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Preface

This is the era of global warming with the associated climate change, and increase in the frequency of extreme events. Beginning with the Industrial Revolution since circa 1750, the atmospheric concentration of heat-trapping greenhouse gases (GHGs) has increased significantly as a result of anthropogenic activities. Three major GHGs and their current atmospheric abundance relative to Industrial Era circa 1750 are carbon dioxide (CO_2) 145%, methane (CH_4) 254%, and nitrous oxide (N_2O) 121%. Other human-created GHGs are sulfur hexafluoride (SF_6), and many halogenated species. Emission of GHGs to the atmosphere is of a primary concern worldwide because the radiative properties of the atmosphere are strongly impacted by their abundance in the atmosphere. These gases have sometimes been referred to as well-mixed or long-lived GHGs because they are sufficiently mixed in the troposphere such that concentration measurements from few remote surface sites can characterize their atmospheric burden and their atmospheric lifetimes are much greater than timescales of few years of atmospheric mixing.

The Earth′s climate is determined by the flows of energy into and out of the planet and to and from the Earth’s surface. Increasing GHGs in the atmosphere therefore, creates imbalance in energy flows in and out of the Earth system by trapping more radiation energy. Trapped energy is manifested in many ways, including rising global surface temperatures, melting Arctic sea ice, accelerating the water cycle, altering the intensity and frequency of storms, and many more changes. In addition to impact on global climate, CO_2 also interact strongly with the biosphere and oceans. The atmospheric content of these gases also represent gaseous phase of the global biogeochemical cycles that control the flows and transformation of C and N between the different compartments of the Earth system, namely atmosphere, biosphere, hydrosphere, and lithosphere, by both biotic and abiotic processes. The increase in atmospheric CO_2 concentration is the main driver of the anthropogenic climate change, accounting for 1.939 of 2.974 $W\ m^2$ or 65% of the global-radiative forcing between 1750 and 2015. From 1990 to 2015, the radiative forcing by the long-lived GHGs increased by 37.4% with CO_2 accounting for about 80% of this increase. The two major sources of CO_2 emission are fossil fuel combustion and land use conversion. As a result of increase in anthropogenic emission of GHGs, the global annual mean land and ocean temperature increased by about 1.11 °C between 1750 and 2015, accompanied by the worldwide melting of glaciers and rising of the sea level.

Whereas the land use conversion was the major source of atmospheric CO_2 emissions ever since the dawn of settled agriculture, fossil fuel combustion has been increasingly important since the Industrial Revolution that began circa 1750. Presently, energy production and the environment are the two most important challenges facing the humanity in the twenty-first century. More than 80% of the energy comes from the fossil fuel combustion, and fossil fuels will remain the dominant energy source for years to come. Emission of CO_2 from the fossil fuel combustion process is the dominant anthropogenic GHG causing climate change because burning fossil fuels releases the CO_2 to the atmosphere that was stored millions of years ago, and thus, was unavailable for C cycling. Therefore, fossil fuels combustion transfers large quantities of C from slow domain C cycling to fast domain C cycling. Fossil fuel combustion accounts for about 75% of anthropogenic CO_2 emissions and is expected to further increase by 53 to 55%, while meeting 83% of the increase in energy demand by 2030. Prompt global action to resolve CO_2 emission crisis is needed in the short term, and the need to move away from C economy in longer term. In addition to energy conservation, C sequestration is one of an alternative method to reduce the rate of atmospheric CO_2 increase and mitigate climate change.

Global climate change presents a unique challenge to mankind, which requires a joint global effort to address. Whether global governments and public will act sufficiently fast to stabilize the global temperature at an acceptable levels and avoid dangerous impact remains the most uncertain proposition. For the policy makers, regulating fossil fuel use to the levels that will avoid dangerous warming is most difficult task because fossil fuel use has direct impact on economic prosperity. To the experts in physics, climate scientists, and others, the physics of radiation and energy balance, together with ocean circulation and Earth's long climate history, the global warming evidence is compelling.

Carbon (C) sequestration is the process of transferring atmospheric CO_2 that would otherwise be emitted into and/or remain in the atmosphere, and securely storing it in other long-lived C pools or protecting C that is stored in long-term pool that would otherwise be emitted, either through natural biological, enhanced natural biological processes, or anthropogenically driven non-biological engineering techniques. It aims at prevention of CO_2 from emission into atmosphere or transferring C from the atmosphere into long-lived pools—including biota, soil, geologic strata, and ocean. Strategies for C sequestration can be grouped into biotic and abiotic. Biotic strategies utilize ecological process of photosynthesis and transfer of CO_2 from atmosphere into plant biomass C through mediation of green plants, followed by utilization of biomass to substitute for fossil fuels or use of wood to substitute cement in construction. Biomass also can enhance soil organic C (SOC) storage, transferred to pedologic storage through OM burial and transformation into fossil C. Ocean CO_2 fixation also occurs through photosynthesis, followed by OM burial in deep ocean sediments. Abiotic strategies involve separation, capture, and storage of CO_2 into geologic strata using geoengineered processes which keeps industrial CO_2 emissions from reaching the atmosphere. The overall objective of the C sequestration—both biological and anthropogenic—is to balance the global C budget such that the current and future economic growth is based on C neutral or C negative strategy where there is either no net CO_2 emission or net negative CO_2 emission.

The *Carbon Sequestration and Climate Change Mitigation and Adaptation* book sets out a scientific basis of the current understanding of the role of increased CO_2 emission on climate change. The book explores an extensive field of current scientific knowledge that includes the general science of Earth's climate, how and why climate is changing, and consequences of those changes to food security and prosperity. The paleoclimatological studies form the basis of distinguishing between natural and anthropogenic climate change. The book also describes the role of C sequestration—both ecological engineered and geoengineed options—for mitigating the increasing atmospheric CO_2 concentration. In addition, the role of a proposed and emerging climate engineering and chemical sequestration option is briefly examined with the emphasis on their limitations and possible risks. Information from different scientific disciplines is collated and integrated to present a holistic approach towards the role of CO_2 and other GHGs on global warming, climate change, and the approaches for mitigating climate change and its impacts. The book is specifically prepared to provide academic and research knowledge for undergraduate and graduate university students, scientists, researchers, and policy makers interested in general understanding of the anthropogenic CO_2 emissions and its impact on global C cycling and C budgets, approaches for reducing CO_2 emissions, and available options for mitigating global warming.

We thank Springer Dordrecht and the Life Sciences staff for extending the opportunity to publish with them and share this knowledge. Particularly, we are indebted to Melanie van Overbeek and the staff of the Agronomy for their patience and tireless guide which allowed the completion of this task.

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Contents

Chapter 1
Introduction: Climate Overview

Abstract Energy exchange between Sun, Earth, and space controls the global climate. Earth is in dynamic equilibrium such that it receives the radiation from the Sun and emits the same amount of heat as infrared (IR) energy to space. Earth's energy imbalance is the difference between the incoming solar radiation absorbed by the Earth and the amount of heat the Earth radiates to the space. If positive imbalance occurs, such that the incoming radiation from the Sun is more than outgoing heat from the Earth, Earth becomes warmer. In contrast, if the imbalance is negative, such that more energy is going out than it receives, then Earth will cool. Earth's energy imbalance is the single most important measure of the status of the Earth's climate system which defines the expectations of future global climate change resulting from the anthropogenic perturbation or the greenhouse effect. The energy budget of the Earth's climate system is discussed in this chapter. The processes that Earth retains more electromagnetic radiation energy than it receives are also explained. In addition, the role of greenhouse gases (GHGs) in regulating the energy balance is discussed with the emphasis on carbon dioxide (CO_2). The concentrations of GHGs have increased significantly since the Industrial Revolution $\sim$ circa 1750. Most notable is the increase in concentration of CO_2 which have played a significant role in the current and future global temperature increases.

Keywords Climate system · Infrared radiation · Greenhouse gases · Ultraviolet radiation · Energy budget · Global warming

Contents

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1.1 Weather and Climate

Weather is the physical condition or state of the atmosphere at a certain places at a given time with reference to meteorological elements. It is what is happening in the atmosphere at any time or over any short period of time. The principal meteorological elements which defines the weather are: temperature, pressure, precipitation, wind, moisture, humidity, and other key parameters of meteorological importance such as presence of clouds, and occurrence of special phenomena such as thunderstorms, dust storms, tornados, and others. Therefore, the large fluctuations in the atmosphere from hour to hour or day to day constitute weather. These fluctuations occur as the weather system moves, develops, evolves, matures, and decays as a form of atmospheric turbulence. The weather systems arise mostly from atmospheric instabilities which are nonlinear chaotic dynamics such that they are not predictable in the individual deterministic sense beyond a week or so in the future. Meteorologists put a great deal of effort into understanding and predicting these day-to-day evolution of weather systems, and using physical based concepts that govern changes in atmosphere, they are able to predict the weather successfully only beyond several days into the future due to fundamental dynamical properties of the atmosphere.

According to Intergovernmental Panel on Climate Change (IPCC 2001, 2007) climate is generally defined as the average weather at a given period of time and space. It is described in terms of statistical quantities of mean and variability of surface weather variables over a period of time ranging from months to thousands or millions of years, and possibly over a certain geographical region. Climate description includes mean condition and the associated statistics such as frequency, magnitude, persistence trends, etc., often combining these statistical parameters to describe phenomena such as droughts. The classical period which has been adopted by World Meteorological Organization (WMO) for averaging these variables is 30 years. Temperature, precipitation, and wind are the most commonly used quantities to describe climate and to classify it into specific categories assigned to different parts of the world. Therefore, climate in a wider sense is an average state of the atmosphere observed as the weather over a finite period such as season for a number of different years. Climate is described in terms of mean and variability of weather elements such as temperature, precipitation, and wind over a specified time. It can range from months to millions of years. Climate comprises a variety of space and timescales from diurnal cycle to inter-annual variability such as El-Nino Sothern Oscillation (ENSO) to multi-decadal variations. There is no such thing as global weather but there is a global climate. Climate system is a complex relative system which involves the status of the entire Earth system, including atmosphere, land, oceans, snow, ice, living things that serves as the background conditions that determines weather patterns. Climate varies from place to place depending on latitude distance, distance to the ocean, vegetation, presence or absence of mountains, or other geographical factors. Climate also varies in time, from season to season, year to year, decade to decade or much longer timescales such as Ice Ages. The statistically significant variations of the mean state of climate or its variability that can be identified using statistical tests by change in mean and/or variability of properties persisting for extended periods, typically decades or longer are referred to as climate change. Although many other factors continues to influence the climate, human activities have become a dominant force and are responsible for most of warming observed in the past 50 years.

Traditionally, weather and climate focuses on those variables that affect daily life most directly—such as average, minimum and maximum temperature, wind near the surface of the Earth, precipitation in different forms, humidity, cloud type and amount, solar radiation—which are observed hourly by a large number of weather stations. But this is only part of reality that determines weather and climate. The climate of the Earth depends on factors that influence the radiative balance such as atmospheric composition, solar radiation or volcanic eruptions (Baede et al. 2001).

1.2 Solar Radiation and Climate

The amount and distribution of incoming radiation from the Sun determines weather and climate on the Earth (Trenberth et al. 2009). Therefore, solar radiation provides nearly all the energy that drives global climate system, and approximately half of the energy from the Sun is supplied by the visible part of electromagnetic spectrum. Solar energy leaves the Sun as electromagnetic radiation and travels through the space and atmosphere to reach the Earth's surface. Electromagnetic waves (also called electromagnetic radiation) are produced by the motion of electrically charged particles. The electromagnetic spectrum consists of light varying from long wavelength (low energy) to very short wavelength (very high energy). The solar radiation reaching the top of the atmosphere is (a) partially transferred, (b) partially transformed into other forms of energy which are dissipated by general circulations of the atmosphere and oceans, and (c) partially used in chemical and biological processes.

Within the climate system, energy occurs in different types including heat, potential energy, kinetic energy, chemical energy, short wave and long wave radiations. The climate system can therefore be described as weather generating heat engine driven by the solar radiation energy input and thermal radiation output (Peixoto and Oort 1992). The Sun emits radiation over a spectrum of energies that exist in the form of waves; the radiation wavelength is the inverse of energy. On the high energy side of solar spectrum is ultraviolet (UV) and on the low energy side is infrared (IR) radiation. Although the solar radiation covers the entire electromagnetic spectrum from gamma rays and X-rays through microwaves and radio waves, about 99% of the electromagnetic radiation emitted by the Sun reaching the Earth has the wavelengths (λ) of 0.15–4.0 μm (i.e., 1 μm = 10^{-6} m), with 9% in UV ($\lambda < 0.4$ μm), 49% in the visible spectrum ($0.4 < \lambda < 0.7$ μm), and 42% in IR ($\lambda > 0.7$ μm) ranges. The balance between the solar energy that Earth receives from the Sun and that which it radiates out to the space is a major driver of the Earth's climate. Quantification of the amount of energy flow in and out of the Earth system and identification of the factors determining the balance between the incoming and outgoing energy helps in understanding the climate change.

1.2.1 Radiation Balance of Earth and Atmosphere

Although there are various atmosphere, ocean, and land phenomena that couple the energy balance, for the equilibrium climate over time, and absorbed shortwave solar radiation from Sun balances the outgoing long wave radiation from Earth. Variations in global energy balance affects thermal conditions on Earth and various other climate elements such as atmospheric and oceanic circulations, hydrological cycle, glacier dynamic, plant productivity and also terrestrial carbon (C) uptake (Ramanathan et al. 2001; Ohmura et al. 2007; Wild et al. 2008; Mercado et al. 2009). The knowledge of the energy exchange between Sun, Earth and space has been improved through new satellite missions—Cloud and Earth's Radiation Energy System (CERES, Wielicki et al. 1996) and Solar Radiation and Climate Experiment (SORCE, Anderson and Cahalan 2005; Kopp et al. 2005) which began acquiring data in 2000 and 2005, respectively (Wild et al. 2013). These have allowed determination of the radiative flux exchanges on the top of the atmosphere with higher accuracy than previously published records (Loeb et al. 2012a). The radiant energy that falls on a surface of one square meter in area outside the atmosphere directly facing the Sun during 2008 and recorded by Total Irradiance Monitor (TMI) is 1360.8 ± 0.5 W (Kopp and Lean 2011). This value is ~4.5 W m^{-2} lower than previously reported value, and the difference has been attributed to instrumental bias for the older measurements recorded by older instrumentation. The new more accurate record requires an updating of the energy budget to reflect these new measurements (Hartmann et al. 2013). Only few parts of Earth faces the Sun directly, and also half of the time half of the Earth is pointing away from the Sun at night. Therefore, the average solar irradiance falling on one square meter of the level surface at the top of atmosphere is only a quarter of this (i.e., the area of a sphere is four times the area of a disk), which corresponds to a global average solar radiation of 340 W m^{-2} averaged over the Earth's sphere (Hartmann et al. 2013). The radiation balance of Earth and atmosphere with the updated annual mean radiation balance for the climate system as a whole is presented in Fig. 1.1. It is separated into incoming solar radiation, outgoing radiation and different components of terrestrial radiation and energy budgets.

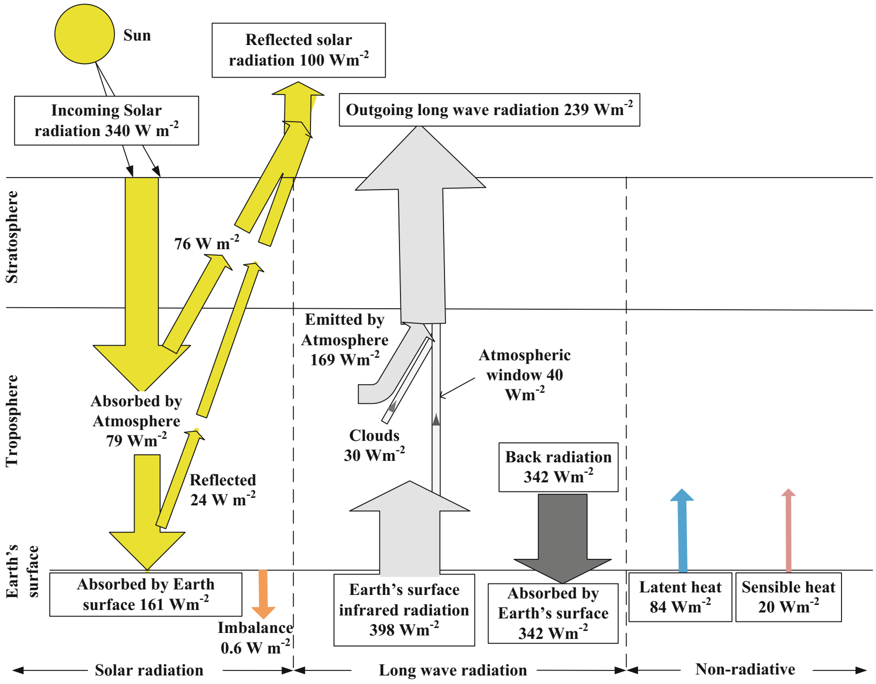

Fig. 1.1 Global mean energy balance of the Earth. *Numbers* and *text* in *box* indicate measured values, other *numbers* indicate best estimates for the magnitudes of globally averaged energy balance to close the balance. Adapted from Ussiri and Lal (2013), with an updated data from Wild et al. (2013), Hartmann et al. (2013)

As the solar radiation passes through the atmosphere, some of it is reflected back to the space by the atmospheric molecules. The total solar radiation reflected back to space measured at the top of the atmosphere is 100 W m^{-2} (Loeb et al. 2012b; Wild et al. 2013). Therefore, a total of 240 W m^{-2} (i.e., 340–100 W m^{-2}) of the solar radiation is available to the climate system. This radiant energy is either absorbed or reflected at the Earth's surface. It is also transformed into sensible heat, latent heat involving different water states, potential energy, and kinetic energy before being emitted as long wave radiant energy. Energy may be stored for a duration of time in various form and converted among different types of energy, which might produce varieties of weather or turbulent phenomena in the atmosphere and ocean (Trenberth et al. 2009).

The atmosphere is fairly transparent to short wavelength solar radiation. It is estimated that the atmosphere absorbs only about 80 W m^{-2} of the incoming solar radiation (Kim and Ramanathan 2008, 2012; Trenberth et al. 2009; Trenberth and Fasullo 2012; Wild et al. 2013; Kato et al. 2013). This leaves about 161 W m^{-2} to be transmitted and reach the Earth surface. Much less is known however about the energy distribution within the climate system and at the Earth's surface. The surface energy fluxes cannot be measured directly by the satellites as those at the top of the atmosphere (TOA), but they are inferred from the measurements at the TOA radiances using empirical calculations and physical modelling to account for the atmospheric attenuation (Wild et al. 2013). The downward thermal IR radiation at the surface established after incorporation of cloud base heights from the space-borne radar and lidar instruments is 342 W m^{-2} (range 338–348 W m^{-2}) (Fig. 1.1, Stephens et al. 2012b; Kato et al. 2013). This is the radiation emitted by GHGs and clouds, also known as back radiation. Additionally, direct surface radiation measurements from ground based radiation network of instrumentations propose similar values of downward thermal radiation (Wild et al. 2013). The land surface receives 185 W m^{-2} and absorbs about 161 W m^{-2} of the solar radiation, while reflecting an estimated 24 W m^{-2} back to space. Therefore, ~76 W m^{-2} of the solar radiation is directly reflected into space from the atmosphere (Fig. 1.1). The energy absorbed by the vegetation layer drives the plant processes such as evapotranspiration, photosynthesis, and C assimilation, while the remaining fraction available in the underlying soils controls evaporation on land and oceans, snow melting, and other temperature-related processes (Sellers et al. 1997).

To balance for this incoming energy, Earth itself must radiate the same amount of energy back to space in the form of thermal radiation. All objects emit this form of radiation, and if they are hot enough the emitted radiation falls in the visible spectrum. For example, the Sun is at the temperature of 6000 °C and looks white (shortwave radiation). Cooler objects emit radiation in the IR range (long wave radiation). The amount of thermal radiation emitted by the Earth's surface depends on its temperature, and how absorbing the surface is. The warmer the surface is, the more radiation is emitted, and also the greater the absorption, the more the radiation is emitted. All the surfaces on Earth absorb nearly all the thermal radiation which falls on them instead of reflecting it. The Earth radiates thermal energy equivalent to solar radiation energy received back. The solar flux energy intercepted per second by the Earth's surface can be expressed as Eq. (1.1):

$$F_s(1 - A)\pi R_e^2 \tag{1.1}$$

where, F_s is the solar flux constant at the top of atmosphere (1360 W m^{-2}), R_e is the radius of the Earth (6.38×10^6 m), and A is the Earth's albedo, which correspond to reduction of incoming solar radiation flux by absorption and scattering of radiation by aerosol particle (average value = 0.28). Based on the temperature of the Earth's surface, the majority of outgoing energy flux from the Earth is in the longwave range of spectrum. This longwave radiation is also referred to as infrared (IR) radiation. The IR energy emitted per second from the Earth's surface (black body radiation) is expressed as Eq. (1.2):

$$4\pi \mathrm{R}_e^2 \mathrm{s} \mathrm{T}_e^4 \tag{1.2}$$

where, s is Stephan-Boltzman constant (5.67×10^{-8} J $m^{-2} \times K^{-4}$), and $4\pi R_e^2$ is the surface area of the Earth. At equilibrium, the temperature of the Earth (T_e) is expressed as Eq. (1.3):

$$T_e = [F_s^*(1 - A)^* 1/4_s]^{1/4} \tag{1.3}$$

If the Earth was to emit thermal energy equivalent to solar radiation received back to space, temperature at the Earth surface will be around −19 °C (255 K) based on the energy balance requirements calculated using Eq. (1.3), which is the temperature observed at the altitude of 5–6 km above the Earth's surface (Peixoto and Oort 1992). However, an average of current temperatures measured near the surface across the globe over the land as well as over the oceans over the whole year indicates a global temperature of about 15 °C.

The Earth, being colder than the Sun, is warmed and it radiates heat as long waves (Fig. 1.1), primarily IR. The surface IR of 398 W m^{-2} (or about 114% of solar radiation from the Sun) corresponds to black body emission at 15 °C on Earth's surface, decreasing with altitude, and reaching mean temperature of −58 °C at the top of the atmosphere (i.e., troposphere, the layer closest to the Earth) about 15 km above the Earth's surface. The thermal radiation leaving the top of the atmosphere in the IR part of spectrum can be measured from instruments mounted on orbiting satellites. The outgoing thermal emission measured at the top of the atmosphere from 2005 to 2010 is 239 W m^{-2} (Hansen et al. 2011; Loeb et al. 2012b). Therefore, the heat radiation emitted by the surface (398 W m^{-2}) is greater than 239 W m^{-2} by the atmosphere by 159 W m^{-2}, which is the measure of greenhouse trapping. The global heat storage is estimated at 0.2–1.0 W m^{-2} (average = 0.6 W m^{-2}). This leaves 106 W m^{-2} of surface net radiation available globally for distribution among the non-radiative surface energy balance components—sensible heat, latent heat, and residual energy. Globally estimated sensible heat is estimated as 15–25 W m^{-2} (Trenberth et al. 2009; Stephens et al. 2012a). The estimates for global latent heat (i.e., energy equivalent of evaporation, globally equals precipitation) is estimated at 84 W m^{-2} (Trenberth and Fasullo 2012); but uncertainty remains higher due to variation in precipitation from year to year (Adler et al. 2012).

1.3 Greenhouse Effect

1.3.1 The Natural Greenhouse Effect

The gases nitrogen (N_2), oxygen (O_2) and argon (Ar) that make up the bulk of the atmosphere (Table 1.1) do not absorb or emit thermal radiation. If they were the only atmospheric components there would not be any clouds and no greenhouse effect, and to achieve radiative balance the average Earth's surface temperature

Table 1.1 The global average concentration of well mixed atmospheric constituents, their changes since industrial era and radiative efficiency (IPCC 2007, 2013; Schlesinger and Bernhardt 2013)

Gas	Radiative efficiency W m^{-2} ppb^{-1}	Mixing ratio			Global increase (2005–2011)
		1750	2005	2011	
Major constituents (%)					
Nitrogen (N_2)	0	78.084	78.084	78.084	–
Oxygen (O_2)	0	20.946	20.946	20.946	–
Argon (Ar)	0	0.934	0.934	0.934	–
Water vapor (H_2O)		0–0.02	0–0.02	0–0.02	–
Parts per million (ppm) constituents					
Carbon dioxide (CO_2)	1.37×10^{-5}	278 ± 2	379	390 ± 0.28	11.67 ± 0.37
Helium	0	5.24	5.24	5.24	5.24
Krypton	0	1.14	1.14	1.14	1.14
Parts per billion (ppb) constituents					
Methane (NH_4)	3.63×10^{-4}	722 ± 22	1774	1803 ± 4.8	28.9 ± 6.8
Nitrous oxide (N_2O)	3.00×10^{-3}	270 ± 7	319	324.0 ± 0.1	4.7 ± 0.2
Chlorofluorocarbons (parts per trillion)					
CFC-11	0.26	0	251	236.9 ± 0.1	−13.0 ± 0.1
CFC-12	0.32	0	542	539.5 ± 0.2	−14.1 ± 0.1
CFC-113	0.30	0	78.6	74.3 ± 0.06	−4.35 ± 0.02
CFC-115	0.20	0	8.36	8.37	–

would be −6 °C (Houghton 2005). The difference between this and the actual observed temperature is about 20 °C. Presence of trace gases, those which account for less than 1% of the total volume of dry air in the atmosphere, plays important role in Earths' energy budget by absorbing and re-emitting IR radiation emitted by Earth surface, preventing it from escaping to the space. Water vapor ($H_2O(g)$), CO_2, methane (CH_4), nitrous oxide (N_2O) are known as the trace gases because of their smaller quantities in the atmosphere, they are also called GHGs because they absorb some of the thermal radiation leaving the surface and emit long wave radiation into all directions, while acting as partial blanket and keeping the Earth warm. As a result, most of the radiant heat flows back and forth between Earth's surface and atmosphere, and absorbed in the atmosphere to keep the Earth's surface warm. The downward directed component of IR adds heat to the lower layers of the atmosphere and the Earth's surface causing the so called greenhouse effect. The dominant energy loss of IR radiation from the Earth occurs from higher layers of troposphere.

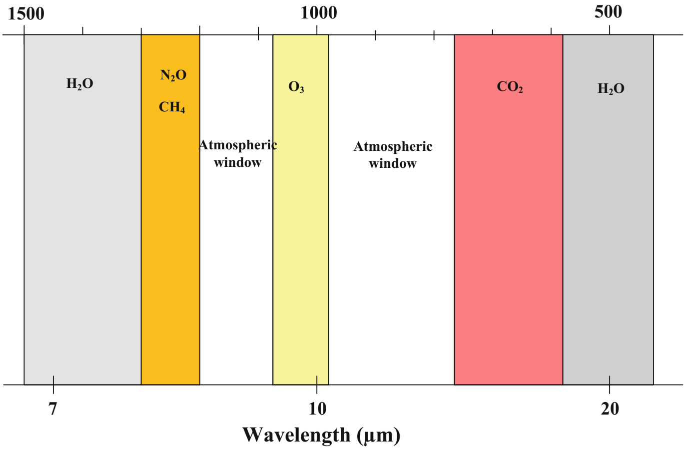

Fig. 1.2 Part of infrared spectrum (7–21 µm) showing locations where different gases contribute to the radiation. Between 8 and 14 µm, apart from O_3 in the absence of clouds is transparent to radiation, this part of the spectrum is called 'atmospheric window'. Modified from Houghton (2005)

Transfer of radiation in the atmosphere as seen by satellites orbiting the Earth is shown in Fig. 1.2. At some wavelengths (8–14 µm) in the IR the atmosphere in the absence of clouds is transparent, and almost all radiation originating from the Earth's surface leaves the atmosphere. All other wavelength radiation from the surface of the Earth is strongly absorbed by water vapor, CO_2, CH_4 and N_2O present in the atmosphere. Particularly water vapor and CO_2 are the strongest absorbers. Objects which are good absorbers of radiation are also good emitters of it.

The amount of radiation they emit depends on the temperature. At the top of atmosphere (5–10 km high) the temperature is much colder (30–50 °C colder than the surface) because of convection processes (Fig. 1.3). Because these gases are cold, they emit less radiation out to the space. They, therefore, act as a radiation blanket over the surface, and help to keep it warmer than it would otherwise be. This partial blanketing is known as natural greenhouse effect, and these gases are known as GHGs. This phenomenon is natural because these trace gases were present in the atmosphere even prior to any anthropogenic perturbation. The amount of water vapor present in the atmosphere is variable and mostly dependent on the surface temperature of the oceans, and most of it originates from the evaporation from the ocean surface and is not directly influenced by anthropogenic activities. The natural greenhouse effect is important in maintaining the Earth's climate with its suitability for life to flourish.

Clouds also play significant role in maintaining Earth's radiation balance (Fig. 1.1). Clouds reflect some of the incident radiation from the Sun back to space. They also absorb and emit thermal radiation and have a 'blanketing effect' similar to the trace gases. These two effects of clouds tends to cancel each other, leaving

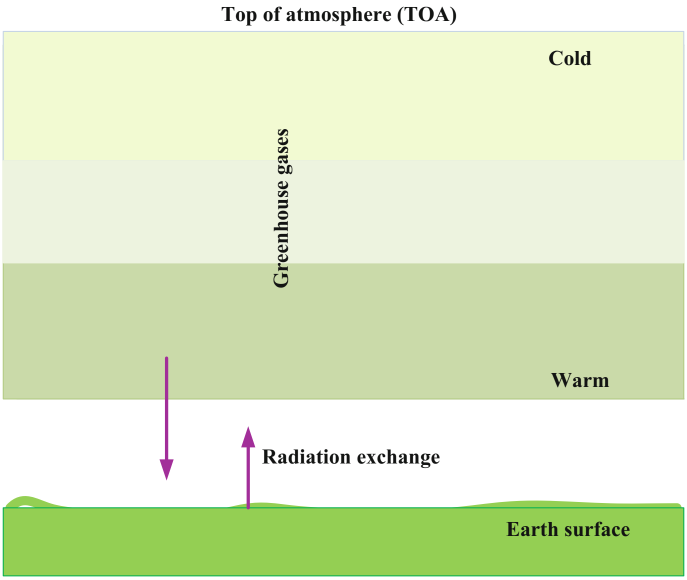

Fig. 1.3 Illustration of blanketing effect of greenhouse gases in the atmosphere

total radiation balance unchanged or slight cooling of the Earth's surface. Sun provides its energy to the Earth primarily in tropics and subtropics, and this energy is then partially redistributed to middle and high latitudes by atmospheric and oceanic transport processes, while the outgoing long wave radiation is more uniformly distributed with latitude (Fasullo and Trenberth 2008a, b).

1.3.2 Discovery of the Science of Greenhouse Effect

The warming effect of the GHGs in the atmosphere was first recognized by a French scientist Jean-Baptiste Fourier who pointed out the similarity between what happens in the atmosphere and inside the greenhouse in 1827. In 1838, Fourier and Claude Pouillet were able to measure the heating effects of radiation with mercury-in-glass (Mudge 1997). They observed that the atmosphere absorbs less of the incoming radiation than the outgoing radiation and suggested that this difference would account for the Earth remaining at the higher temperature than it would if there were no atmosphere. This is the origin of the name 'greenhouse effect'.

A British scientist John Tyndall considered the part played by the minor components of the atmosphere in producing remarkable temperature conditions of the mountainous country. To measure the intensity of heat directly, he designed and built the first infrared spectrometer. In 1860 he measured the absorption of infrared radiation by CO_2 and water vapor (H_2O) using this device. He was able to show that

O_2 and N_2 are almost completely transparent to heat and CO_2 and water vapor are powerful absorbers and radiators of heat. He also suggested that the cause of ice ages might have been the decrease in the greenhouse effect of CO_2. A Swedish chemist Svante Arrhenius calculated the effect of increasing concentration of GHGs in 1896 and estimated that doubling the concentration of CO_2 would increase the global average temperature by 5–6 °C. His estimates are not far from present understanding of 2–4.5 °C quoted in many modern day literatures.

Investigations of how CO_2 absorbs radiation were further advanced by S. P. Langley of the Allegheny Observatory in the USA, who designed the device for measuring the solar constant (i.e., the amount of heat radiated by the Sun). Langley was also the pioneer of the link between the variations in atmospheric composition and long-term climate change. In 1940, G.C. Callendar was the first to calculate the warming associated with increase in CO_2 concentration from burning of fossil fuels. He used calculations to link various threads of evidence which had been observed and link them to the theory of global climate change and the role of CO_2 which was widely accepted. Callendar is often regarded as the originator of the modern theory connecting atmospheric CO_2 concentration and global climate change because of his pivotal role in distinguishing the CO_2 absorption bands from that of water vapor which led to current understanding of greenhouse warming. However, his calculations and work did not raise any concern at that time.

The first expression of concerns about climate change which might be brought about by increasing GHGs occurred in 1957 when Roger Revelle and Hans Suess of Scripp Institute of Oceanography in California published a paper which pointed out that the buildup of CO_2 in the atmosphere by human activities is like carrying out a large-scale geophysical experiment. This motivated C.D. Keeling to start the routine measurement of CO_2 concentration at Mauna Loa in Hawaii. Finally, with more accurate measurements of atmospheric CO_2 concentration, Keeling was able to link statistically the evidence for increase in global temperature with increase in atmospheric concentrations of CO_2 (Keeling et al. 1976b). The rapidly increasing use of fossils together with the availability of observatory data confirming the increase of CO_2 and its influence on global temperature lead to the topic of global warming moving up in political agenda. Eventually this political attention led to Climate Change Convention in 1992 and the formation of Intergovernmental Panel on Climate Change (IPCC) under the auspices of the United Nations (UN).

1.3.3 Enhanced Greenhouse Effect

As discussed in the previous section, Earth is a planet in dynamic equilibrium, in that it continuously absorbs and emits electromagnetic radiation. It receives UV and visible radiation from the Sun and it emits IR, and energy balance requires that the energy received must be equal to energy emitted for the temperature of the Earth to be constant. The Earth emits IR radiation with a range of wavelengths spanning from ~4 to 50 μm, and the majority of emission are in the range 5–25 μm (400–

2000 cm^{-1}). The argument that greenhouse effect has maintained Earth at a stable temperature assumes that the concentration of trace gases remains constant over a long period of time. But this is not the case for CO_2, CH_4, N_2O and O_3. Their concentrations in the atmosphere have increased substantially since the industrial revolution, circa 1750 due to the anthropogenic activities (Table 1.1).

In addition, some man-made GHGs that are not naturally occurring which are more potent heat absorbers, including hydrofluorocarbons (HFCs), perfluorocarbons [PFCs; a class of organofluorine compounds that have all hydrogen (H) replaced with fluorine (F)], and sulfur hexafluoride (SF_6) generated from a variety of industrial processes have been added to the atmosphere (Baede et al. 2001). These compounds are the most potent GHGs because they have large heat-trapping capacity and some of them have extremely long atmospheric lifetimes (Table 1.2). Once emitted, these GHGs can remain in the atmosphere for centuries, making their accumulation almost irreversible. The amount of water vapor in the atmosphere mostly depends on the temperature of the surface of the ocean, since oceans cover larger Earth's surface than the lands. Most of it originates from evaporation from the ocean surface, and is not directly influenced by anthropogenic activities. The amount of radiation trapped in the atmosphere depends on gaseous composition of the atmosphere and the spectral properties of the gases.

Table 1.2 Atmospheric lifetimes and the global annual mean surface dry-air mole fraction of greenhouse gases (Hartman et al. 2013; WMO 2016)

Greenhouse gas	Atmospheric lifetime (years)	Recent (2015) tropospheric concentration	Global warming potential (100-yr time horizon)	Industrial Era increased radiative forcing (W m^{-2})
Conentrations in parts per million (ppm)				
Carbon dioxide (CO2)	100–300	400.1 ± 0.1 ppm	1	1.94
Conentrations in parts per billion (ppb)				
Methane (CH4))	9.1	1845 ± 2 ppb	28	0.50
Nitrous oxide (N2O)	131	328 ± 0.1 ppb	265	0.20
Tropospheric ozone (O3)	hours-days	237 ppb	n.a.	0.40
Conentrations in parts per trillion (ppt)				
Sulfur hexafluoride (SF_6)	3200	8.6 ppt	23,500	0.005
CFC-11	45	232	4,660	0.06
CFC-12	100	516	10,200	0.166
CFC-113	85	72	5,820	0.022
HCFC-22	11.9	233	1,760	0.049
HCFC-141	9.2	24	782	0.004
HFC-134a	13.4	84	1,300	0.013

Anthropogenic activities in post-industrial era have resulted in enhanced emission of four major GHGs namely CO_2, CH_4, N_2O, and O_3. It is the changes in the concentrations of these gases that has caused enhanced greenhouse effect to occur in the post- industrial era. The increase in the concentration of GHGs causes imbalance in radiation budget. By trapping more IR radiation, the Earth's surface responds by warming to restore the energy balance. The atmospheric concentration of CO_2 has increased due to fossil fuel use in transportation and power generation, cement manufacturing, deforestation and accelerated processes of organic matter decomposition. The CH_4 has increased because of agricultural activities, natural gas distribution, and landfills. Wetlands also release CH_4 naturally. The N_2O has increased as a result of agricultural soil management and N fertilizer use, livestock waste management, mobile and stationary fossil fuel, combustion, and industrial processes. Soils and oceans also emit N_2O naturally. Hydrofluorocarbons (HFCs) are man-made chemicals developed as alternatives to ozone-depleting substances for industrial and consumer products, for example, HFC-134a, used in automobile air-conditioning and refrigeration. Perfluorocarbons (PFCs) are chemicals primarily produced from aluminum production and semi-conductor manufacture, while sulfur hexafluoride (SF_6) is a gas used for insulation and protection of current interruption in electric power transmission and distribution equipment. Other GHGs include ozone (O_3) continually produced and destroyed in the atmosphere by chemical reaction.

Anthropogenic activities have increased O_3 in the troposphere (i.e., the atmospheric layer closest to the Earth) through the release of gases such as CO, hydrocarbons, and NO which chemically reacts to produce O_3 (Forster et al. 2007; Myhre et al. 2013). Changes in atmospheric water vapor and O_3 are climate feedbacks due to indirect effect of anthropogenic activities. Because GHGs absorb IR radiation, changes in their atmospheric concentration alter the energy balance of the climate system. Increase in atmospheric GHGs concentrations produces net increase in absorption of energy of the Earth, leading to warming of Earth's surface.

The characteristic absorption of CO_2 in the IR radiation range of the atmospheric window of the Earth makes it a potent GHG. Since 1980s, a scientific consensus has emerged that human activities through increasing the concentration of GHGs in the atmosphere have enhanced the greenhouse effect and set in motion a global warming trend (IPCC 2001, 2007, 2013). For example, CO_2 in the atmosphere has increased from about 280 ppm in pre-industrial era (1750) to the current 400.0 ± 0.1 ppmv (WMO 2016). Similarly, concentrations of CH_4 and N_2O have increased from 700 and 270 ppb in pre-industrial era to current levels of 1845 ± 2 and 328 ± 0.1 ppbv, respectively (WMO 2016). This change represents an abundance of 144, 256, and 121 for CO_2, CH_4, and N_2O, respectively, relative to year 1750. The mean growth rate estimates of CO_2 concentration in the atmosphere is at 2 ppm yr^{-1} over the past 10 years (WMO 2016).

The increase in atmospheric CO_2 concentration has contributed about 72% of the enhanced greenhouse effect to date, CH_4 about 21%, and N_2O about 7% (Houghton 2009). The CO_2 is stronger in enhancing greenhouse effect because its strong IR absorption band at 15 μm (Fig. 1.2) occurs close to the peak of blackbody function at the temperatures representative of the Earth's atmosphere and surface (Zhong and

Haigh 2013). Therefore, anthropogenic activities have dramatically altered the chemical composition of the global atmosphere with great implications for current and future climate. Atmospheric theory predicts that changes in the concentration of trace gases will have dramatic consequences for the habitability of the earth, which may include (i) food insecurity, (ii) loss of biodiversity and ecosystems change (iii) destruction of the stratospheric ozone layer due to increase in N_2O and halogenated compounds, and (iv) increase in the amount of tropospheric ozone due to increased emissions of NO_x, CO, and hydrocarbons. With the current trends, the earth is likely to warm by 3–5 °C for the next century (Le Treut et al. 2007). This is as much as it has warmed since the last ice age. Such a warming would have adverse impacts on ecosystems because of inability to adjust to such a rapid temperature changes.

Although the atmospheric concentrations of CH_4 and N_2O are much lower than that of CO_2, they each make a disproportionate contribution to atmospheric anthropogenic greenhouse effect in relation to their concentrations in the atmosphere. Methane contributes some 15%, and N_2O 6% of the greenhouse effect, making them the second and third most important GHGs after CO_2. This is because CH_4 has a global warming potential 28 times and N_2O is 265 times that of CO_2 on 100-year timescale (Hartmann et al. 2013).

1.4 Natural Versus Anthropogenic Climate Change

1.4.1 Climate System

Climate system is a composite system consisting of five main interactive components, namely the: (1) atmosphere, (2) hydrosphere, (3) cryosphere, (4) lithosphere, and (5) biosphere. These are forced by various external forcing mechanisms; the most important one is the Sun (Fig. 1.1). All the systems are open, interactive, and linked by complex feedbacks processes and a great variety of timescales within the individual components. A change in one part of subsystem may eventually affect all other parts. Feedback processes from the slower subsystems such as hydrosphere (i.e., oceans) or cryosphere (i.e., glaciers) can initiate quasi-periodicities with very long time scale in the faster responsive subsystem such as atmosphere. This leads to what is generally known as climatic cycles and climate change. The atmosphere, hydrosphere, cryosphere and biosphere generally act as a cascading system linked by a complex system of fluxes of energy, momentum and matter across the boundaries and generating numerous feedback mechanisms.

The climate system evolves in time under the influence of its own internal dynamics and due to changes in the external factors that affect global behavior known as “forcings”. Two main external forcing that provide external energy input to the climate system are solar radiation and the earth rotation which causes gravitational energy. However, solar radiation is regarded as the primary forcing mechanism since it provides all the energy that drives the climate system. The spherical shape of the Earth, its rotation and orbital characteristics also influence the climate system. Within the climate system, the energy occurs in different forms including heat, potential energy, kinetic energy, chemical energy, short and long wave radiation. Within the climate system, the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere act as a cascading system interconnected by flows of energy, momentum and matter.

The shortwave solar radiation is unequally distributed over different parts of the climatic system due to spherical nature of the Earth, the orbital motion and the tilt of Earth's axis. As a result, more radiation is absorbed in the inter-tropical regions than at polar latitudes, leading to excess energy in the tropics and deficit in the polar (40°) latitude. This source and sink of energy distribution is the main cause of thermodynamic processes occurring inside the climatic system such as general circulations in atmosphere and oceans. Except for small imbalances, the Earth system loses the same amount of energy through infrared radiation as it gains from the incoming solar radiation (Fig. 1.1). The direct effect of human activities on climate system is also considered an external forcing.

1.4.1.1 Atmosphere

The atmosphere is comparatively a thin film which comprises the mixture of gaseous envelope surrounding the Earth and formed by several layers of different compositions and nature of energy involved. Atmosphere is the most unstable and rapidly changing part of the climatic system. In the vertical direction, more than 99% of its mass is found below the altitude of only 30 km. The atmosphere can be divided into several layers which differ in composition, temperature, stability, and energy (Fig. 1.4). The main layers from Earth's surface are troposphere, stratosphere, mesosphere, and thermosphere; each separated by conceptual partition called pauses (e.g., tropopause). The composition of the atmosphere up to the mesopause is generally uniform in terms of O_2, N_2 and other inert gases. The abundance of molecules per unit volume is greater at sea level due to higher pressure (Fig. 1.4). The troposphere contains about 80% of the atmospheric mass (Warneck 1988). Among the variable components, water vapor is found predominantly in the lower troposphere and ozone in the middle stratosphere. The CO_2, which has been increasing in recent times, is well mixed below the mesopause. The composition of the atmosphere is further complicated by the presence of various substances in suspension, e.g., liquid and solid water (clouds), dust particles, sulfate aerosols, and volcanic ash. The concentrations of these aerosols vary in time and space. The atmosphere composition is relatively well mixed, therefore changes in its composition can be assumed as first index of changes in global biogeochemical processes.

The atmosphere has evolved as a result of the history of life on the Earth, and is now changing rapidly as a result of human activities, as some evidence presented in next chapters will reveal. The atmosphere is the climatic system component most

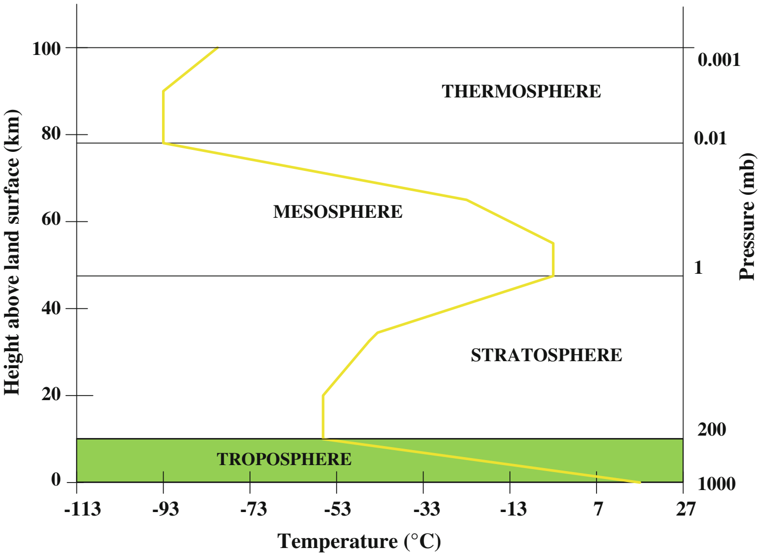

Fig. 1.4 Temperature and pressure profile of the atmosphere to 100 km with estimated subdivisions of the atmosphere. Modified from Peixoto and Oort (1992), Schlesinger (1997)

variable in time and space and exhibit the shorter response time to an imposed change or perturbations applied to its boundary conditions or forcings, mostly due to its compressibility, and low specific heat. These properties make the atmosphere more fluid and unstable. The troposphere shows a large-scale general circulation with eddy motions in the mid-latitudes such as weather systems and random turbulent motions mainly in the planetary boundary layer and near jet streams. These circulations transport biogeochemical constituents between land and sea, causing the circulation of elements (Fig. 1.4).

The atmosphere is held on Earth's surface by the gravitational attraction of the Earth. At any altitude, the downward pull is related to the mass of the atmosphere e.g., (Eq. 1.4):

$$F = Mg \tag{1.4}$$

where, g is the acceleration due to gravity. The pressure decreases with increasing altitude (Fig. 1.5) because the mass of the overlying atmosphere is smaller (Walker 1977). Because of gravity, the atmosphere is stratified with dense layers at the surface, and the atmosphere is in a state of almost hydrostatic equilibrium in the vertical. The atmosphere is set into motion primarily through differentiated heating by the Sun. Motions in the atmosphere are influenced by many other factors including rotation of the Earth. The atmosphere controls Earth's climate and determines the environment in which living creatures live.

1.4.1.2 Hydrosphere

Hydrosphere consists of all water in liquid phase distributed on the Earth. It includes oceans, seas, lakes, rivers, and subterranean waters. The most important for the climatic studies are the oceans which covers approximately two thirds of the earth's surface, so that most of the solar radiation reaching the Earth's surface falls on oceans and is absorbed by the oceans. Because of this large mass and specific heat, the oceans form a large reservoir to store energy. Energy absorbed by the oceans results in relatively small change of surface temperatures compared to that which would have occurred over the land. Due to their thermal inertia, the oceans act as a buffer and regulator for the temperature. Because oceans ore more dense than the atmosphere, they also have a large mechanical inertia and more pronounced stratification. The upper part of ocean is the most active. It contains surface mixed layer with thickness on the order of 100 m. the oceans show much slower circulations than the atmosphere. They form large circulation gyres with the familiar ocean currents and slow thermocline overturning due to density variations associated with changes in temperature and salinity.

The response or relaxation time for the oceans varies within wide range that extends from weeks to months in the upper mixed layer to seasons in the thermocline—at several hundred meters depth to centuries and millennia in the deep ocean. The ocean currents transport part of heat energy stored in the oceans from the inter-tropical regions where there is an excess of heat due to more incident solar radiation towards colder mid-latitudes and Polar Regions. The atmosphere and oceans are strongly coupled. Air—sea interactions occur on many scales in space and time through the exchanges of energy matter and momentum at the atmosphere—ocean interface. The exchange of water vapor through evaporation into the atmosphere supplies the water vapor into the atmosphere and part of energy for the hydrological cycle leading to condensation, precipitation, and runoff. Precipitation strongly influences the distribution of ocean salinity. The lakes and subterranean waters are essential elements of terrestrial part of the hydrological cycle and also play important role in global climate. They also influence the climate on regional and local scale. Rivers are also an important factor in ocean salinity near coasts.

1.4.1.3 Cryosphere

Cryosphere comprise a large masses of snow and ice of the Earth's surface. It includes the extended ice fields of Greenland and Antarctica, another continental glaciers and snow fields, sea ice and permafrost. The cryosphere is the largest reservoir of freshwater on earth. Its importance in climatic system results mainly from its albedo (i.e., high reflectivity of solar radiation) and its low thermal conductivity. Continental snow cover and sea ice change seasonally leading to large intra- and inter annual variations in energy budget of the continental regions and of the upper mixed layer of the ocean. Due to the high reflectivity of snow and ice for solar radiation and low thermal diffusivity of sea ice compared to that of stirred