

## Chapter 2

# Greenhouse Gases and Their Role in Climate Change

Robert Dilmore and Liwei Zhang

*The Sun, with all the planets revolving around it, and depending on it, can still ripen a bunch of grapes as though it had nothing else in the Universe to do.*

—Galileo Galilei

**Abstract** The chapter begins with a comprehensive review of the representative greenhouse gases and their role in the Earth's radiative balance. Eight greenhouse gases ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , HFC-23, HFC-134a, PFC,  $\text{SF}_6$ , and  $\text{NF}_3$ ) and their contributions to radiative heating of the atmosphere are analyzed, and the mechanisms associated with global warming potential are discussed. To illustrate the reported evidence of changes in the radiative balance attributed to greenhouse gases, the correlation between the global temperature rise and the increase in atmospheric concentration of  $\text{CO}_2$ , the most important greenhouse gas, is presented. The primary anthropogenic  $\text{CO}_2$  emission sources and the amount of  $\text{CO}_2$  emissions by region, and the disturbance of anthropogenic  $\text{CO}_2$  emission to global carbon cycle are discussed. At the conclusion of this chapter, a brief review of global actions to mitigate anthropogenic  $\text{CO}_2$  emissions is presented.

Human activity since the advent of the Industrial Revolution has contributed to the gradual increase in atmospheric concentration of carbon dioxide ( $\text{CO}_2$ ) and concentrations of other greenhouse gas constituents. These concentration increases, in combination with other human-induced changes, have driven additional retention of solar energy, in the form of thermal infrared radiation, by the atmosphere. This has led to the increase in mean global temperature at the Earth's surface, with significant and impactful effects such as reduction in extent and thickness of Earth's sea

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and terrestrial ice, sea level rise, increased incidence of extreme weather events, increased incidence of crop failure and famine, and loss of health and biodiversity in the Earth's ecosystems. Furthermore, atmospheric CO<sub>2</sub> concentration rise also contributes to the acidification of our planet's oceans, with implications for the health and productivity of marine ecosystems, and likely impacts to the contribution of our oceans to the global carbon cycle.

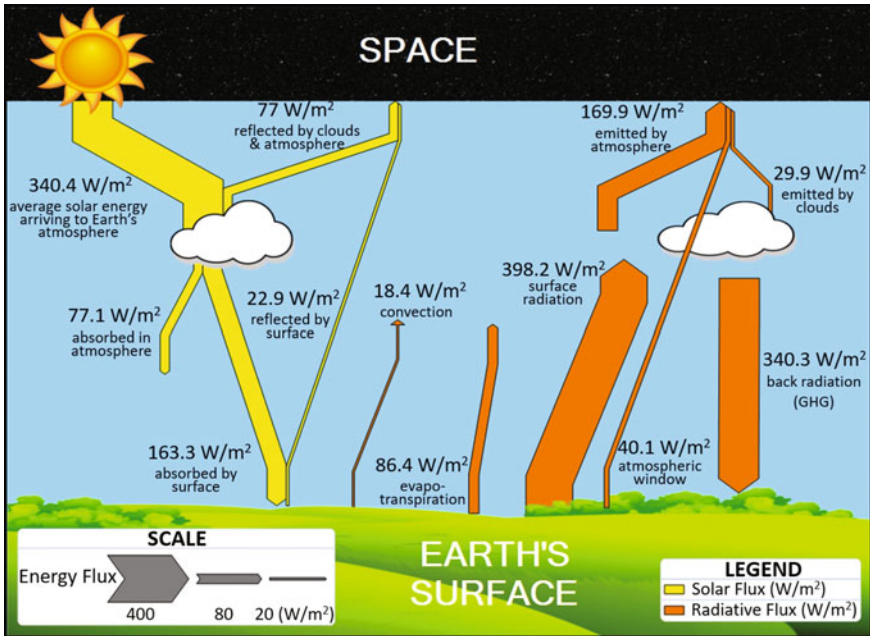
Identifying and implementing ethical and effective approaches to stabilize atmospheric greenhouse gas concentrations at a level that would avoid the worst weather, environmental, and social impacts, and prevent irreparable damage to Earth's climate system is the focus of significant technical and policy research. In this chapter, a general review of the basic physical and chemical phenomena that underpin the Earth's response to the greenhouse gas effect and the role of atmospheric CO<sub>2</sub> in the context of global carbon cycle is provided—to give context to the technical discussion of technology alternatives to mitigate atmospheric GHG concentration rise.

## 2.1 Radiative Forcing and Greenhouse Gases

Energy from the sun travels to Earth in the form of electromagnetic radiation. In classical electromagnetic wave theory, this radiation is considered to take the form of oscillating waves of various frequencies. While the frequency of solar energy reaching the Earth spans the broader electromagnetic spectrum, most of that energy is in the visible to near-infrared range, with a smaller amount falling in the ultra-violet frequency range. A little less than a third of the energy that reaches the Earth's atmosphere is reflected back into space by the atmosphere itself, clouds, and the Earth's surface, as a function of the reflectivity (the albedo) of those bodies. The remaining approximately 70% of that solar energy passes into the atmosphere and is absorbed by the atmosphere, clouds, and Earth's surface (water and ground). The vast majority of that absorbed radiation is radiated out from those absorbing bodies as infrared energy (energy in the infrared spectrum) (Kiehl & Trenberth, 1997; NASA, 2016a). A portion of that radiated energy is trapped by the Earth's atmosphere—warming the lower atmosphere, moderating the extreme diurnal variations in temperature that would otherwise exist, and allowing our planet to be habitable.

The difference in the balance between the energy entering the Earth's atmosphere and that which is radiated back out to space (Fig. 2.1) drives changes in the mean atmospheric temperature at the Earth's surface (NASA, 2016b). Maintaining equilibrium (zero difference) in that balance means that average surface temperatures will remain stable.

The contribution that a system component makes to disequilibrium in that system is termed 'radiative forcing.' Radiative forcing, as defined by the IPCC (2007), is



**Fig. 2.1** Simplified Sankey diagram illustrating example of the Earth's radiative balance with solar energy input to the Earth and thermal infrared energy in relation to the Earth's surface, its atmosphere, and outer space (modified from NASA, 2014)

a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism.

The publication (IPCC, 2007) specifies values of radiative forcing as being in terms of changes relative to preindustrial conditions (based on the year 1750 as a selected datum) and reports that in units of Watts per square meter ( $\text{W/m}^2$ ).

Factors contributing to changes in radiative balance (agents of radiative forcing) include changes in the amount of radiation delivered to the Earth from the Sun and changes in the composition or characteristics of the material with which that radiation comes in contact. That includes changes in reflective and absorptive properties of the terrestrial Earth (e.g., changed reflectance and absorbance resulting from deforestation) and changes in the composition of the Earth's atmosphere that impact how the atmosphere behaves in response to incoming solar radiation and infrared radiation emitted by Earth's surface, and the atmosphere itself (e.g., increased reflectance of insolation associated with increased concentration of particulate matter in the upper atmosphere resulting from volcanic activity).

One type of radiative forcing agent that is of significant concern as a contributor to perturbations in radiative balance is the increase in atmospheric (tropospheric and stratospheric) concentrations of certain constituents that lead to the trapping of

thermal infrared energy in our Earth's lower atmosphere, such as carbon dioxide, methane, halocarbons, and nitrous oxide, collectively called "greenhouse gases" (White et al., 2003; IPCC, 2007) because of the blanketing role that they play in trapping thermal energy near the Earth's surface. Increases in the atmospheric concentrations of these gases directly contributes to positive radiative forcing and increases in atmospheric temperature, but can also indirectly cause radiative forcing in response to physical/chemical changes that their increased concentrations in the atmosphere induce (e.g., chemical alteration of ozone concentrations and distribution in the upper atmosphere, and greenhouse effects from increases in atmospheric water vapor concentration resulting from atmospheric warming).

An index has been developed to estimate the contribution of incremental increases in greenhouse gases to the atmosphere. This index, called global warming potential (GWP) allows the relative comparison of the direct global warming effects of different greenhouse gas constituents and is commonly applied in policy and planning related analyses to understand the GWP contribution of various activities. GWP of a greenhouse gas is a function of the amount of time it spends in the atmosphere before being destroyed, the frequency ranges in which it absorbs radiation, and the strength of that absorption, its molecular weight, and the time period over which the GWP analysis is being considered. A convention has been adopted in which the GWP is normalized to that of CO<sub>2</sub>, such that the GWP factor is the time integrated radiative forcing of a greenhouse gas divided by the time integrated radiative forcing of CO<sub>2</sub> for the same time interval. Table 2.1 provides a list of calculated GWP values of select GHGs, as reported in the IPCC Fifth Assessment Report (2013). Because GWPs are indexed to CO<sub>2</sub>, the GWP of CO<sub>2</sub> is 1.

These values are calculated based on the best-available scientific information; as the research community's understanding of the behavior of these constituents in the atmosphere evolves, these values are revised. Also, it should be noted that there are other, perhaps more technically rigorous approaches for considering the contribution of GHGs to radiative forcing that are advocated by some in the scientific community; consideration of those is outside the scope of this overview. For a far more detailed consideration of radiative forcing and GWP associated with these and

**Table 2.1** Summary of 20- and 100-year GWP values of select GHG constituents (IPCC 2013)

	Half-life (years)	GWP time horizon	
		20 years	100 years
Carbon dioxide (CO <sub>2</sub> )	Complex	1	1
Methane (CH <sub>4</sub> )	12.4	84	28
Nitrous oxide (N <sub>2</sub> O)	121	264	265
HFC-23	222	10,800	12,400
HFC-134a	13.4	3710	1300
CF <sub>4</sub> (PFC)	50,000	4880	6630
Sulfur hexafluoride (SF <sub>6</sub> )	3200	17,500	23,500
Nitrogen trifluoride (NF <sub>3</sub> )	500	12,800	16,100

many other GHG constituents, please refer to the Chap. 8 of the IPCC Fifth Assessment Report (2013).

The greenhouse gas with the largest atmospheric concentration, and the largest volumetric rate of anthropogenic emission, by far, is carbon dioxide, a byproduct of the large-scale use of fossil fuels as an energy source for electricity generation, transportation, and industrial processes. Electricity generation is the largest contributor to CO<sub>2</sub> emissions, which accounted for 37% of CO<sub>2</sub> emissions from 1990 to 2014. Transportation is the second largest contributor to CO<sub>2</sub> emissions, which accounted for 31% of CO<sub>2</sub> emissions from 1990 to 2014 (U.S. Environmental Protection Agency, 2016). Among all GHGs, CO<sub>2</sub> is the largest contributor to global warming. The anthropogenic radiative forcing induced by CO<sub>2</sub> emissions in 2011 was 1.68 relative to a datum radiative forcing value of zero for the year 1750 (IPCC, 2013).

Another greenhouse gas that significantly contributes to global warming is methane (CH<sub>4</sub>). In the United States, 33% of CH<sub>4</sub> emissions came from natural gas and petroleum systems from 1990 to 2014, followed by enteric fermentation (22%), landfills (20%), coal mining (9%) and manure management (8%) (U.S. Environmental Protection Agency, 2016). CH<sub>4</sub> is the second largest contributor to global warming. The anthropogenic radiative forcing induced by CH<sub>4</sub> emissions in 2011 was 0.97 relative to a datum radiative forcing value of zero for the year 1750 (IPCC, 2013).

Developing and deploying technology and policy measures to reduce the rate at which these greenhouse gases are being emitted into the atmosphere as a result of human activity and, in some cases, to reduce the concentration of these gases in the atmosphere is the focus of international efforts. These technologies include the capture of anthropogenic CO<sub>2</sub> from large industrial point sources and transportation of that CO<sub>2</sub> to locations where it can be stored away from the atmosphere or beneficially reused.

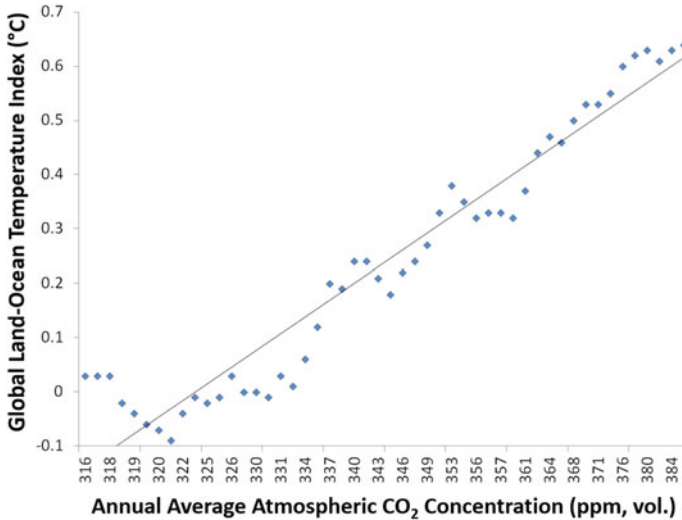
## 2.2 Climate Change

Anthropogenic emissions of CO<sub>2</sub> are recognized as the predominant contributor to the observed rise in atmospheric concentrations of CO<sub>2</sub>. Atmospheric CO<sub>2</sub> concentration increase was observed after the Industrial Revolution, and the increase was accelerated after 1900. From 1800 to 1900, atmospheric CO<sub>2</sub> concentration increased from 280 ppmv to 290 ppmv. Over the next century from 1900 to 2000, atmospheric CO<sub>2</sub> concentration increased from 290 to 370 ppmv (Halmann & Steinberg, 1999; Keeling et al., 2009).

Detailed consideration of the role that GHGs and anthropogenic emissions of GHGs play in shifting the radiative balance, mean temperature, and related issues of weather patterns, distribution of water in the atmosphere and Earth's surface, and other issues potentially impactful to global stasis, is beyond the focus of this summary.

Corresponding to that trend of increasing CO<sub>2</sub> concentration, the IPCC reported that the Earth's average global surface temperature increased  $0.6 \pm 0.2$  °C, over the twentieth century (IPCC, 2007). A plot of indexed mean land-ocean temperature (an average temperature at the Earth's surface derived from surface air temperature measurements and satellite data-derived estimates of sea surface temperature in regions without sea ice) as reported by the NASA Goddard Institute for Space Studies (GISTEMP Team, 2016; Hansen, Ruedy, Sato, & Lo, 2010) as a function of the atmospheric concentration of CO<sub>2</sub> between 1959 and 2008 (Keeling, Piper, Bollenbacher, & Walker, 2009) shows a strong correlation between CO<sub>2</sub> concentration change and land-ocean temperature change (Fig. 2.2).

Concurrent with observations of the rise of the Earth's average global surface temperature, other related significant effects have been observed with important implications for the health of our planet. A global rise in sea level of 0.1–0.2 m was observed through the twentieth century—with this rise primarily attributed to a decrease in snow and ice cover over the northern hemisphere (NASA, 2016c). Also, as atmospheric concentrations of CO<sub>2</sub> rise, the amount of CO<sub>2</sub> that is absorbed into surface water bodies at the atmosphere/water interface also increase. While this absorption does remove significant amounts of CO<sub>2</sub> from the atmosphere, the dissolution of this gas causes the acidity of that water to increase. Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units, which represents approximately a 30% increase in acidity. Future predictions indicate that the oceans will continue to absorb CO<sub>2</sub> and become even more acidic. Estimates of future carbon dioxide levels, based on business-as-usual emission scenarios, indicate that the surface waters of the ocean could be nearly



**Fig. 2.2** Plot of the mean land-ocean temperature index as reported by the NASA Goddard Institute for Space Studies (GISTEMP Team, 2016; Hansen et al., 2010) as a function of the atmospheric concentration of CO<sub>2</sub> through time, derived from in situ air samples collected at the Mona Loa, Hawaii, USA (Keeling et al., 2009) for years of 1959 through 2008

150% more acidic by the end of this century, resulting in a pH that the oceans have not experienced for more than 20 million years (National Oceanic & Atmospheric Administration, 2016a).

In 2010, countries agreed in Cancún, Mexico, that global temperature rise above preindustrial levels should not be allowed to exceed 2 °C and made pledges to limit their emissions by 2020. However, an analysis by the Intergovernmental Panel on Climate Change (IPCC) published in 2013 concluded that measures called out by that agreement will be insufficient to address this challenge and will likely lead to the warming of more than 3 °C by the end of the twenty-first century.

## 2.3 Carbon Cycle

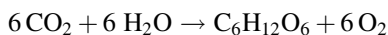
The carbon cycle is the biogeochemical cycle by which carbon is exchanged among atmosphere, land, and oceans of the Earth (Wigley & Schimel, 2005). Exchange of carbon between atmosphere and land is mainly achieved by uptake/release of CO<sub>2</sub> by the terrestrial biosphere, and exchange of carbon between atmosphere and oceans is mainly achieved by dissolution of CO<sub>2</sub> into the oceans and uptake/release of CO<sub>2</sub> by marine biota. The carbon cycle is important because carbon is the fundamental building block of life on Earth and an important component of many chemical processes (National Oceanic & Atmospheric Administration, 2015). Moreover, as described previously, CO<sub>2</sub> in the atmosphere acts like a blanket over the planet by absorbing infrared radiation that would otherwise radiate excess heat away from the planet. In short, maintaining the balance of the carbon cycle is crucial to sustain the stability of the Earth's ecosystems.

### 2.3.1 *Exchange of Carbon Between Atmosphere and Land*

Carbon in the atmosphere mainly exists in two forms: carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>). Methane exists in much lower concentrations than CO<sub>2</sub> in the atmosphere, and methane is less stable than CO<sub>2</sub> in the atmosphere. Therefore, CO<sub>2</sub> plays a major role in the exchange of carbon between atmosphere and land. Carbon in the atmosphere represents only a small fraction of total carbon on Earth (720 gigatonnes, where a tonne or “metric ton” is equivalent to 1000 kilograms, or approximately 1.1 short tons, and a gigatonne refers to billions of tonnes) of carbon in the atmosphere, representing 1.9% of total carbon in the oceans and less than 0.001% of total carbon in the lithosphere (Falkowski et al., 2000). The atmosphere, however, acts as a “nexus” with respect to the carbon cycle, and the other carbon reservoirs interact with each other primarily by trading carbon through the atmosphere (Archer, 2010; Archer, Buffett, & Brovkin, 2009). The terrestrial biosphere takes carbon from the atmosphere mainly through photosynthesis. Photosynthesis is the process by which plants synthesize organic compounds from carbon dioxide

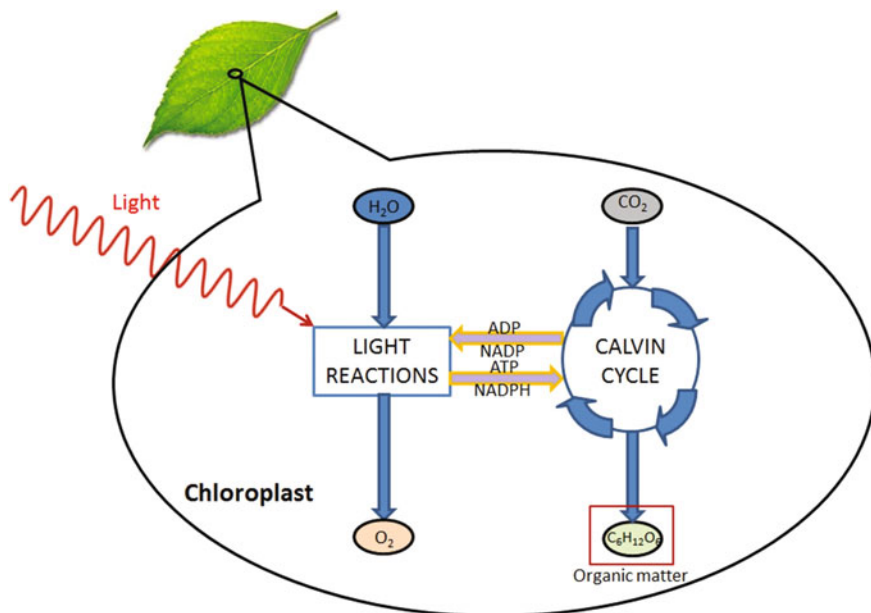
and other inorganic raw materials in the presence of sunlight (Hall & Rao, 1999). Plants convert about  $1.20 \times 10^{17}$  g carbon per year into hydrocarbons (gross primary production, GPP) via photosynthesis (Ciais et al., 1997).

Photosynthesis occurs in chloroplasts in plant cells. Photosynthesis can be divided into two steps: (1) light reactions, which take energy from light to produce adenosine triphosphate (ATP) for reactions in the next step; (2) Calvin Cycle (dark reactions) which is composed of a series of reactions to convert  $\text{CO}_2$  into organics. ATP and protons (supplied by nicotinamide adenine dinucleotide phosphate—NADPH) from light reactions are needed for Calvin Cycle reactions. Specifically, ATP provides energy for Calvin Cycle reactions to reduce  $\text{CO}_2$  and convert  $\text{CO}_2$  into organic matter rich in chemical energy, and NADPH provides  $\text{H}^+$  that will combine with  $\text{CO}_2$  to produce H-containing organic matter. Net photosynthesis reaction can be simply written as:



A diagram of simplified photosynthesis processes can be found in Fig. 2.3.

Based on the mechanism of  $\text{CO}_2$  fixation via Calvin Cycle, plants can be divided into “C3” plants and “C4” plants. C3 plants have the first measurable  $\text{CO}_2$  fixation product in the Calvin Cycle as an organic compound with three carbons [e.g., phosphoglycerate ( $\text{C}_3\text{H}_7\text{O}_7\text{P}$ )]; and C4 plants have the first measurable  $\text{CO}_2$  fixation product in the Calvin Cycle as an organic compound with four carbons (e.g.,

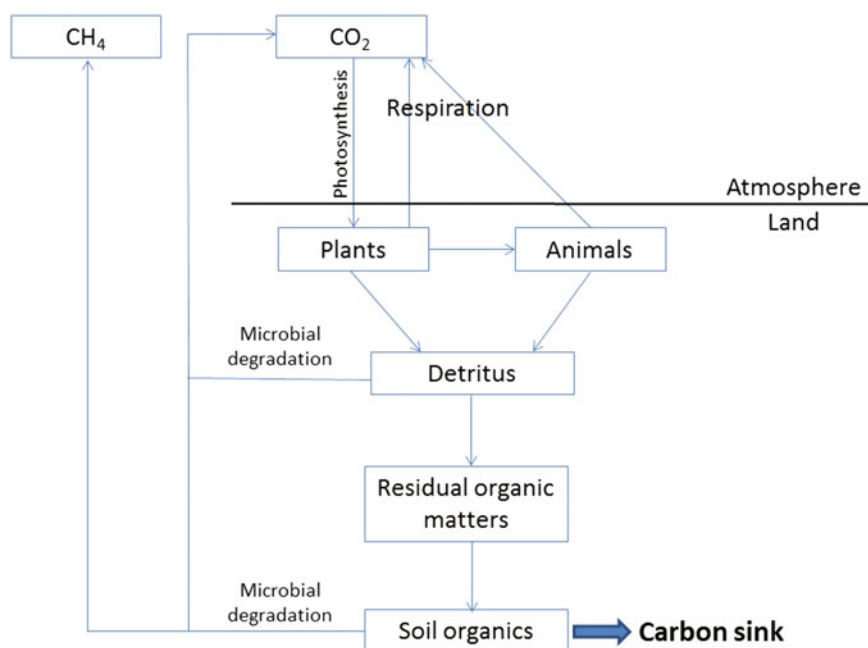


**Fig. 2.3** Simplified photosynthesis processes (modified from Hall & Rao, 1999)



malate, aspartate, and oxaloacetate) (Mohr & Schopfer, 1995). Compared with C3 plants, C4 plants possess the ability to greatly reduce photorespiration, and have a higher rate of net photosynthesis and greater light saturation (Mohr & Schopfer, 1995). For more thorough treatment of these complex reactions, the interested reader is directed to textbooks on biology and biochemistry.

A large portion of the organic matter stored via photosynthesis is returned to the atmosphere via numerous respiratory pathways (Falkowski et al., 2000): (1) autotrophic respiration by the plants themselves; (2) heterotrophic respiration, in which plant-derived organic matter is consumed and oxidized by animals and soil microbes; (3) oxidation of organic matter by combustion (e.g., use of biomass as fuel, or forest fire). A small amount of carbon accumulates in the soil in the process of microbial decomposition, becoming organics in the soil. If that accumulated organic carbon remains stable, the terrestrial biosphere globally would represent a carbon sink. Based on the use of atmospheric  $O_2$  and  $CO_2$ , and the isotopic signature of atmospheric  $CO_2$ , the net (per annum) flux of  $CO_2$  from the atmosphere to the soil was estimated to be  $0.2 \pm 0.7 \times 10^{15} \text{ g C a}^{-1}$  during the 1980s and  $1.4 \pm 0.7 \times 10^{15} \text{ g C a}^{-1}$  during the 1990s (Prentice et al., 2001). A diagram showing the movement of carbon between atmosphere and land can be found in Fig. 2.4.



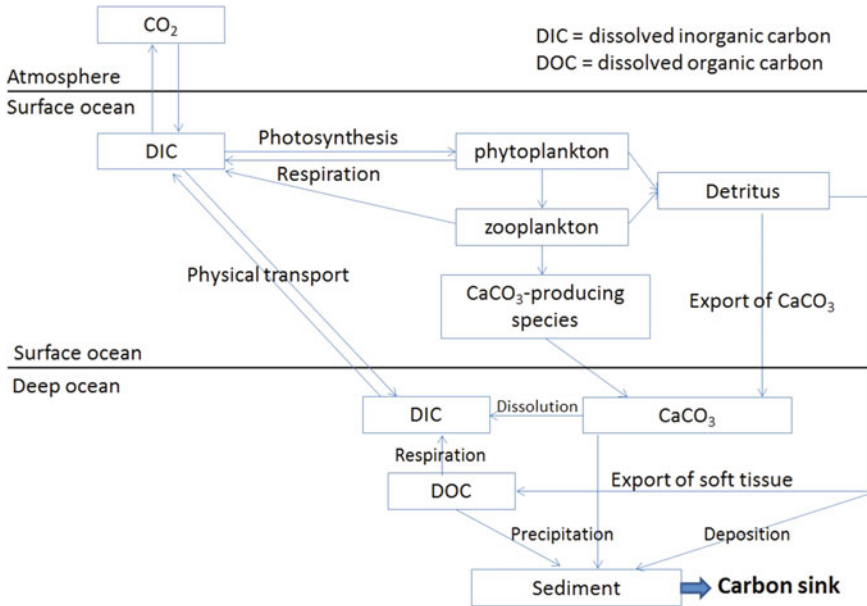
**Fig. 2.4** Carbon exchange between atmosphere and land, and carbon cycle in the land (modified from Marini, 2007)

### ***2.3.2 Movement of Carbon Between Atmosphere and Oceans***

The oceans play a crucial role in the climate system by redistributing heat and carbon across the planet through a complex interplay of physical, chemical, and biological processes (Williams & Follows, 2011; Burwicz, Rupke, & Wallmann, 2011). The total amount of carbon contained in the oceans is 63 times the carbon contained in the atmosphere, with the large carbon content of the oceans mainly as dissolved  $\text{CO}_2$  in the oceans. Due to the particular chemistry of seawater, more than 99% of the dissolved  $\text{CO}_2$  in the oceans is in the form of bicarbonate and carbonate ions (hereafter referred to collectively as dissolved inorganic carbon, or DIC). Physical transport of DIC-rich water from the surface to the deep ocean brings a large quantity of DIC to the deep ocean, and more DIC can be held in deep oceans compared with surface oceans, due to the large volume of water, and the high pressure and low-temperature conditions in the deep ocean environment (Williams & Follows, 2011). A certain portion of DIC is taken up by phytoplankton via photosynthesis, which lowers the partial pressure of  $\text{CO}_2$  in the upper ocean and thereby promotes the absorption of additional  $\text{CO}_2$  from the atmosphere (Falkowski et al., 2000).

$\text{CO}_2$  dissolved in the ocean can directly react with  $\text{Ca}^{2+}$  in the ocean to form  $\text{CaCO}_3$ , and biologically-mediated processes in the ocean (e.g., uptake of DIC by phytoplankton, zooplankton, shells, and corals) can also catalyze the production of  $\text{CaCO}_3$ .  $\text{CaCO}_3$  contained within the detritus of marine life contributes to sediment, effectively taking significant amounts of carbon away from the carbon cycle. Export of soft tissue from detritus of phytoplankton and zooplankton produces dissolved organic carbon (DOC), and some DOC forms organic sediment, which takes additional carbon away from the active carbon cycle. Additionally, a significant portion of this detritus is deposited with inorganic sediment and deeply buried—effectively removing it from ocean carbon cycle on a long-term basis. Therefore, the oceans and ocean sediments globally represent a carbon sink. A diagram showing the movement of carbon between the atmosphere and the oceans can be found in Fig. 2.5.

Oceanic absorption of  $\text{CO}_2$  is one of the most important forms of carbon sequestration—partially offsetting the human-caused rise of atmospheric  $\text{CO}_2$  concentration. However, the capacity of the oceanic carbonate system to uptake  $\text{CO}_2$  is limited. Firstly, the  $\text{CO}_2$  uptake capacity of the ocean is dependent on the addition of cations from weathering of rocks, which is a relatively slow process. Given several orders of magnitude greater anthropogenic  $\text{CO}_2$  emissions than the supply of mineral cations, the ability of the surface oceans to absorb  $\text{CO}_2$  will decrease eventually (Falkowski et al., 2000).  $\text{CO}_2$  absorption also makes water more acidic, which affects ocean biosystems. The projected rate of increasing oceanic acidity could inhibit the biogeochemical processes associated with conversion of  $\text{CO}_2$  to calcium carbonates in the ocean, thus decreasing the ocean's capacity to absorb  $\text{CO}_2$  (Kleypas et al., 1999; Langdon et al., 2000). The transfer of



**Fig. 2.5** Carbon exchange between atmosphere and the ocean, and carbon cycle in the ocean (modified from Marini, 2007)

organic matter from the land to the oceans via fluvial systems also brings carbon to the ocean, which also impairs the ocean's ability to absorb atmospheric  $\text{CO}_2$ . In summary, it is not sufficient to rely on the ocean alone to counter  $\text{CO}_2$  concentration increase induced by anthropogenic  $\text{CO}_2$  emissions.

## 2.4 Impact of Human Activities on Carbon Cycle

Over the past 200 years, human activities have altered the global carbon cycle significantly. It is crucial to understand the consequences of human activities on the global carbon cycle and to find a clear path to mitigate global carbon-cycle alteration caused by human activities.

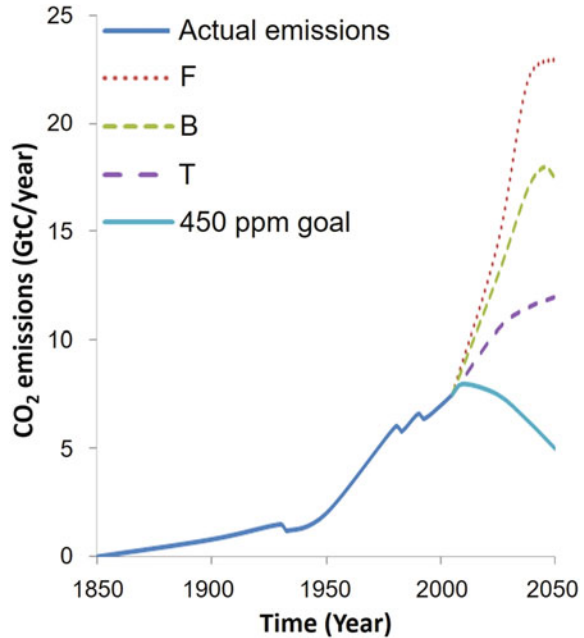
Human activities have released half a trillion ton of carbon to the atmosphere in the form of  $\text{CO}_2$  since the beginning of the Industrial Revolution (Richardson, Steffen, & Liverman, 2011). These emissions have led to an increase of about 45% in atmospheric  $\text{CO}_2$  from 280 ppm in 1750–387 ppm in 2009 and 407 ppm in 2016 (National Oceanic & Atmospheric Administration, 2016b). Major contributors to  $\text{CO}_2$  concentration increase includes (Sabine et al., 2004; Field & Raupach, 2004; U.S. Environmental Protection Agency, 2015):

- Carbon emissions from electric power sector. The electric power sector accounted for 32% of U.S. total greenhouse gas emissions in 2012. Greenhouse gas emissions from electricity have increased by about 11% since 1990 as electricity demand has grown and fossil fuels have remained as the dominant source for electricity generation (U.S. Environmental Protection Agency, 2015). Fossil fuel-fired power plants are the largest source of U.S. CO<sub>2</sub> emissions.
- Cement production, which contributes about 6% of the global anthropogenic CO<sub>2</sub> budget. About 50% of CO<sub>2</sub> emissions in cement production sector come from calcination of limestone to produce lime and CO<sub>2</sub>, and the remaining emissions are from the energy required to fire the kiln.
- Steel production, which contributes 4–7% of global anthropogenic CO<sub>2</sub> emissions. CO<sub>2</sub> is generated from two processes: energy for steel production by burning of fuel and the use of reducing agents for steel production from iron ore, the most readily available reducing agent being coal (Birar, 2010).
- Transportation, which accounted for 28% of U.S. total greenhouse gas emissions in 2012 (U.S. Environmental Protection Agency, 2015).
- Underground coal fires, some of which are induced by mining activities, are an additional, as-yet unaccounted for, source of carbon to the atmosphere—potentially, as large a contributor as cement production.
- Carbon emissions from land use and land management (deforestation, the expansion of crop land and pasture, infrastructure extension and other effects driven by market growth, and demographic pressures). Prior to 1910, cumulative carbon emissions attributed to land use and land management were larger than cumulative carbon emissions from fossil fuel combustion. Land use and land management still play an important role in carbon emissions, though the contribution as a fraction of total emissions is smaller.

Raupach et al. (2007) have summarized possible global CO<sub>2</sub> emission scenarios based on the actual CO<sub>2</sub> emission data from 1850 to 2005 and various actions that can be taken to mitigate anthropogenic CO<sub>2</sub> emissions (Fig. 2.6). Under the worst-case scenario (F, intensive dependence on fossil fuels) annual global CO<sub>2</sub> emissions reach 23 gigatonnes of carbon per year (GtC/year) in 2050, which is 3.1 times of annual CO<sub>2</sub> emissions in 2005. Under the best-case scenario (T, alternative technologies largely replace fossil fuels) annual CO<sub>2</sub> emissions reach 12 GtC/year in 2050, which is 1.6 times of annual CO<sub>2</sub> emissions in 2005. However, even under the best-case scenario, the annual CO<sub>2</sub> emissions are still more than the CO<sub>2</sub> emission cap considered necessary to reach the International Energy Agency (IEA) CO<sub>2</sub> concentration stabilization goal of 450 ppm by 2050 (International Energy Agency, 2015). Therefore, switching energy source from fossil fuel to alternative energy is not sufficient to achieve the CO<sub>2</sub> reduction goal, and other approaches (e.g., increasing end-use energy efficiency, implementing carbon capture, and sequestration (CCS) technology need to be taken together with energy source switching (Global CCS Institute, 2014).

It is widely accepted that the global carbon cycle will be further disturbed due to a continuous increase in atmospheric CO<sub>2</sub> concentration given the current rate of

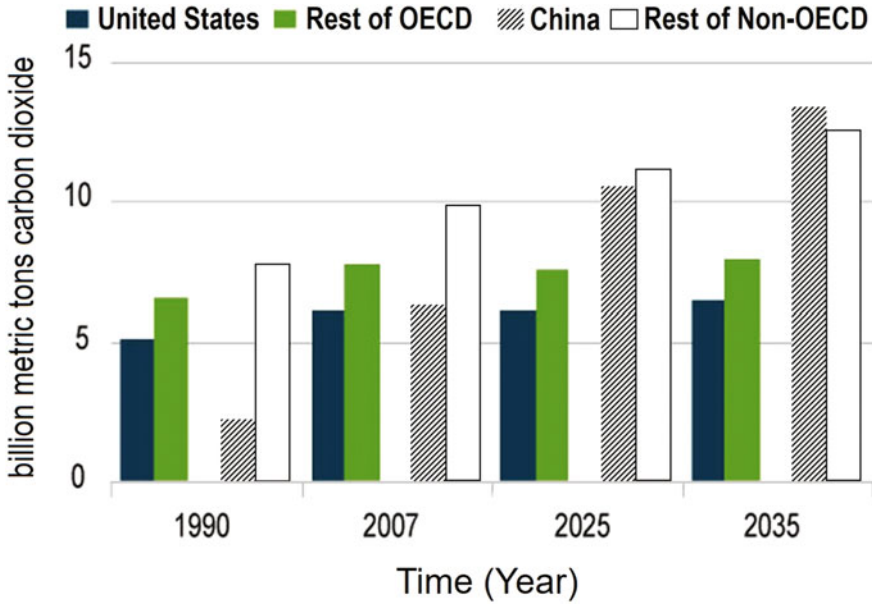
**Fig. 2.6** Comparison between different projected CO<sub>2</sub> emission scenarios (Raupach et al., 2007). Projected scenarios: *F* (intensive dependence on fossil fuels), *B* (balanced energy supply between fossil fuels and alternatives), *T* (alternative technologies largely replace fossil fuels), and 450 ppm goal (CO<sub>2</sub> emission cap to keep atmospheric CO<sub>2</sub> concentration at or below 450 ppm by 2050). *Note:* Units are in terms of gigatonnes of carbon (not of CO<sub>2</sub>) per year (GtC/year).



anthropogenic CO<sub>2</sub> emissions. Broecker et al. showed that the oceans only took up to 35% of the CO<sub>2</sub> released from fossil-fuel burning during the period from 1958 to 1980 (Broecker, Peteet, & Rind, 1985; Post et al., 1990). Falkowski et al. conclude that there is no “natural savior” to assimilate all the anthropogenic CO<sub>2</sub> in the twenty-first century. Their global carbon-cycle models suggest that the feedbacks between carbon and other biogeochemical and climatological processes will lead to weakened natural sink strengths in the foreseeable future (Falkowski et al., 2000). Anthropogenic CO<sub>2</sub> emissions will affect Earth’s biogeochemical cycles for hundreds of years to come (Joos et al., 1999).

### 2.4.1 CO<sub>2</sub> Emissions by Region

Since 1990, energy-related CO<sub>2</sub> emissions have grown slower in the mature economies of member countries of the Organization for Economic Cooperation and Development (OECD) as a group, than they have worldwide (OECD, 2015). In 1990, all OECD countries had a total CO<sub>2</sub> equivalent emission of 11.6 gigatonnes (where equivalent CO<sub>2</sub> emissions account for both direct CO<sub>2</sub> emissions and emissions of other greenhouse gases using GWP factors). In 2007, that value reached 13.7 gigatonnes, representing an 18% increase from 1990 to 2007. For non-OECD countries, emissions were 10 gigatonnes in 1990 and 16 gigatonnes in 2007, representing a 60% increase from 1990 to 2007 (Fig. 2.7). The United States



**Fig. 2.7** Demonstration of total CO<sub>2</sub> emissions by region (U.S. Energy Information Administration, 2011)

is the biggest contributor to CO<sub>2</sub> emissions among OECD countries, with an annual CO<sub>2</sub> emission of ~5 gigatonnes (CO<sub>2</sub> only, not CO<sub>2</sub> equivalent) in 1990 and ~6 gigatonnes in 2007 (Fig. 2.7). U.S. energy-related CO<sub>2</sub> emissions were projected to increase by an average of 0.2% per year from 2007 to 2035 (U.S. Energy Information Administration, 2011); and in other OECD countries they were projected to increase by an average of 0.08% per year from 2007 to 2035 (see Fig. 2.7). Among the non-OECD countries, China is the biggest contributor to CO<sub>2</sub> emissions, and China has been the biggest CO<sub>2</sub> emitter in the world since 2007 (Rosenthal, 2007). China's share of global energy-related CO<sub>2</sub> emissions is projected to grow from 21% in 2007 to 31% in 2035, and China will account for 56% of the projected increase in world emissions over the period. India accounts for the second largest (7%) share of the projected increase (U.S. Energy Information Administration, 2011).

#### 2.4.2 CO<sub>2</sub> Emissions by End-Use Sector

Based on end-use sector, CO<sub>2</sub> emissions can be classified into residential emissions (CO<sub>2</sub> from direct fuel use in households and CO<sub>2</sub> emissions from purchased electricity for households), commercial emissions (CO<sub>2</sub> from direct fuel use in

buildings for commercial purpose and CO<sub>2</sub> emissions from purchased electricity for commercial activities), industrial emissions (CO<sub>2</sub> from direct fuel use in industrial activities and CO<sub>2</sub> emissions from purchased electricity for industrial activities) and transportation emissions (CO<sub>2</sub> emissions from mobile source combustion). In 2009, industrial emissions account for the largest share in total U.S. CO<sub>2</sub> emissions (2240 megatonnes (million metric tons) equivalent CO<sub>2</sub> or 34.1% of total U.S. equivalent CO<sub>2</sub> emissions), and residential emissions, commercial emissions and Transportation emissions account for 18.0, 19.6, and 28.3% of total equivalent CO<sub>2</sub> emissions in the U.S., respectively, (U.S. Energy Information Administration, 2011).

## 2.5 Actions to Mitigate CO<sub>2</sub> Emissions and Climate Change

To mitigate greenhouse gas emissions, the U.S. has taken a series of actions at the federal level. The U.S. Environmental Protection Agency (EPA) finalized Rules for Mandatory Reporting of Greenhouse Gases by 31 industries and emissions sources in October 2009. Final rules and methods were proposed in April 2010 for a second group of industries: five industries that emit fluorinated greenhouse gases; oil and natural gas systems; and facilities that inject and store CO<sub>2</sub> underground for the purposes of geologic sequestration or enhanced oil and gas recovery (U.S. Energy Information Administration, 2011). Due to significant emissions of greenhouse gases and other pollutants from light-duty vehicles, the EPA has classified light-duty vehicles as a danger to public health and welfare. In April 2010, the EPA and the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) jointly published Corporate Average Fuel Economy (CAFE) and GHG emissions standards to regulate emissions from light-duty vehicles of model years 2012–2016. Regarding R&D activities to mitigate CO<sub>2</sub> emissions, the U.S. Department of Energy (DOE) has invested significantly in developing and demonstrating technologies to capture CO<sub>2</sub> from large anthropogenic sources and store it safely and effectively in geologic formations—enabling continued use of our abundant fossil energy resources while reducing emissions from their use (U.S. Department of Energy, 2015).

Climate change is a global challenge and requires a global solution. An effective global strategy to mitigate CO<sub>2</sub> emissions requires commitments and actions by all the world's major economies (Center for Climate and Energy Solutions, 2015). A major step that reflects a global effort to mitigate CO<sub>2</sub> emissions is the Kyoto Protocol, which was agreed upon in 1997 by countries participating in the United Nations Framework Convention on Climate Change (UNFCCC). Under the Kyoto Protocol's first commitment period (2008–2012) developed countries were charged with reducing their emissions by an average of 5% below 1990 levels by 2012. The 15 countries that were the EU Member States at the time that Kyoto Protocol was

agreed upon committed to an 8% cut (European Commission, 2015). A second commitment period of the Kyoto Protocol runs from 2013 until 2020, and the EU has committed to reduce its greenhouse gas emissions by 20% below 1990 levels by 2020 (European Commission, 2015).

On September 16th, 1987, the Montreal Protocol, an international treaty designed to protect the ozone layer by phasing out hydrofluorocarbons (HFCs) and other substances causing ozone depletion, was agreed upon. U.S., Canada, and Mexico released a proposal in 2009 to include a binding schedule for phasing down production and consumption of 20 HFCs. The proposal calls for developed countries to reduce their production and consumption of the 20 HFCs to 15% of a 2004–2006 average baseline by 2033, and for developing nations to meet the same level by 2043 (U.S. Energy Information Administration, 2011).

Other major developing economies, like China and India, have pledged to cut their carbon emissions. On November 11, 2014, the U.S. and China released a joint announcement on climate change and clean energy cooperation. In this announcement, the U.S. set a new target to cut net greenhouse gas emissions 26–28% below 2005 levels by 2025. At the same time, China announced targets to peak CO<sub>2</sub> emissions around 2030, and to increase the nonfossil fuel share of all energy to around 20% by 2030 (The White House, 2014). India filed its climate action plan at the U.N. Climate Secretariat in Germany on October 1, 2015. In this climate action plan, India would reduce carbon emissions relative to its GDP by 33–35% from 2005 levels by 2030. India also pledged that 40% of the country's electricity would come from non-fossil fuel-based sources, such as the wind and solar power, by 2030 (Plucinska, 2015).

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