climate pollutants are "those

compounds whose impact on climate occurs primarily within the first decade after their emission". These forcers as shorter lifetimes. They include methane, ozone and aerosols. Their impact on the climate is near-term.

Radiative forcing of climate between 1750 and 2011

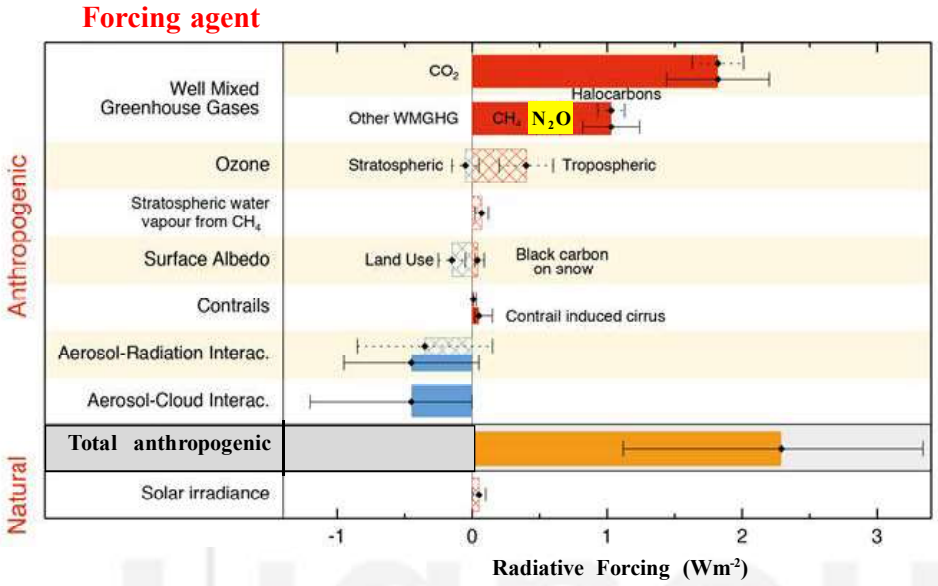

Fig 3.1: Radiative forcing of climate between 1750 and 2011. (Source: IPCC 2013)

Check Your Progress 1

Note: 1) Use the space given below for your answers.
2) Check your answers with those given at the end of this unit.

1. Explain the natural drivers' of climate change.

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2. What are the Milankovitch Oscillations?

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3. Write about the relation between volcanic eruptions and earth's climate.

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4. What are the essential differences between natural and anthropogenic drivers of climate change?

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3.5 LET US SUM UP

Earth's climate is not static. Since its formation, earth's climate was changing due to natural drivers of climate change. However, the human activities in the post-industrialization era resulted in increases of radiatively active gases in the atmosphere leading to increase in global mean surface air temperature. At any given time, the earth's climate is subjected to a number of influences. The drivers' of climate change are both of natural origin and anthropogenic activity. The important natural drivers of climate change in the industrial era are changes in solar irradiance, Milankovitch cycles, volcanic eruptions, etc. Anthropogenic drivers include changes in GHGs concentration, changes in land-use, changes in aerosol concentration, etc. In this unit, we have discussed the drivers of climate change and the concept of radiative forcing.

3.6 KEYWORDS

Solar Activity : **"**General term describing a variety of magnetic phenomena on the Sun such as sunspots, faculae (bright areas), and flares (emission of high-energy particles). It varies on time scales from minutes to millions of years".

Solar ('11-year') Cycle : "A quasi-regular modulation of solar activity with varying amplitude and a period of between 8 and 14 years".

External Forcing : "External forcing refers to a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations, etc. are external forcings. Orbital forcing is also an external forcing as the insolation changes with orbital parameters eccentricity, tilt and precession of the equinox".

Radiative Forcing : Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of atmosphere due to a change in the drivers of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun.

3.7 SUGGESTED FURTHER READING/ REFERENCES

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

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IPCC, 2013: Annex III: Glossary [Planton, S. (ed.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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Web Links

http://www.ipcc.ch/report/ar5/wg1/

http://www.ipcc.ch/report/ar5/wg2/

http://www.ipcc.ch/report/ar5/wg3/

http://www.ipcc.ch/report/ar5/syr/

https://www.ipcc.ch/sr15/

3.8 ANSWERS TO CHECK YOUR PROGRESS

Check Your Progress 1

1. The natural drivers' of climate change include "solar variability", "astronomical effects", "tectonic processes" and "volcanic eruptions". As regards the solar variability, the sun's energy appears constant but undergoes small changes over an extended time period. There are different types of solar activities, such as solar flares and sunspots. The sun goes through roughly 11-year-long periodic variations in the frequency of sunspots, solar flares, and other solar activity. During the solar minimum, the sun has fewer sunspots and solar flares. It gives off less energy. Solar activity affects climate on earth. The "Little Ice Age" is believed to have been triggered off due to decreased solar activity. Further, the solar constant exhibits small periodic variations of about 1 Wm^{-2} due to the sunspot activity. With respect to orbital variations, the amount of solar radiation reaching the earth surface is influenced by the orbital oscillations. Further, the tectonic processes have influenced the atmospheric circulation pattern, and also the ocean circulation. For instance, the Permo-Carboniferous glaciation of Gondwanaland were due to the changes in continental location. Volcanic eruptions which include sulphate aerosols influence the earth's climate. They in fact have a cooling effect on the planet.

2. The relation between the orbital variations and climate of the earth was proposed by Milutin Milankovitch. Milankovitch oscillations are important from the perspective of understanding the past climate including the ice ages and interglacial periods. The shape of the earth's orbit oscillates from elliptical to circular orbit with a period of about 1,00,000. This is called as eccentricity of the orbit. The varying distance of the earth from the sun causes variations in solar energy received by the earth. Due to the eccentricity of the earth's orbit around the sun, the solar energy received on the earth surface varies between perihelion and aphelion. The earth's tilt angle also varies between 21.5 degrees and 24.5 degrees with a period of about 41,000 years, which is called as the obliquity. Precession or wobble of earth's spin axis involves 23,000 year period.

3. The importance of volcanic eruptions was recognised way back in 1883 when Krakatao volcano in Indonesia erupted. Cooler conditions was observed after the eruption, due to the release of aerosols into the stratosphere layer of the atmosphere. It is reported that the "aerosols from

equatorial eruptions can disperse into both hemispheres whereas those in middle and high latitudes cannot be transferred equator ward due to the upper circulation structure". Nevertheless, basaltic shield volcanoes are non-explosive in nature and so they do not release the aerosols into the stratosphere layer. As regards the volcanic eruptions, the atmospheric effects are due to the sulphate aerosols and dust particles. Sulphate aerosols reduce the transmission of insolation by increasing the atmospheric turbidity. It is reported that subsequent to major volcanic eruptions, the surface air temperature in the mid-latitudes decrease by 0.5 to 1.0°C.

4. Natural drivers of climate change affect the earth's climate over a long period of time and are usually part of a cycle. For instance, the solar activity varies over an 11 year cycle. The earth's tilt angle also varies between 21.5 degrees and 24.5 degrees with a period of about 41,000 years. Volcanic eruptions are one-time event but their effect lasts only a couple of years. Anthropogenic drivers of climate change on the other hand, are not cyclical. For instance, the increase in concentration of GHGs has very long lasting effects and the changes they induce are much rapid. The increase in GHGs since industrialization has caused an increase in global average temperature of 1^{o}C.