UNIT 20 CLIMATE CHANGE: OZONE DEPLETION

Structure

20.0 LEARNING OUTCOME

After studying this Unit, you should be able to:

- discuss the thermal and chemical structure of the earth's atmosphere;
- describe the latitude-wise variation of the ozone in the stratosphere and troposphere from equator to pole;
- understand the role that stratospheric depletion of ozone and tropospheric increase of ozone play in climate change with consequences on climate-related natural disasters;
- bring out the role of stratospheric ozone in absorbing most of the harmful ultraviolet (UV) component of the incoming solar radiation from reaching the Earth's surface.
- explain the hazard of ozone depletion and the phenomenon of ozone-hole in the Antarctic stratosphere; and
- highlight the regulatory measures adopted under the Montreal Protocol on the use of such compounds, which lead to ozone destruction.

20.1 INTRODUCTION

Human beings, by excessive use of energy and similar other activities, have created conditions which may threaten the fragile environment and ecology of the earth and in turn trigger global changes resulting in disturbing the present radiative and chemical balance in the atmosphere. One of the important threats, which have been highlighted during the last three decades is the depletion of the protective ozone shield in the stratosphere. This may allow more ultraviolet light (UV) to reach the earth's surface and cause damage to human and animal health; disturb terrestrial ecosystems and adversely affect crops and vegetation. Thus ozone depletion is a serious hazard which may lead to increase in climate-related disasters. Therefore, international efforts have been devoted to tackle the threat of ozone depletion by curtailing use of those chemicals, which destroy ozone. In this Unit, we will discuss the thermal and chemical structures of the atmosphere and explain the production and distribution of ozone in the stratosphere and troposphere. In addition, causes for the depletion of stratospheric ozone and creation of the Antarctic Ozone Hole will be discussed. The steps being taken to reduce or arrest ozone depletion will be described. Lastly, we will highlight the threats posed to human health and terrestrial ecosystems from depletion of ozone in the stratosphere.

20.2 CHARACTERISTICS OF EARTH'S ATMOSPHERE

20.2.1 Thermal and Chemical Structure of the Earth's Atmosphere

i) **Thermal Structure** of **the atmosphere**

The Earth's atmosphere is arranged into different layers one above the other. The mean temperature structure of these layers determines their dynamical properties. The first two such layers are the troposphere and the stratosphere, extending altitude-wise from surface of fhe earth to about 50 km above it. The layer immediately above the earth's surface is called the 'troposphere' in which the temperature, on global average basis, decreases with height. The rate of decrease of temperature with height is called 'lapse rate', which on the average is about 6°C per km in the troposphere. The troposphere, because of its lapse rate, and moisture content is convectively unstable and hence all weather events occur in this layer of the atmosphere. The upper boundary of the troposphere, known as tropopause, is at about 16 km height in the tropics and is low in the polar region at about 8-10 km. A break in the tropopause is observed in mid-latitudes, which is important for the leakage of stratospheric ozone into the troposphere.

The second region above the troposphere is known as stratosphere, which extends from about 10-16 km to 50 km height in the atmosphere. In the stratosphere, there is increase of temperature of the atmosphere with height over the equator rather fast and it is either almost constant or increases slowly with height in the Polar Regions.

ii) **Chemical Structure of the Atmosphere: Atmospheric Ozone**

The chemical composition of the atmosphere has evolved over geological time scales and finally atmosphere has settled itself as a mixture of different gases in a constant proportion (well mixed) up to 80 km height (called the Homosphere) except for ozone, nitrous oxide and water vapour whose proportion in the atmosphere is variable. Major gaseous constituents of the earth's atmosphere by volume are nitrogen (78.09 per cent), oxygen (20.95 per cent) and small amount of chemically inert noble gases like argon (0.93 per cent), neon (0.0018 per cent) and helium (0.0002 per cent). Other gases in the atmosphere like carbon dioxide (CO_2), ozone (O_3), methane (CH_4) also occur in small quantities of 0.035 per cent, 0.0008 per cent, and 0.0017 per cent respectively by volume. Human activities are tending to increase CO_2 and CH, in atmosphere. All gases, of natural and anthropogenic origins, which occur in small quantities in the atmosphere, are called minor constituents or trace gases. Trace gases play important role in maintaining the radiative balance in the Earth-Atmosphere system. Among these minor constituents, bulk of ozone (nearly 90 per cent) exists in the stratosphere alone.

All atinospheric problems threatening the delicate balance of life on earth, for example the ozone depletion, ozone hole, atmospheric pollution, acid rain etc. are resulting from chemical reactions among the minor constituents in the atmosphere. These minor constituents, which exist in the atmosphere in very small quantities, are measured in terms of parts per million by volume (ppmv). Several of these constituents have been increasing in the atmosphere due to human activity and this increase has become a cause of concern as it may lead to global warming or climate change. For example CO_2 which is the product of burning process was 280 ppmv during the pre-industrial era and at present it is about 370 ppmv and CH_4, which was 730 parts per billion by volume (ppbv) during the pre-industrial era is now about 1750 ppbv. It may be recalled that CO_2, CH_4 and **O,** are greenhouse gases (GHGs) and are mainly responsible for global warming.

20.2.2 Earth-Atmosphere Radiation Balance

Earth's climate is driven by the radiant energy received from the Sun. The Earth's radiation budget is a complex balance sheet between the incoming energy from the Sun, received mostly as ultraviolet (uv) radiation in shortwave spectrum and the emission of thermal radiation by the earth's surface (ocean and land) in the long-wave part of the spectrum (infra red or IR). Part of IR energy radiated by the earth's surface is returned to the earth after being absorbed by GHGs molecules and emitted back to the lower atmosphere and the Earth's surface. The stability or thermal equilibrium of the Earth-Atmosphere radiation budget through absorption and emission processes in short and longwave bands respectively ensure the stability of the earth's climate. On the global annual average basis, equatorial regions receive excess solar energy and the Polar Regions receive less and are therefore colder. To maintain the equator-pole temperature gradients in equilibrium, atmospheric wind systems and ocean currents transport excess solar energy from equatar to the poles.

20.3 PRODUCTION AND DESTRUCTION OF ATMOSPHERIC OZONE

20.3.1 Stratospheric Ozone

Ozone is an allotrope of oxygen. Ozone molecule is made up of three oxygen atoms and is given the symbol O_3. It is a strong oxidizing and chemically highly reactive gas and is present in the free ahnosphere in varying quantities. About 90 per cent of the total ozone in the atmosphere is located in the stratosphere and only about 10 per cent is in the layer between 12 krn and earth's surface. The amount of ozone in the atmosphere is measured in terms of the thickness or height of a column of ozone if all the ozone in that atinospheric column were brought to earth's surface under conditions of standard temperature and pressure (STP). The unit of measurement of ozone in the atmospheric column is Dobson Unit (DU). One DU is equal to 10^{-3} cm (one thousandth of a cm at standard pressure and temperature). Concentration of ozone begins to increase from about 12-14 km and the maximum is achieved at a height of about 25 km in the stratosphere. Even in the stratosphere, total amount of ozone is quite small as only 10 ozone molecules per million molecules of air (10 ppmv) are present. Total column ozone varies between more than 300 DU to 260 DU at poles and equator respectively. The total thickness of ozone layer is very very small and is equivalent to about 3 millimetres of the column of atmosphere at standard atmospheric temperature and pressure at the earth's surface.

Ozone is produced in the stratosphere by ionization or photodissociation of oxygen in the presence of UV radiation from the Sun. Inspite of splitting of oxygen molecule, oxygen remains abundant in the stratosphere by reconversion of ozone into oxygen. Thus natural production and destruction of ozone occur in the stratosphere. The process of ozone production is described by the following chemical equation:

$$2O_2 + \text{(UV radiation)} \rightarrow O_3 + O$$

$$O + O_2 \rightarrow O_3$$

O denotes atomic oxygen which, being unstable, combines rapidly with another molecule of oxygen (O_2) to produce O_3. In this process molecular oxygen starts to absorb wavelength of about 250 nanometre (nm) wavelength in the UV band. The net result of the production process of O_3 described in the above two chemical equations is that two O_3 molecules are produced from three O_2 molecules and some of the ultraviolet radiation coming from the sun is used up in the process.

Several natural and man-made minor constituents in the atmosphere play an important role in the destruction of O_3. The destruction proceeds with the reaction of O_3 with free radicals symbolised below as X and XO.

$$X + O_3 \rightarrow XO + O_2$$

$$O_3 + (UV) \rightarrow O + O_2$$

$$O + XO \rightarrow X + O_2$$

Thus, two ozone molecules are destroyed to produce three oxygen molecules and the minor constituent (here denoted by X) reappears or remains "undestroyed" in the process. Thus it acts as a catalyst in the process of destruction of ozone and the chain of generation of ozone and its destruction goes on in the stratosphere. As water vapour (H_2O) and Nitrogen (N) and oxides of Nitrogen are available in fair quantities in the atmosphere, the above mentioned chemical processes proceed with H and N taking the place of symbol X in the above equations. Some man-made chemicals (like chlorofluorocarbons – CFCs) inject chlorine (Cl) in the stratosphere and it also destroys ozone in the same manner.

Thus CFCs, which are used in the refrigeration industry and house hold cans of aerosol deodorants etc., are also agents of destroying ozone because they release free chlorine (Cl) atom and free radical ClO into the stratosphere which destroy ozone by acting like X and XO in the above illustrated equations.

20.3.2 Tropospheric Ozone

Small quantity of ozone occurs also in the troposphere and near the earth's surface. Pre-industrial era estimate of global average tropospheric ozone is 25 Dobson Units. At present this has increased to a global average of 34 Dobson units (northern hemisphere -36 Units and southern hemisphere-32 Units). Ozone is injected down into the troposphere from the stratosphere in the region of tropopause break in the middle latitudes. Also, such exchanges take place in the regions of deep convection in the tropics, which allow stratospheric-tropospheric exchanges through penetrative convective cloud tops. Small quantities of O_3 can be also locally produced by flushes of atmospheric electricity in thunderstorms or through any electric spark.

In pristine environment, surface ozone is present in very very small quantity of about 10-20 parts per billion molecules by volume (ppbv) but it exceeds even 100 ppbv in highly polluted environments.

This is injurious to human health and also to vegetation. Trends in tropospheric ozone are difficult to establish unlike that in the stratosphere. Ozone is a greenhouse gas in the troposphere and hence contributes to global warming. Photochemical production and destruction processes of ozone have been estimated by complex 2-dimensional and 3-dimensional mathematical models.

20.4 MEASUREMENT OF ATMOSPHERIC OZONE

Although systematic observations of atmospheric ozone in research mode had commenced at a few places in Europe in the 1920's, regular measurements of total column ozone from the surface of the earth to the top of the atmosphere began in 1950 and a global network of stations was established during the International Geophysical Year (1957-58). Dobson Spectrophotometer is the standard instrument used for the purpose which determines total ozone through differential absorption of ozone by two nearly UV sources with one wavelength strongly absorbing and the other weakly absorbing O_3. India has also a network of Dobson instruments and the improved Brewer instruments for total column ozone operated by the India Meteorological Department (IMD) at 7 stations, viz., Ahmedabad, Srinagar, Varanasi, Kolkata, New Delhi, Kodaikanal and Pune. India also operates a total ozone measurement Dobson spectrophotometer at its Maitri station in Antarctica. Also several surface ozone measuring stations are operated by different research organisations in India. Vertical distribution profile of ozone is measured by flying an automatic instrument called ozonesonde with a high altitude balloon. For this purpose IMD operates three stations at Pune, New Delhi and Thiruvananthapuram, which make biweekly measurements. Vertical distribution of ozone is also determined by Dobson spectrophotometers at Ahmedabd, Srinagar, Vasanasi, Kolkata and Kodaikanal. Special atmospheric lidar systems are also used to provide vertical profile of ozone. One such lidar system is installed at the Indian Institute of Tropical Meteorology (IITM), Pune. Satellite based total ozone and vertical profiles of ozone are also being collected by the U.S. satellites and the data are made available worldwide to interested scientists for research. Satellite-based ozone observations provide a global picture of ozone distribution on daily, monthly and annual basis for study of spatio-temporal variability of atmospheric ozone.

20.5 GEOGRAPHICAL AND SEASONAL DISTRIBUTION OF TOTAL COLUMN OZONE

As already mentioned, ozone is produced by the ionization of atmospheric oxygen by the action of UV radiation in the stratosphere. Even though on yearly average, basis equatorial stratosphere receives excessive sunlight compared to higher latitudes, the total column ozone is minimum in equatorial latitudes compared to high latitudes. This apparent paradox was explained by Dobson who concluded that ozone, after production in the equatorial stratosphere, is transported towards polar latitudes by atmospheric meridional (south to north) circulation processes which carry ozone molecules toward poles. Thus total column ozone is maximum in sub-polar regions (about 350 Dobson units) and minimum near the equator (about 260-270 Dobson units).

Seasonally maximum total column ozone is found in the spring season and minimum in the summer in middle and high latitudes. The seasonal variation of ozone in the low latitudes is very small. For India the maximum amplitude of ozone on annual basis is observed at Srinagar.

Ozone is mostly, confined within a layer of the atmosphere extending from 15-35 km in the stratosphere. Its concentration is rather small in the troposphere i.e. from ground surface to 10 km (global average 34 Dobson units). Amount of ozone in the atmosphere varies with latitude, longitude, altitude and season. Surface ozone also varies diurnally as it is produced by photochemical action during sunlit hours near the ground surface where air contains anthropogenic pollutants.

20.6 STRATOSPHERIC OZONE DEPLETION AND ANTARCTIC OZONE HOLE

20.6.1 Depletion (loss) of Stratospheric Ozone

Total column ozone from 1950 to 1980 showed decreasing trends in middle and high latitudes. These was no apparent reason for this loss of ozone in the stratosphere, hence it became a matter of grave concern. In 1974, two U.S. scientists, Mario Molina and Sherwood Rowland, working in the University of California, studied about what happens to the large volume of industrially produced chlorine containing molecules like chlorofluorocarbons (CFC-11 and CFC-12) being released into the lower atmosphere by refrigeration and household aerosol sprays. These CFCs had by then no known atmospheric sinks. Molina-Sherwood's research work led to the understanding of the role played by these CFCs in destruction of ozone. These CFCs emitted at ground are carried into the stratosphere where they get broken into chlorine atoms, which in turn destroy molecules of ozone thus depleting ozone in the stratosphere. The chemical reactions taking place in this type of ozone loss are :

$$O_3 + Cl + UV \rightarrow ClO + O_2$$

$$O_2 + W \rightarrow O + O$$

$$ClO + O \rightarrow Cl + O_2$$

Ozone depletion results in thinning of the ozone layer which leads to more ultraviolet radiation to reach the earth's surface with adverse impacts on human health and terrestrial and aquatic systems.

20.6.2 Antarctic Ozone Hole

In 1985, three British Scientists, Joe Forrnan, Brian Gardiner and Jonathan Shanklin, working in the British Antarctic Survey discovered drastic reduction in total ozone during September-October in southern hemisphere spring season. They found that nearly 30 per cent of total ozone was destroyed during September-October 1985 and its value had reduced from over 300 Dobson units in 1960 to 200 Dobson units in 1985. Earlier in 1979, satellite measurements had also indicated sudden depletion of Antarctic ozone but the data was not believed and was rejected as not acceptable. The sudden loss of Antarctic ozone, as found by Forrnan and his colleagues, was also confirmed by other research teams working on Antarctic research. This large-scale depletion of ozone over Antarctica in each spring season over an area equivalent to the size of the entire north America, is khown as Antarctic Ozone Hole. Ozone destruction in the Antarctic spring of 1993 had surpassed all previous records. Very low temperatures in the Antarctica accelerate ozone destruction in the presence of chlorine atoms. Ozone destruction though more abrupt in Antarctic spring is not confined to this region. The process also occurs in Arctic region but is less severe than over the Antarctic region.

20.7 REGULATORY POLICY MEASURES TO ARREST ANTARCTIC OZONE HOLE

The discovery of the Antarctic Ozone Hole in 1985 led to amassive programme on Antarctic Stratospheric Chemistry with aircraft measurements taken by U.S. scientists in 1987. These observations confirmed the role of chlorine atoms in ozone destruction. Several other chemical reactions.have since been discovered in the Antarctic stratosphere, which include nitrogen compounds and hydrochloric acid too. Computer models made predictions about the expansion of the ozone hole if emission of CFCs and other Ozone Depleting Substances (ODS) were not checked. The scientific opinion was so strong that it resulted in a major international policy agreement in 1987, known as the Montreal Protocol, to check the release of such ozone depleting substances (ODS) into the atmosphere. The Montreal Protocol used different scenarios for controlling the release of such chemicals and one such option has been to enforce 80 percent freeze on the use of CFCs in 1994 from its level, as it was in 1986. Developing countries were, however, given some concessions to slowly decrease the use of CFCs in ten years. The Protocol calls for periodic review. The London amendment to the Protocol was made in 1990 and the Copenhagen amendment was made in 1992, which if fully followed, would bring significant improvements in total restrictions on use of CFCs. Such drastic actions would lead to'arrest and finally disappearance of the ozone hole in the next several decades. Observations taken in 2002 Antarctic spring season have shown encouraging effect of these regulatory measures as the ozone hole in 2002 is found to split into two parts and shrunk in size too, to the level of 1988. However, the ozone Hole has again shown a tendency to increase in size in the years 2003 and 2005. This indicates that the monitoring has to continue and the internationally accepted regulatory decision needs to be observed fully.

20.8 IMPACTS OF CHANGES IN ATMOSPHERIC OZONE

Decrease in stratospheric ozone, observed over large parts of the globe, has raised alarm bells as ozone loss would allow increased penetration of solar UV-Biological (UV-B) radiation over 280-320 nm waveband to the lower atmosphere and surface of the earth. As such, all living beings existing on the Earth's land surface and in the oceans too would be exposed to higher dose of UV-B, which would be injurious to them. In particular, this would increase the incidence of cataract and skin cancer. Thus, the thinning of the protective shield of ozone layer in the stratosphere would upset the adaptation mechanism of living beings against UV-B dosage. There is a danger that damage may also be caused to the biosphere by increased UV-B dosage and may even increase the accumulation of CO, in the air.

i) **Effects on Human Health**

'In humans exposure to sunlight and hence UV-B is via eye and skin as solar energy is absorbed by molecules known as chromophores present in tissues and cells of these organs. Hence, increased UV-B would cause conjectival and cornea diseases of eyes and may lead to even blindness. Damage to skin may be caused due to sunburns and even skin cancer. The risk is far more in fair and light skinned population compared to dark skin population particularly in middle and high latitudes where people follow the practice of sun bathing. Even though people living in the tropics are naturally exposed to more UV-B, as the ozone is less in the tropics compared to high latitudes, relatively dark skinned people of India, Africa, and South and South East Asia are naturally protected by adaptation to higher dosage of UV-B. However, people in the tropics suffer from higher risk of eye diseases like cataract. Increased UV-B may also affect human health through altered pattern of gene activity.

ii) **Effects on Terrestrial and Aquatic Ecosystems**

Increased UV-B would be damaging to terrestrial ecosystems like agricultural land, forests, grassland and plants, organisms and microbes living in these ecosystems. Effects of increased UV-B may accumulate from year to year in long-lived perennial plants and from generation to generation in annual plants. Plant reproductive processes such as flowering; fertilization etc, could be also altered by increased UV-B. There could be loss in agricultural production due to toxic effects of increase in tropospheric ozone. These effects may be taken into account along with other effects due to global change like increase in CO,, water stress etc.

Sunlight enters the top layer of the ocean and supports aquatic life like fish, phytoplanktons and even zooplanktons. Increased penetration of UV-B into the upper ocean layer wouldcause damage to algae, sea grasses, phytoplanktons and zooplanktons directly and inay even lead to decrease in photosynthesis. Enhanced level of UV-B exposure may disturb the food web in the ocean, Also damage to phytoplanktons may reduce their capacity to use CO,, which may affect the capacity of ocean to serve as sink absorber of CO, and may further add to global warming.

iii) **Effect on Air Quality**

UV-B is energetic enough to cause photolysis (changes due to photochemistry) of atmospheric gases. UV-B in clean environment reduces troposphere ozone. Assuming other factors to remain constant, Increased UV-B would increase the rate at which primary pollutants are removed from troposphere. However, such effects are difficult to detect as pollutants are far more influenced by variables like emissions from industrial and agricultural sources. Tropospheric ozone in the air causes damage to materials such as rubber and other polymers used in household and industrial products.

20.9 CONCLUSION

This Unit dealt with Ozone Depletion - a hazard, which has come to light in the last three decades. Ozone depletion primarily occurs in the stratosphere. After describing the temperature structure of troposphere and stratosphere and cheinical composition of the atmosphere, radiation balance in the Earth-Atmospheric system is briefly discussed. Natural production and destruction of stratospheric and tropospheric ozone by photochemical processes are discussed. Search for the negative trends in total ozone in middle and high Iatitudes has led to discovery of causes for the depletion of stratospheric ozone by long-lived chemical coinpounds containing chlorine. In addition, Antarctic ozone hole and the adoption of regulatory measures under the Montreal Protocol and amendments made to it, a major policy decision at the international level, are highlighted. Last but not the least, major hazards to human health and terrestrial ecosystems due to ozone depletion, consequent to increased penetration of solar UV-B, are described.

20.110 KEY CONCEPTS

Allotrope : Another form of a chemical element resulting from a different molecular arrangement.

Antarctic Ozone Hole : Abrupt loss of ozone in the Antarctica during spring season (September-October) when total column ozone is abruptly reduced by over 30 per cent over a vast region of Antarctica. This is caused by Chlorine-Ozone chemistry under very low temperatures in Antarctica.

Anthropogenic climate change, global warming : Rise in the surface temperature (global warming) of the earth due to increased emissions of green house gases as the result of excessive human activity (excessive energy use, intensive agriculture etc).

Dobson Unit : Scientific unit to describe thickness of total ozone layer. One Dobson unit is equivalent to 1/1000 of one cm at standard pressure and temperature at sea level.

Greenhouse Effect : The trapping of long wave (infra-red) radiation by certain gases (known as Green House Gases) like water vapor, carbon dioxide, methane, ozone, oxides of nitrogen which keep the earth's lower atmosphere and surface warm enough to allow life to thrive on earth.

Minor Constituents : Gases of Natural or Anthropogenic origin, which occur in small quantities in the atmosphere; also called Trace Gases.

Montreal Protocol : A major international policy decision, adopted by the international community in 1987 to control or even completely suppress use of ozone depleting substances.

Ozone Depletion : Loss of total column ozone as well as stratospheric ozone content due to chemical compounds, chiefly chlorinated hydrocarbons (CFCs) injected in to the atmosphere by human activity.

Ppbv : Concentration of minor constituents of air is expressed as parts per billion by volume of air.

Ppmv : Concentration of a minor constituents of air expressed as parts permillion by volume of air.

Stratosphere : The layer of atmosphere from top of the troposphere (tropopause) to about 50 km in which the temperature is either nearly constant or increases with height. 90 per cent of atmospheric ozone resides in this layer.

Troposphere : The layer of the atmosphere from earth surface to about 10-16 km up to tropopause. In the layer, temperature decreases with height at a lapse rate of 6°C per km.

UV-Biological Radiation : **UV** radiation in the wavelength band (290-320 nanometre) is injurious to human health, terrestrial and aquatic systems and air quality near the surface.

20.11 REFERENCES AND FURTHER READING

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20.12 ACTIVITY

1) Describe the regulatory policy measures adopted to regulate the adverse impacts of ozone depleting substances on stratospheric ozone.
2) What are the characteristics of earth's atmosphere?
3) Discuss the process for natural production and destruction of ozone.
4) Prepare a list of possible impacts of changes in atmospheric ozone and briefly describe any three types of effects.
5) What do you understand by Antarctic Ozone Hole? Is there a similar event over the Arctic?