# Chapter 1
# Climate Change: An Overview

**Mukhtar Ahmed, Shakeel Ahmad, and Ahmed M. S. Kheir**

**Abstract** Climate variability and change is the main concern for scientific communities since the past decades. This chapter gives an overview about the basics of climate change. It firstly provides detail information about climate change and its responsible factors. Techniques that have been used to quantify climate change were discussed. It includes the application of general circulation or global climate models (GCMs) and use of borehole temperature, cores from deep accumulations of ice, flora and fauna records, sea records and sediment layer analysis. Furthermore, a historical milestone in the science of climate change was given. The Coupled Model Intercomparison Project (CMIP) and its application were discussed in detail. Similarly, the relationship between radiative forcing (RF) and climate change showed that the earth's radiative balance is changed. This was mainly because of the climate change drivers that resulted to the change in air temperature. True picture about climate change was further confirmed by using different climate change drivers coming from different sources. Data showed that climate change is a real phenomenon causing real threat to the human race on planet earth. Meanwhile, the applications of strategic management tools that include RCP (representative concentration pathway), SSP (shared socio-economic pathways) and SPA (shared climate policy assumptions) were presented as they give clear directions in the field of climate change research. Furthermore, they give directions to do climate impact assessments and design climate and socio-economic adaptation and mitigation options. Finally,

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the responses of the different systems to climatic variables were given as indicators of climate change.

**Keywords** Climate change · Radiative forcing · Scenario analysis · Climate change drivers · Indicators

## 1.1 What Is Climate Change?

Climate variability and change is the centre of work in most of the research activities across the globe in the recent decade. Climate variability is the fluctuations in the climatic parameters from its long-term mean. Climate change is the significant variation in weather conditions for the longer period. It is the change in the climatic variables on decadal timescale, i.e. conditions becoming wetter, drier or warmer over several decades. It is different from the natural weather variability as it deals with only shorter time or seasonal climate variability. Climate change is affecting every living being, and it is displaying itself in myriad ways. It can be seen across the globe in the form of extreme events of raging storms, record floods and deadly heat. Different natural and anthropogenic factors are responsible for climate variability and change.

Several techniques have been used to collect data that can be applied to understand the past and future climate. These include borehole temperature, cores from deep accumulations of ice, records of flora and fauna, sediment layer analysis and sea records. GCMs are used extensively to confirm past data and make future projections. GCMs are mathematical models that can model the response of global climate to the increasing greenhouse gas (GHG) emission (IPCC 2013). These models can represent the earth in a few latitudinal bands and can be divided into atmospheric GCMs (AGCMs), the ocean GCMs (OGCMs) and both atmospheric and ocean GCMs (AOGCMs). The basic structure of GCM is shown in Fig. 1.1. The history of these models is closely connected with computing power. Thus, these models are in continuous state of development and evolution so that they can give accurate prediction. Details of the commonly used GCMs have been given in Table 1.1, which are in the process of improvement since their origin as they have shortcomings in computing power due to incompetence to solve crucial climate mechanisms. Similarly, low-resolution models are not capable to portray phenomena at local and smaller scales while its downscaling to higher-resolution propagate error (Lupo et al. 2013). One example of application of GCM has been shown in Fig. 1.2. It shows simulation of global average annual surface temperature changes (°C) from 1860 to 2005 by the geophysical fluid dynamics laboratory coupled model (GFDL-CM3) under four ‘representative concentration pathway’ (RCP) scenarios. Another category of models includes earth system model (ESM). It can predict $CO_2$ in atmosphere by using carbon cycle approach. It also has also biological and chemical models that can simulate aerosols, trace gases and cloud condensation nuclei (Hartmann 2016). In most of the earlier GCM simulations, atmosphere and ocean data was generated by fixing different climate drivers. These drivers include

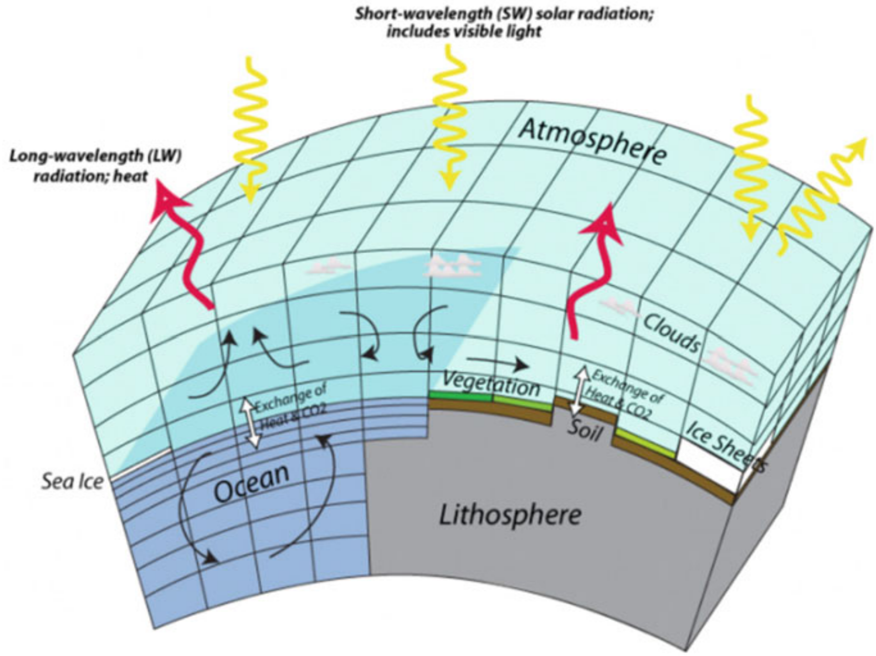



**Fig. 1.1** Schematic representation of general circulation model (GCM). (Source: Penn State University)

wind stress, air temperature, sea surface temperature (SST), precipitation and radiative forcing. They all determined the fluxes of heat, exchange of moisture and momentum between the ocean and the atmosphere. However, coupled atmosphere-ocean climate models have shown deficiencies that could be solved by including ESM that consider land surface processes. The components of ESM are shown in Fig. 1.3. It includes physical climate system, biosphere and human influences. ESM can predict vegetation changes, atmospheric composition, biogeochemical cycling, elevated $CO_2$ effect on leaf stomata, transpiration losses, soil moisture and temperature. Diagrammatic representation of the physical components of GCM has been shown in Fig. 1.4. It has three physical components of the climate system (atmosphere, ocean and land). The frozen places of planet earth are called cryosphere, and it has a significant impact on climate as it has high albedo/reflectivity, acts as insulator, requires latent heat of fusion and absorbs GHG (e.g. permafrost contains 1400–1600 billion tonnes of carbon). Under 1.5 °C–2.0 °C climate warming scenario, it has been reported that the melting of permafrost will produce 150–200 and 220–300 Gt $CO_2$-eq emissions, respectively (Pörtner et al. 2019). The atmosphere component of GCMs mainly involved weather forecasting through numerical weather prediction systems that can forecast weather in advance for short intervals. However, for longer forecasts, different climatology-based models have been used. In numerical modelling the components of systems (atmosphere or ocean) are

**Table 1.1** List of the commonly used GCMs with resolution

| S. No. | GCMs | Resolution | |
|---|---|---|---|
| | | Latitude | Longitude |
| 1. | ACCESS-CM (Australian Community Climate and Earth System Simulator Coupled Model) (ACCESS1.0 & 1.3) | 1.25 | 1.875 |
| 2. | BCC_CSM1.1 (Beijing Climate Centre Climate System Model) | 2.7906 | 2.8125 |
| 3. | BNU-ESM (Beijing Normal University Earth System Model) | 2.7906 | 2.8125 |
| 4. | CCSM (Community Climate System Model) | 0.9424 | 1.25 |
| 5. | CESM (Community Earth System Model) | 0.9424 | 1.25 |
| 6. | CESM1(BGC) (Community Earth System Model (CESM1) carbon cycle) | 0.9424 | 1.25 |
| 7. | CESM1(CAM5) (Community Earth System Model version 1 (Community Atmospheric Model; CAM)) | 0.9424 | 1.25 |
| 8. | CESM1(FASTCHEM) (Community Earth System Model version 1 (CAM and Chemistry Model)) | 0.9424 | 1.25 |
| 9. | CESM1(WACCM) (NCAR Community Earth System Model (Whole Atmosphere Community Climate Model)) | 1.8848 | 2.5 |
| 10. | CFSv2–2011(National Centers for Environmental Prediction (NCEP) Climate Forecast System Version 2) | 1 | 1 |
| 11. | CMCC-CESM (Centro Euro-Mediterraneo per I Cambiamenti Climatici-Earth System Model) | 3.4431 | 3.75 |
| 12. | CMCC-CM (Centro Euro-Mediterraneo per I Cambiamenti Climatici-Climate Model) | 0.7484 | 0.75 |
| 13. | CMCC-CMS (Centro Euro-Mediterraneo per I Cambiamenti Climatici-Climate Model with a resolved stratosphere) | 3.7111 | 3.75 |
| 14. | CNRM-CM5 (Centre National de Recherches Météorologiques-Coupled Model Intercomparison Project) | 1.4008 | 1.40625 |
| 15. | CSIRO-Mk3.6.0 (Centre of Excellence and Commonwealth Scientific and Industrial Research Organization) | 1.8653 | 1.875 |
| 16. | CSIRO Mk3L (a computationally efficient coupled atmosphere-sea ice-ocean general circulation model) | 3.1857 | 5.625 |
| 17. | CanAM4 (Canadian Fourth Generation Atmospheric Global Climate Model) | 2.7906 | 2.8125 |
| 18. | CanCM4 (Canadian Fourth Generation Coupled Global Climate Model) | 2.7906 | 2.8125 |
| 19. | CanESM2 (Canadian Second Generation Earth System Model) | 2.7906 | 2.8125 |
| 20. | EC-EARTH (European Earth System Model) | 1.1215 | 1.125 |
| 21. | FGOALS-g2 (Flexible Global Ocean-Atmosphere-Land System Model: Grid-point Version 2) | 2.7906 | 2.8125 |
| 22. | FGOALS-gl (Flexible Global Ocean-Atmosphere-Land-Sea-ice) | 4.1026 | 5 |
| 23. | GFDL-CM3 (Geophysical Fluid Dynamics Laboratory-Coupled Model 3) | 2 | 2.5 |
| 24. | GISS-E2_R (Goddard Institute for Space Studies, USA) | 2 | 2.5 |
| 25. | HadGEM2 (Hadley Centre Global Environment Model version 2/UK) | 1.25 | 1.875 |
| 26. | MIROC5 (Model for Interdisciplinary Research On Climate/Japan) | 2.7906 | 2.8125 |
| 27. | MPI-ESM-MR (The Max Planck Institute for Meteorology-Earth System Model) | 1.8653 | 1.875 |
| 28. | MRI-CGCM3 (Meteorological Research Institute Coupled Global Climate Model Version Three, Japan) | 1.12148 | 1.125 |

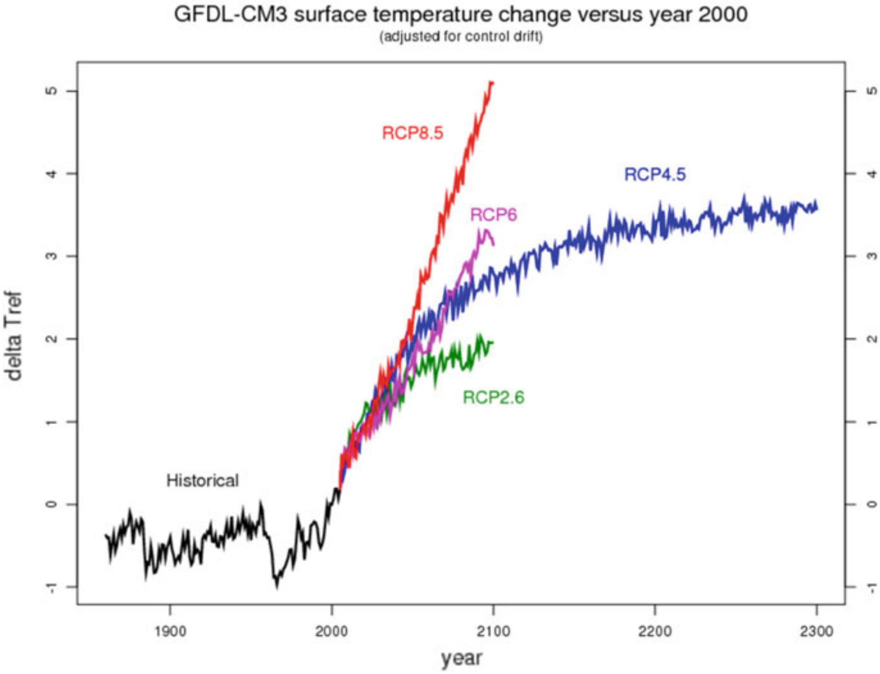



**Fig. 1.2** Simulation of changes in surface temperature by GFDL-CM3

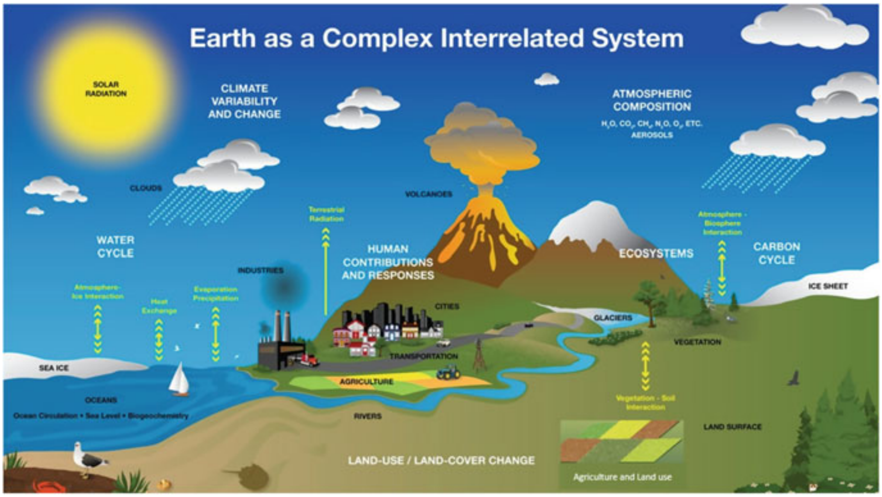



**Fig. 1.3** Earth as a complex interrelated system. (Source: NASA)

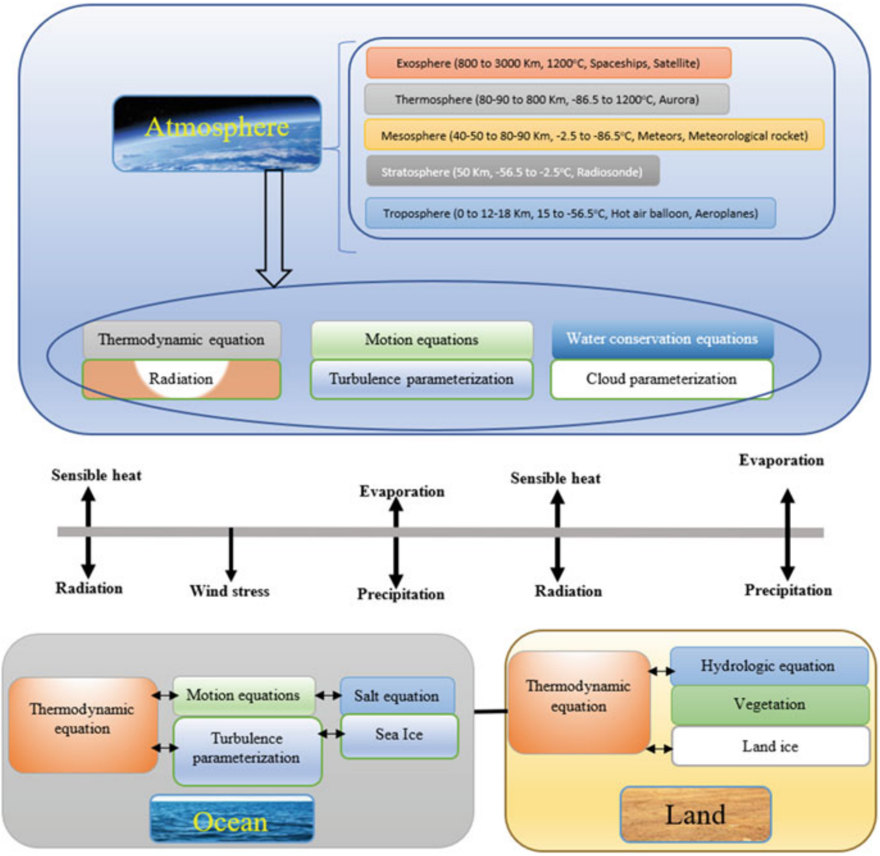



**Fig. 1.4** Physical components (atmosphere, ocean and land) of global climate model

divided into spatial grid work with further application of physics equations. The land component of GCM considers surface heat balance and moisture equation as well as model for snow cover. In the case of the ocean component of GCM, the motion equations explaining the general circulation of the ocean were considered. Recent accelerated work in climate change science resulted to the improvement of GCMs. This includes incorporation of physical processes in GCMs that can accurately simulate different phenomena at ocean-atmosphere and land scale (Fig. 1.5). Hence, GCMs could be used to accurately detect climate change causes, future predictions and matching of past climate data (Bhattacharya 2019). Different causes or drivers of climate are called climate forcings. These include alterations in solar radiation, changes in the earth's orbits and albedo/reflectivity of the continents and changes in GHG concentrations.

The Intergovernmental Panel on Climate Change (IPCC) published its first assessment report (FAR) in 1990, and nobody accepted at that time that climate change will be a real issue in the future. The IPCC is the leading body that provides

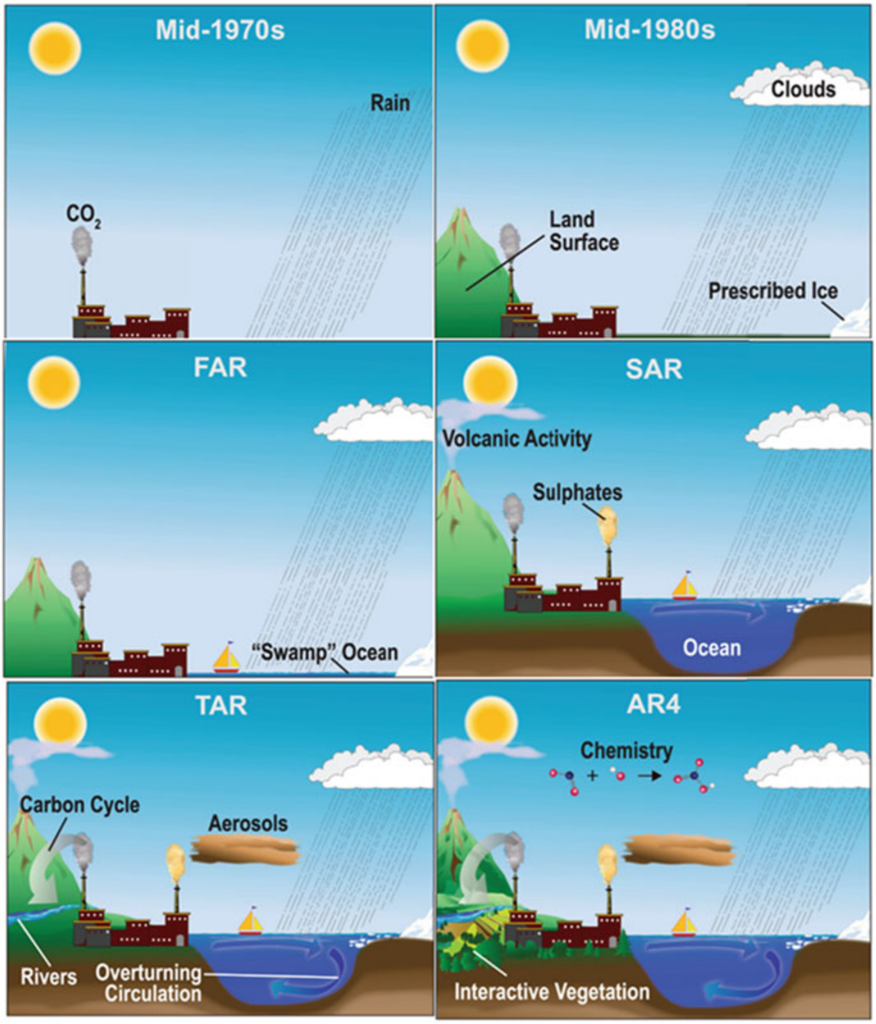



**Fig. 1.5** Pictorial description in the climate model complexity over the last few decades. (Source: Le Treut 2007)

true scientific picture about climate change. It also illustrates the potential socio-economic and environmental consequences across the globe. In the 2007 IPCC report, it has been elaborated that significant climate changes are going to happen, which will be mainly due to higher GHGs (Solomon 2007). Higher build-up of GHGs in the environment leads to global warming. Thus, climate change is a broader term that could be due to global warming resulting to the changes in rainfall and ocean acidification. The different important terms that the reader should know to understand the phenomenon of climate change include the following: abatement (decreased greenhouse gas emission); adaptation (adjustment/shifting); adaptability (adjustment ability); adaptive capacity (system ability to adjust to climate change); aerosols; afforestation; agriculture, forestry and other land use (AFOLU); albedo; black carbon; biogeochemical cycle; $CO_2$ equivalent (scale to compare the emissions from GHGs based upon their GWP (global warming potential)); $CO_2$ fertilization; carbon footprint; carbon sequestration; Conference of the Parties (COP); chlorofluorocarbons; El Niño-Southern Oscillation (ENSO); enteric fermentation; greenhouse gases; global warming; GWP (total energy a GHG can absorb per 100 years); greenhouse effect; nitrogen oxides (NOX); mitigation; parameterization; risk; risk assessment; uncertainty; validation; and vulnerability.

Climate change importance was already pointed by the Swedish scientist Svante Arrhenius in 1896. He has given the relationship between fossil fuels and increased amount of $CO_2$ in the air. Detailed historical milestones in the field of climate science had been given in Table 1.2.

**Table 1.2** History of milestones in the field of climate change

| Years | Milestones |
|---|---|
| 1820 | Fourier description about atmosphere contribution to planetary temperature |
| 1850 | Foote observed heat-trapping variability in $H_2O$ and $CO_2$ |
| 1859 | Tyndall described $CO_2$ blocking of infrared and elaborated radiative properties of gases |
| 1896 | Warming due to doubling of $CO_2$ by Arrhenius (father of climate change science) |
| 1928 | Rate of lunar heat loss was measured |
| 1932 | Calculation of 4 °C warming due to doubling of $CO_2$ by Hulburt |
| 1938 | Callendar confirms that warming is occurring |
| 1950–60 | $CO_2$ sources were identified, and models described the earth systems, carbon cycle and climate |
| 1960 | Charles keeling started Mauna Loa observatory |
| 1965 | Water vapour feedback was described |
| 1965 | Warnings by climate scientist to policymakers |
| 1967 | Syukuro Manabe and Richard Wetherald ($CO_2$ and temperature rise have perfect relationship) |
| 1967–68 | The first climate models by Syukuro Manabe and Richard Wetherald showing that global temperatures would increase by 2.0 °C (3.6 °F) if the $CO_2$ content of the atmosphere doubled |
| 1979 | Charney report (carbon dioxide and climate: A scientific assessment) doubling of $CO_2$ leads to 3 °C change in temperature with probable error of 1.5 °C |
| 1988 | Hansen predictions about warming |
| 1988 | Birth of the IPCC |
| 1992 | Establishment of the United Nations framework convention on climate change (UNFCCC) with the aim to combat climate change |
| 1995 | Conference of the parties 1 (COP1): The first conference of the parties to the UNFCCC (COP-1) met in Berlin |
| 1996 | COP2 in Geneva |
| 1997 | COP3, Kyoto protocol; GHG reduction treaty |
| 1998 | COP4-Buenos Aires-Argentina |

(continued)

**Table 1.2** (continued)

| Years | Milestones |
|---|---|
| 1999 | COP5-Bonn-Germany |
| 2000 | COP6-The Hague-Netherlands |
| 2001 | COP7-Marrakech-Morocco |
| 2002 | COP8-New Delhi-India-Technology transfer |
| 2003 | COP9-Milan-Italy-Adaptation Fund |
| 2004 | COP10, Buenos Aires, Argentina, climate change mitigation and adaptation |
| 2005 | COP11-Montreal-Canada (biggest intergovernmental conferences on climate change) |
| 2006 | COP12-Nairobi-Kenya |
| 2007 | COP13-Bali-Indonesia |
| 2008 | COP14-Poznań-Poland-Funding to poorest nations |
| 2009 | COP15-Copenhagen-Denmark (the Copenhagen accord) |
| 2010 | COP16-Cancún-Mexico (Green climate fund and climate technology centre/network) |
| 2011 | COP17-Durban-South Africa (Green Climate Fund (GCF)) |
| 2012 | COP18, Doha, Qatar, the Doha climate gateway |
| 2013 | COP19-Warsaw-Poland |
| 2014 | COP20-Lima-Peru |
| 2015 | COP21-Paris-France (Paris agreement) |
| 2016 | COP22-Marrakech-Morocco (water-related sustainability, reduction in GHG emissions and utilization of low-carbon energy sources) |
| 2017 | COP23-Bonn-Germany |
| 2018 | COP24-Katowice-Poland |
| 2020 | COP25-Madrid-Spain |
| 2021 | COP26-Glasgow-Scotland (Glasgow climate pact to keep 1.5oC alive and finalize the outstanding elements of the Paris agreement) |

## 1.2 Climate Change and Coupled Model Intercomparison Project (CMIP)

The CMIP (Coupled Model Intercomparison Project) was started by the Working Group on Coupled Modelling (WGCM) of the World Climate Research Programme (WCRP) in 1995 to better recognize the past, present and future climate changes that arise from different natural, unforced variability or due to changes in the radiative forcing. This includes historical assessments of model performance and quantifications of the causes of the spread in future climate projections. The results from CMIP have been used in the IPCC assessment reports. CMIP is the foundational element of climate science, and it includes coupled models of the earth's climate (Fig. 1.6). The CMIP's first two phases were simple. In CMIP1, 18 GCMs were involved in data collection. In CMIP2, simulation was conducted with assumptions of no inter-annual changes in radiative forcing (RF) and doubling of $CO_2$ concentration at a rate of 1% per year (Stouffer et al. 2017). CMIP3 resulted to the paradigm shift in the field of climate science. It has given the state-of-the-art climate change simulations that have

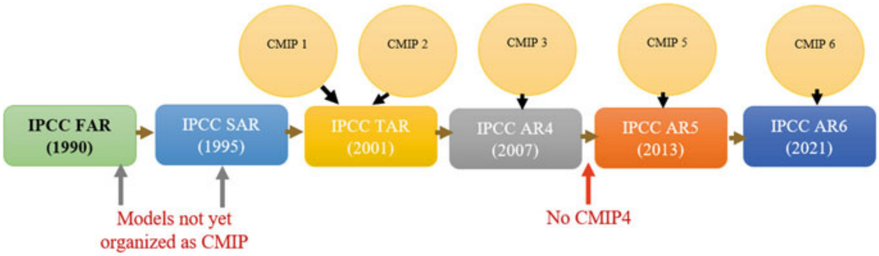



**Fig. 1.6** Historical description of Coupled Model Intercomparison Projects (CMIPs) and their contributions to IPCC assessment reports (ARS)

been used on larger scale (Meehl et al. 2007). However, there was no CMIP4, so CMIP5 was developed upon CMIP3. CMIP5 can help to understand the climate system accurately. It generated 2 petabits (PB) of output from different experiments completed through climate models. The salient features of CMIP5 include climate responses to perturbed atmospheric $CO_2$, impact of atmospheric chemistry on climate, carbon-climate interactions, troposphere-stratosphere interactions, feedbacks and idealized model configurations. The idea of near- and long-term time horizons was implemented in CMIP5. Furthermore, to address the range of advanced scientific questions that come from different scientific communities, CMIP6 was implemented. It has three major components: (i) the DECK (Diagnostic, Evaluation and Characterization of Klima) and CMIP historical simulations (1850–near present); (ii) characterization of the model ensemble and dissemination of model outputs through common standards, coordination, infrastructure and documentation (SCID); and (iii) filling of scientific gaps through the ensemble of CMIP-Endorsed Model Intercomparison Projects (MIPs) that will build on the DECK and CMIP historical simulations. The following three broad questions will be addressed in CMIP6: (i) how does the earth system respond to forcing?; (ii) what are the origins/consequences of model biases?; and (iii) how can future climate change be assessed under the scenarios of uncertainties, predictability and internal climate variability? (Eyring et al. 2016). Further description about CMIP6 has been shown in Fig. 1.7.

### *1.2.1 Application of CMIP*

CMIP/CMIP6 have been widely used in different studies across the globe to quantify the effect of climate change. This includes the climate change effect on soil organic carbon (Wang et al. 2022a); agronomic managements to boost crop yield (Ali et al. 2022); simulation of air-sea $CO_2$ fluxes ($FCO_2$) (Jing et al. 2022); anthropogenic aerosol emission inventory (Wang et al. 2022b); heatwave simulation (Hirsch et al. 2021); prediction of future precipitation and hydrological hazard (Nashwan and Shahid 2022); drought prediction (Mondal et al. 2021; Supharatid and Nafung

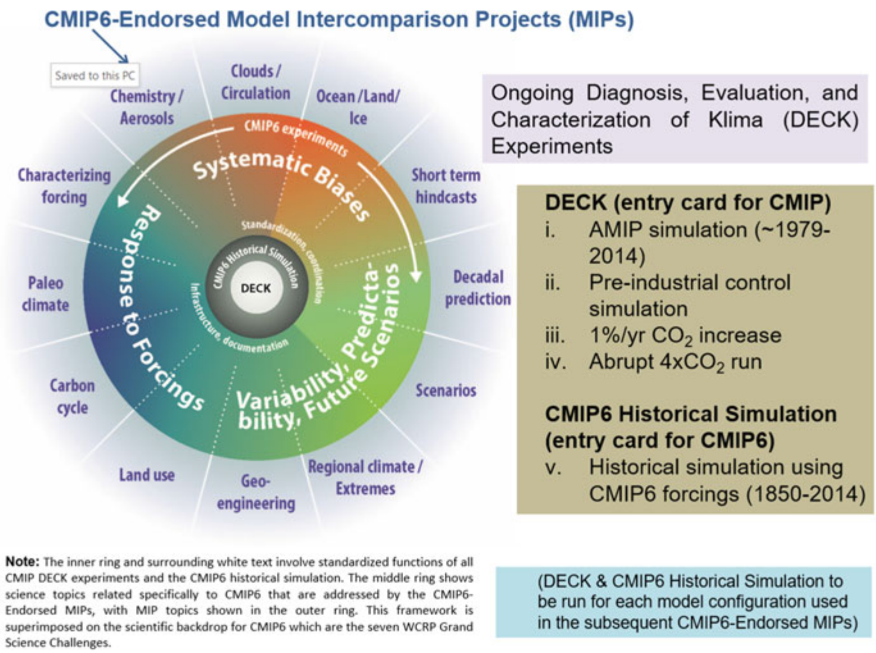



**Fig. 1.7** Schematic representation of CMIP6 experiment design. (Source with permission: Eyring et al. 2016)

2021); evaluation of spatio-temporal variability in drought/rainfall in Bangladesh (Kamal et al. 2021); global assessment of meteorological, hydrological and agricultural drought (Zeng et al. 2021); prediction of crop yield and water footprint (Arunrat et al. 2022); temperature simulations over Thailand (Kamworapan et al. 2021); climate projections for Canada (Sobie et al. 2021); ENSO evaluation (Lee et al. 2021); and simulation of ENSO phase-locking (Chen and Jin 2021).

## 1.3 Radiative Forcing (RF) and Climate Change

Total (downward minus upward) radiative flux (expressed in W $m^{-2}$) at the top of the atmosphere due to changes in the external drivers of climate change (mainly GHGs) is called radiative forcing (RF). Mathematically, it can be expressed as follows:

$$\begin{aligned} \textit{Radiative forcing} &= \textit{Incoming energy}\ (\textit{short wavelength}) \\ &\quad - \textit{Outgoing energy}(\textit{both short\&long wavelength}) \end{aligned}$$

Radiative forcing determines the energy budget of the earth (Fig. 1.8). It can be positive or negative. If radiative forcing is positive, it means the earth is getting higher energy from the sun than it is returning to space. This net gain causes warming. However, if the earth loses more energy to space, then what it gets from the sun it produces cooling. Hence, the temperature of the earth is determined by the RF. Around one-third (29.4%) of radiation that comes from the sun is reflected, while the rest is absorbed by the earth system. Calculation about the earth's energy budget has been presented in Table 1.3. Factors that determine the sunlight reflection back into space include land surfaces and the reflectivity (albedo) of clouds, oceans and particles in the atmosphere. However, the strong determinants are cloud albedo, snow and ice cover as they have much higher albedos. Furthermore, important factors that regulate the earth's temperature are incoming sunlight, absorbed/reflected sunlight, emitted infrared radiation and absorbed and re-emitted infrared radiation (mainly by GHGs). The earth's radiative balance has been changed due to changes in these factors, which resulted to the change in air temperature. Anthropogenic activities have changed radiative balance of the earth (Table 1.4), which resulted to the changes in the rainfall pattern, temperature extremes and other climatic variables through a complicated set of coupled physical processes. Radiative forcing caused by human activities since 1750 has been shown in Fig. 1.9.

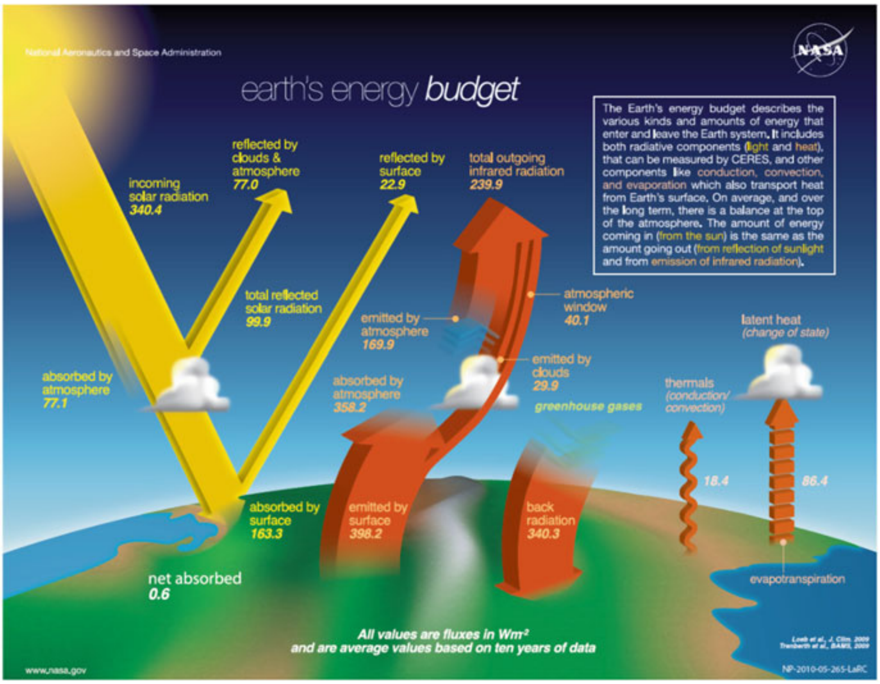



**Fig. 1.8** Earth's energy budget. (Source: NASA)

**Table 1.3** Calculation about the earth's energy budget

| Incoming solar radiation at the top of the atmosphere (TOA) | Outgoing radiation at TOA | Downwelling (back radiation at the surface from GHGs in the atmosphere) | Solar radiation reflected into space |
|---|---|---|---|
| = 340.4 $Wm^{-2}$. (1/4th of 1361.6 $Wm^{-2}$ solar constant, i.e. total solar irradiance at the top of the atmosphere) Solar constant average varies from 1360 to 1370 $Wm^{-2}$ | = 239.9 $Wm^{-2}$ IR + 77.0 + 22.9 = 339.8 $W/m^2$, which is 0.6 $W/m^2$ less than the incoming solar radiation | = 340.3 $Wm^{-2}$ (same as the solar irradiance at TOA) | = 22.6% (77 $W/m^2$) |

Source: Kramer et al. (2021)

**Table 1.4** The earth's radiative forcing relative to 1750

| Year | Radiative forcing relative to 1750 ($Wm^{-2}$) |
|---|---|
| 1750 | 0.0 |
| 1950 | 0.57 |
| 1980 | 11.25 |
| 2011 | 2.29 |

Source: IPCC AR5 WG1

## 1.4 Drivers of Climate Change

Most of the climate change drivers are mainly associated with anthropogenic activity and, to a lesser extent, with natural origin. Well-known natural climate drivers are solar irradiance, volcanic eruptions and ENSO. Drivers of climate change can be categorized into two types: (i) natural and (ii) man induced. Natural climate drivers consist of radiative forcing, variations in the earth's orbital cycle, ocean cycles and volcanic and geologic activity. Human-induced drivers of climate change are burning fossil fuels, cutting down forests and farming livestock. These human activities resulted to global warming due to increased accumulation of GHGs and changes in the reflectivity or absorption of the sun's energy. Details about the drivers of climate change have been further elaborated below.

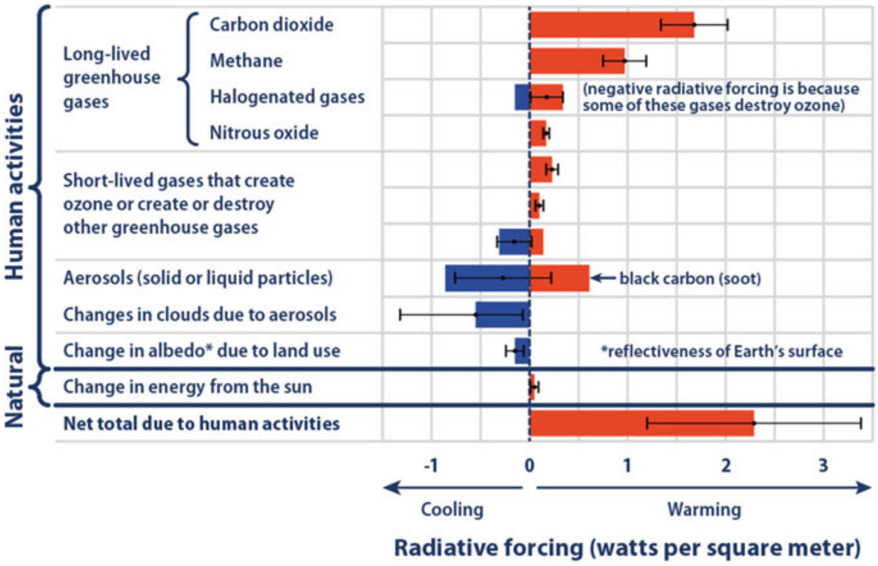



**Fig. 1.9** Radiative forcing caused by human activities since 1750. (Source: IPCC 2013)

## *1.4.1 Anthropogenic Drivers*

### 1.4.1.1 Greenhouse Gases

Greenhouse gases (GHGs) are the main drivers of global climate change. The principal GHGs are carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$). Concentrations of these GHGs have increased significantly since from the industrial revolution, which resulted to the increased greenhouse effect. On annual scale over 30 billion tonnes of $CO_2$ have been released into atmosphere due to human activities. The levels of $CO_2$ have been increased by more than 40% since pre-industrial times. It has been increased from 280 ppm to 417 ppm in 2022. The trend of $CO_2$ based on C. David Keeling (Keeling Curve) has been shown in Fig. 1.10. $CO_2$ has global sources and sinks. The major sources of the rise in the concentration of $CO_2$ are fossil fuel burning, cement industry and changes in land use (e.g. housing sector and deforestation). Sink of $CO_2$ includes absorption by the oceans, carbonation of finished cement products and its use by the plants in the process of photosynthesis. The data depicted that $CO_2$ atmospheric growth rate has been increased exponentially, and it has shown the largest RF as compared to other GHGs (Fig. 1.11). Global distribution of GHGs in percentage with their emissions from different economic sector and countries has been shown in Fig. 1.12. $CO_2$ has been used as reference to define the global warming potential (GWP) of other GHGs. The GWP of $CO_2$ is 1 as it is used as reference, while for $CH_4$ (methane)

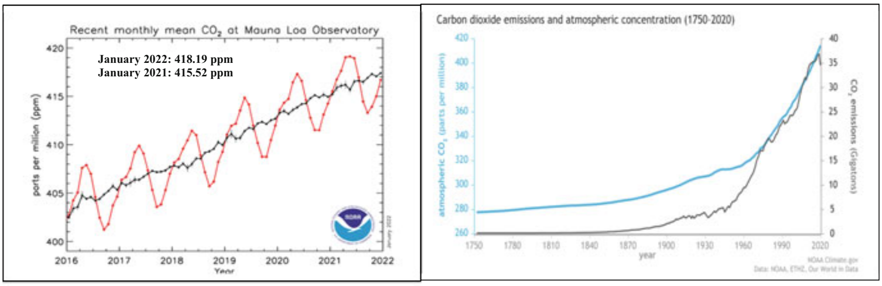
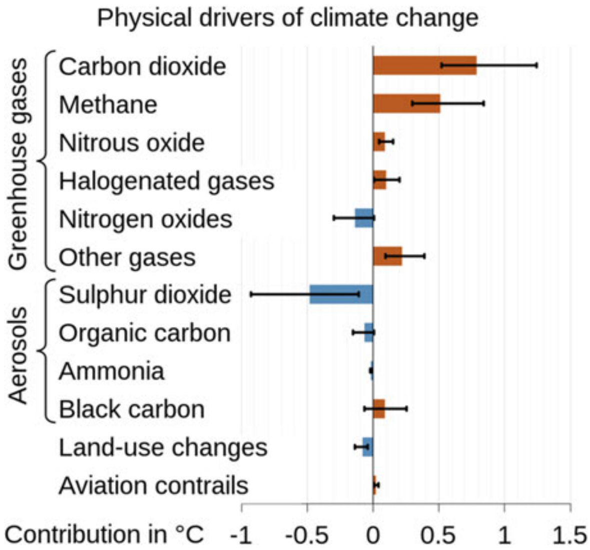



**Fig. 1.10** Trend of $CO_2$ measured at Mauna Loa Observatory, Hawaii. (Source: NOAA)

**Fig. 1.11** Radiative forcing of physical drivers of climate change. (IPCC 2013)




it is 28–36 per 100 year and $N_2O$ has a GWP of 265–298 times that of $CO_2$ for a 100-year timescale. Halogen's derivatives (CFCs (chlorofluorocarbons), HFCs (hydrofluorocarbons), HCFCs (hydrochlorofluorocarbons), PFCs (perfluorocarbons)) and $SF_6$ (sulphur hexafluoride) are called high-ranking GWP gases as they can trap more heat than $CO_2$ (Fig. 1.13) (Vallero 2019). Most of our daily activities are responsible for GHG emissions, and it can be calculated by using apps like carbon footprint calculator and greenhouse gas equivalencies calculator. The methane concentration and RF have also been increased since the industrial era. Unlike $CO_2$, $CH_4$ is increasing at faster rate (Saunois et al. 2016). The major sources of $CH_4$ include decaying of organic material, seepage from underground deposits, digestion of food by cattle, rice farming and waste management (IPCC 2013; Liu et al. 2021; Matthews and Wassmann 2003). $N_2O$ has a variety of natural and human-caused sources that include use of artificial nitrogenous fertilizers, animal waste, biological $N_2$ fixation, crop residue, animal husbandry, burning of waste,

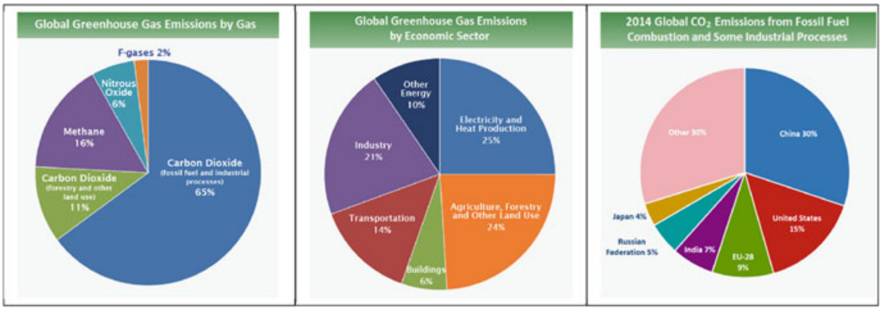



**Fig. 1.12** Percentage distribution of GHG emissions by gas, economic sector and $CO_2$ emissions from fossil fuels. (Source: NOAA)

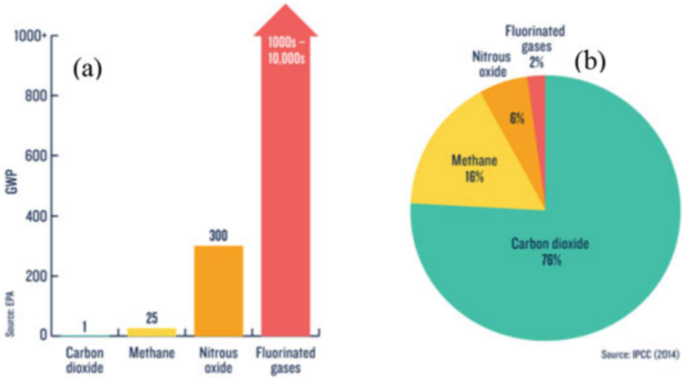



**Fig. 1.13** The global warming potential (GWP) of human-generated GHGs (**a**) and per person share to GHG emissions (**b**). (Source: USA, Environment Protection Agency (EPA); IPCC 2014)

combustion of fuel in automobiles and wastewater treatment. Another issue related to $N_2O$ is its destruction in the stratosphere due to photochemical reactions, which form nitrogen oxides (NOX) that destroy ozone ($O_3$) (Skiba and Rees 2014). Projection of future climate using different climate change scenarios has been well elaborated by the IPCC and presented in Fig. 1.14.

### 1.4.1.2 Water Vapours

Water vapours account for 60% of the earth's greenhouse warming effect. Water vapours are the most abundant GHG. Researchers from the NASA using novel data from AIRS (Atmospheric Infrared Sounder) on NASA's Aqua satellite have estimated that water also has heat-trapping effect in the air. Furthermore, powerful heat-amplifying effect of water has been confirmed, which can double the climate warming effect caused by higher concentrations of $CO_2$ (Matthews 2018). The

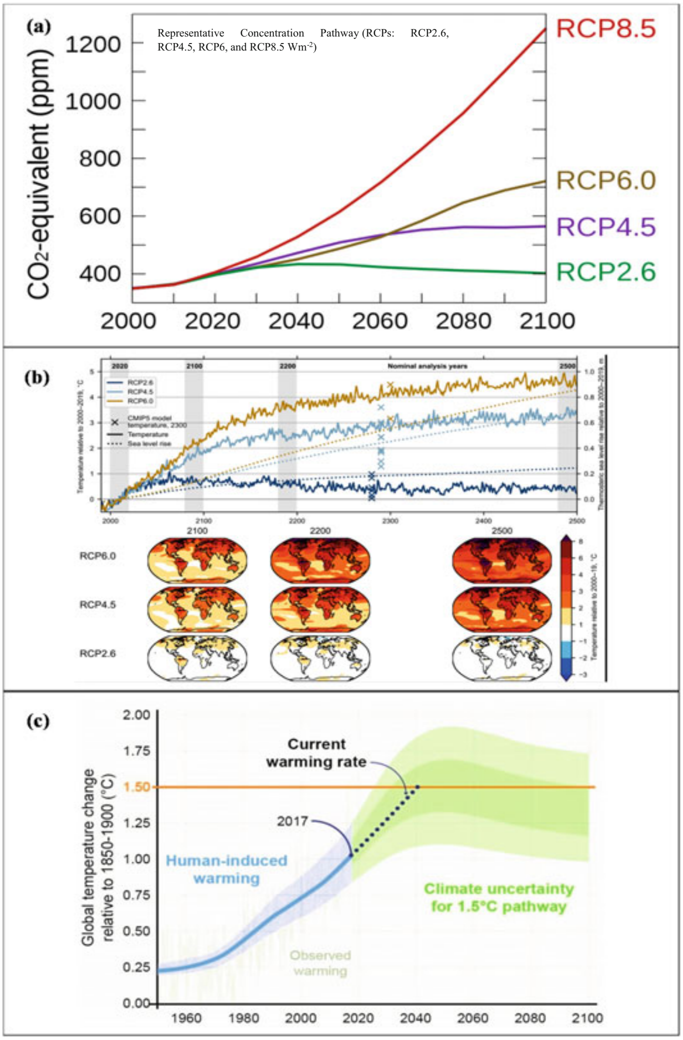



**Fig. 1.14** Diagrammatic representation of future climate using (**a**) RCPs, (**b**) global temperature and (**c**) global temperature trend if the current emissions continue. (Source: IPCC 2014)

strength of water vapour feedback has been estimated by climate models and experts that have found that if the earth warms by 1.8 °F, then the increase in water vapour will trap an extra 2 watts m$^{-2}$. The energy-trapping potential of water vapour at different latitudes has been shown in Fig. 1.15. Water vapours are significantly increasing the earth's temperature. Abundance of water vapours in the troposphere is controlled by two factors: (i) transport from troposphere (the lower atmosphere layer) and (ii) oxidation of $CH_4$. Since the level of $CH_4$ is increasing because of anthropogenic activities, it will, hence, increase stratosphere water vapour that will

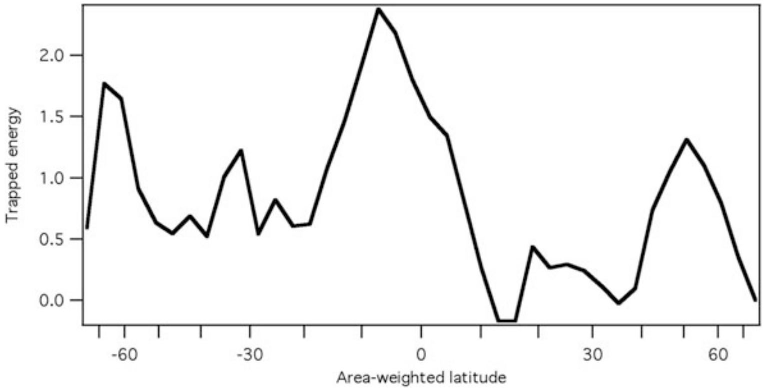



**Fig. 1.15** Water vapour trapped energy (southern to northern latitudes). (Source: NASA, Credit: Andrew Dessler)

lead to positive RF (Solomon et al. 2010; Hegglin et al. 2014). Other less important sources of water vapours include hydrogen oxidation, volcanic eruptions and aircraft exhaust. The relationship between increased stratospheric water vapour and ozone and climate change has been reported in earlier work (Shindell 2001). However, water vapour in the troposphere is controlled by temperature. Circulation in the atmosphere limits the build-up of water vapours. Direct changes in water vapours are negligible as compared to indirect changes due to temperature variability that comes from RF. Hence, water vapours are considered as feedback in the climate system as increase in GHG concentration warms the atmosphere that leads to increase in water vapour concentrations, thus amplifying the warming effect.

#### 1.4.1.3 Ozone

Ozone ($O_3$) is a naturally occurring GHG. It is mainly present in the stratosphere (ozone layer), but a small amount, which is harmful, also generates in the troposphere. $O_3$ is produced and destroyed due to anthropogenic and natural emissions. $CH_4$, NOX, carbon monoxide and volatile organic compounds (VOC) are producing $O_3$ photochemically. This increase in $O_3$ production results to positive RF (Dentener et al. 2005). However, in polar regions, $O_3$ has been destroyed due to halocarbons, which leads to negative RF. $O_3$ is harmful for plants, animals and humans. In plants higher concentration of $O_3$ causes closure of stomata, decrease in photosynthesis and reduced plant growth. Similarly, $O_3$ could cause oxidative damage to the plant cells (McAdam et al. 2017; Vainonen and Kangasjärvi 2015; Li et al. 2021; Jimenez-Montenegro et al. 2021).

#### 1.4.1.4 Aerosols

Aerosols are suspended particles from the surface of planet earth to the edge of space. Aerosols are dispersion of solid/liquid particles in a gas (Hidy 2003). Smoke, particulate air pollutants, dust, soot and sea salt are primary aerosols that come from the anthropogenic activities. Open burning is a major cause of aerosols in the atmosphere (Kumar et al. 2022). Natural aerosols are forest exudates, geyser steam, dust and fog/mist. Aerosols have a significant impact on climate as higher concentrations of aerosols lead to the rise in the temperature. Aerosols have shown an impact on climate change through its two-way interactions: (i) aerosol-radiation interactions (direct effect) and (ii) aerosol-cloud interactions/cloud albedo (indirect effect). The RF for both of this interaction is negative; however, it changes with the types of aerosols. The aerosol, such as black carbon, absorbs light, so they produces positive RF and warms the atmosphere (Flanner et al. 2009).

#### 1.4.1.5 Land Use Change (LUC)

Changes and variability in land use resulted to the alterations in surface features, and it is a major driver of climate change but given less preference (Vose et al. 2004). LUC leads to higher aerosols, $CH_4$ and $CO_2$ in the atmosphere. Similarly, it modifies the surface albedo, which alters the climate variables (e.g. temperature, precipitation, etc.). Spatio-temporal variability in the pattern of thunderstorms and ENSO are well-known examples of LUC (Pielke 2005). LUC influences the mass-energy fluxes, which alter the climate of the surroundings. LUC resulted to the change in the albedo, particularly due to deforestation and afforestation. This leads to alteration in RF and carbon and hydrologic cycles.

#### 1.4.1.6 Contrails

Clouds that are line (linear) shaped are produced by the aircraft engine exhaust in the mid to upper troposphere under elevated ambient humidity. Contrail's production resulted to the change in the earth's radiative balance by absorbing outgoing long-wave radiation. Contrails have intensified the effect of global warming, and it can account for more than half of the entire climate impact of aviation. It can interact with solar and thermal radiation, thus producing global net positive RF. Tweaking flight altitude could minimize the impact of contrails (Caldeira and McKay 2021).

## *1.4.2 Natural Drivers*

### 1.4.2.1 Solar Irradiance

Solar irradiance is the number of solar radiation that reaches the surface of the earth without being absorbed or dispersed. It is a promising source of energy. It also affects different processes such as evaporation, hydrological cycle, ice melting, photosynthesis and carbon uptake and diurnal and seasonal changes in the surface temperatures (Wild 2012). The relationship between climate, solar cycles and trends in solar irradiance has been discussed earlier (Lean 2010). The connection between solar irradiance and climate indicators (global temperature, sea level, sea ice content and precipitation) has been reported in the work of Bhargawa and Singh (2019).

### 1.4.2.2 Volcanoes

Volcanic eruptions are minor events that lead to significant change in the climate. Active volcanoes inject significant amount of sulphur dioxide ($SO_2$) in the air. On oxidation $SO_2$ changes to sulphuric acid ($H_2SO_4$), which resulted to increase in the earth albedo and negative RF. Furthermore, volcanic eruptions also result to $O_3$ depletion and changes in the heating and circulation. It also emits $CO_2$ and water vapour, which then change the climate of surrounding. Volcanic activity has triggered El Niño events due to volcanic radiative forcing. Similarly, decrease in global temperature of 0.5 °C was recorded due to Mount Pinatubo eruption (Cole-Dai 2010).

## 1.5 Scenario Analysis (RCP, SSP and SPA)

A scenario analysis that includes RCP (representative concentration pathway), shared socio-economic pathways (SSP) and shared climate policy assumptions (SPA) is a strategic management tool that has been used to explore future changes across the globe. They can also be used to design adaptation options under the changing climate (Kebede et al. 2018). Furthermore, they can investigate the consequences of long-term climatic-environmental-anthropogenic futures to design robust policies (Harrison et al. 2015). In initial scenarios most of the focus was on climate change (Hulme et al. 1999) that was addressed by the IPCC through SRES (Special Report on Emission Scenarios), which includes both socio-economic and climate change (Arnell et al. 2004). In the IPCC AR5 three-dimensional aspects (climate/socio-economic/policy dimensions of change) were presented using RCP-SSP-SPA scenarios (van Vuuren et al. 2011; O'Neill et al. 2014; Kriegler et al. 2014). These three dimensional frameworks provide basis for the climate change impact assessment, adaptation and mitigation under a wide range of climate and socio-economic scenarios (Fig. 1.16).

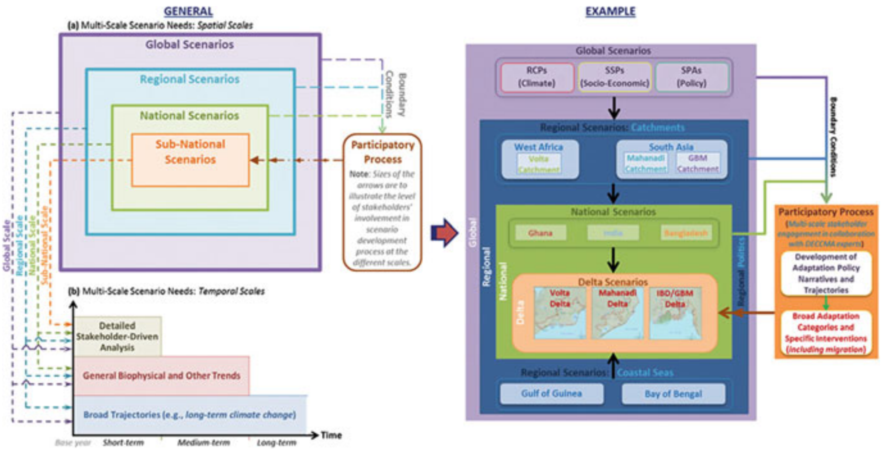



**Fig. 1.16** Application of integrated scenario frameworks. (Source: Kebede et al. 2018)

**Table 1.5** Temperature and mean sea level change under different RCPs in the mid- and late-twenty-first century

| RCP Scenarios | 2046–2065<br>Temperature mean (range) | 2081–2100<br>Temperature mean (range) | 2046–2065<br>Mean sea level (m) increase (range) | 2081–2100<br>Mean sea level (m) increase (range) |
|---|---|---|---|---|
| RCP2.6 | 1.0 (0.4 to 1.6) | 1.0 (0.3 to 1.7) | 0.24 (0.17 to 0.32) | 0.40 (0.26 to 0.55) |
| RCP4.5 | 1.4 (0.9 to 2.0) | 1.8 (1.1 to 2.6) | 0.26 (0.19 to 0.33) | 0.47 (0.32 to 0.63) |
| RCP6 | 1.3 (0.8 to 1.8) | 2.2 (1.4 to 3.1) | 0.25 (0.18 to 0.32) | 0.48 (0.33 to 0.63) |
| RCP8.5 | 2.0 (1.4 to 2.6) | 3.7 (2.6 to 4.8) | 0.30 (0.22 to 0.38) | 0.63 (0.45 to 0.82) |

Source: IPCC (2013)

A representative concentration pathway (RCP) is a GHG trajectory provided by the IPCC. It has been used in climate modelling and impact assessments for the IPCC AR5 and includes four pathways (RCP2.6 (2.6 $Wm^{-2}$ RF), RCP4.5 (4.5 $Wm^{-2}$ RF), RCP6 (6.0 $Wm^{-2}$ RF) and RCP8.5 (8.5 $Wm^{-2}$ RF)). RCP can be further divided into RCP1.9 (limit global warming <1.5 °C as per the Paris Agreement), RCP2.6, RCP3.4, RCP4.5, RCP6, RCP7 and RCP8.5. RCP2.6 is a very strict pathway, and it requires that $CO_2$ emissions should be declined by 2020 and should go to zero by 2100. Similarly, $CH_4$ should be dropped to half by 2020, and $SO_2$ emissions need to be declined by 10%. RCP2.6 requires that global temperature should be kept below 2 °C through absorption of $CO_2$. The most possible pathway is RCP3.4, which forces to keep temperature between 2.0 and 2.4 °C till 2100. RCP4.5 is an intermediate scenario that suggests dropping $CO_2$ and other GHGs by 2045. However, most of the plant and animal species will not be able to adapt because of RCP4.5. Further details about RCP scenarios are given in Table 1.5. The scenarios that are used to project socio-economic changes across the globe are called SSPs. It deals with socio-economic development by working on the aspects of impact assessments of climate change, adaptation and mitigation. Further detail about SSP is given in Fig. 1.17.

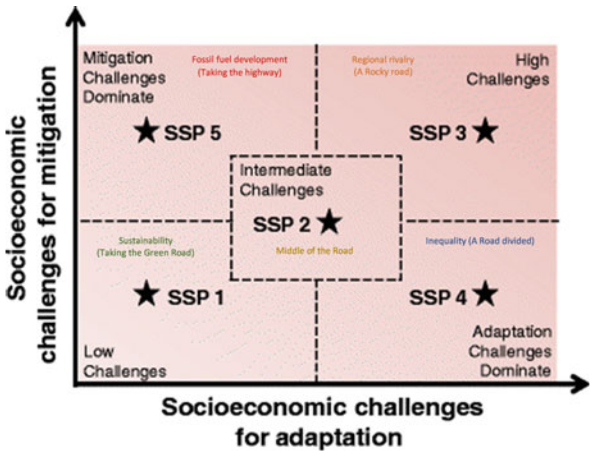



**Fig. 1.17** Concept of SSP (shared socio-economic pathways). (Source: O'Neill et al. 2014)

## 1.6 Indicators of Climate Change

Different indicators could be utilized as early warning signals to identify the impact of climate change. The gathered information can help to design adaptation and mitigation option to the climate change. The major indicators of climate change have been shown in Fig. 1.18. Temperature is the topmost indicator that showed that climate change is a real phenomenon affecting global environment. The average temperature of planet earth has been risen to 1.18 °C since the nineteenth century. Higher concentration of $CO_2$ and human activities are the main drivers of this rise in temperature. However, this temperature rise is not uniform across the globe (Fig. 1.19). The higher temperature will be more on the land particularly in the tropics as compared to the sea. At 1.5 °C rise in temperature, extreme heatwaves will be more common and widespread across the globe. Deadly heatwave due to 2 °C warming was seen in 2015 in India and Pakistan. Cold extremes will be visible in the Arctic land regions. Temperature extremes will lead to drought in some part of the world while extreme precipitation on the other part. The connection between ENSO (El Niño/Southern Oscillation) phenomenon and extreme temperature in Southeast Asia have been seen in April 2016. Results indicated that 49% of the 2016 anomaly was caused by El Niño while 29% due to warming (Thirumalai et al. 2017). Intensification of hydrological cycle (extreme precipitation and flood) due to global warming has been reported over all climatic regions (Tabari 2020). Furthermore, the intensity of drought under the changing climate was studied using different indices (Bouabdelli et al. 2022). The indices include (i) precipitation only and (ii) overall climate (precipitation plus temperature). Results showed that drought events in plains will be more and long-lasting in hot season that will threaten the agricultural production as well as food security under RCP4.5. Temperature extremes will modify crop life cycle and productivity. Since crop vegetative development requires higher optimum temperature than reproductive phase, rise in temperature will,

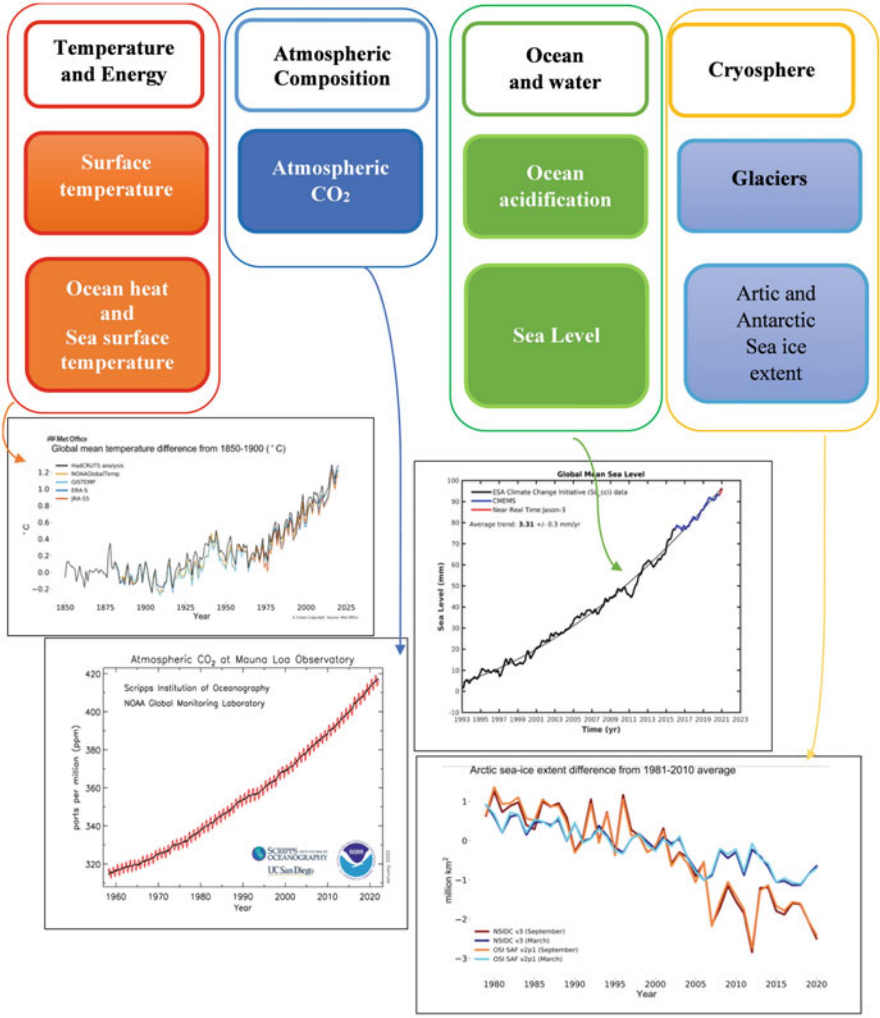



**Fig. 1.18** Major indicators of climate change

hence, severely affect pollen viability, grain development and grain weight. The impact is visible on photoperiod sensitive crops (e.g. soybean). Meanwhile, in crops, pollen viability will be decreased due to its exposure to temperature greater than 35 °C. Similarly, in rice, pollen capability and production decreases when daytime temperature goes above 33 °C and stops when it exceeds 40 °C (Hatfield et al. 2011, 2020; Hatfield and Prueger 2015). Other indirect indicators of climate change include plant pathogens (Hatfield et al. 2020; Garrett et al. 2016), crops and livestock systems (Hatfield et al. 2020), biodiversity (Mashwani 2020; Habibullah et al. 2022), loss of species and extinction (Caro et al. 2022), shift in herbicide paradigm (Ziska 2020) and human health (Carlson 2022). Further details about the responses of different systems to different climatic variables have been given in Table 1.6.

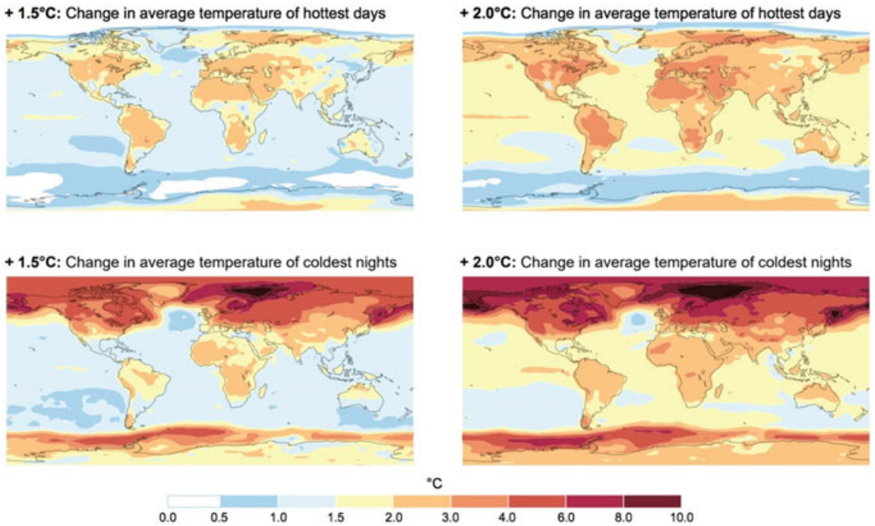



**Fig. 1.19** Projection of global warming of 1.5 and 2 °C with hottest and cold days. (Source: NASA)

## 1.7 Humidity as a Driver of Climate Change

A recent study published in the Proceedings of the National Academy of Sciences (PNAS) by climate scientists reported that temperature is not the only best way to measure climate change (Song et al. 2022). Instead, humidity should also be used as an indicator to measure global warming. They showed that surface equivalent potential temperature (temperature and humidity) is a comprehensive metric to monitor global warming. Similarly, this also has an impact on climate and weather extremes.

## 1.8 Solar Dimming

The earth is dimming due to climate change as shown in Fig. 1.20. The light reflected from the earth, called the earth's reflectance or albedo, is decreasing. It is now ½ a watt less light per $m^2$ than what was received 20 years ago, which is equal to 0.5% reduction in the earth's reflectance. About 30% of the sunlight is reflected by the earth, since the earth's albedo has been dropped due to air pollution, which will reduce the intensity of photosynthetically active radiation (PAR) and agricultural production (Yadav et al. 2022). However, on the other hand, researchers are planning to spray sunlight-reflecting particles (the sun dimmers) into the stratosphere to lower the planet temperature (Tollefson 2018).

**Table 1.6** Responses of different systems to climatic variables

| Systems | Climatic variables | Impact on system | Indicators |
|---|---|---|---|
| **Plants** | Temperature | Plant phenology | Phenological changes |
| | | Chilling hours | Flowering timing |
| | | Growing degree days | Crop zoning |
| | Elevated $CO_2$ | Stimulate photosynthesis, plant productivity, fertilization effect, modified water and nutrient cycles | Crop quality |
| | Elevated $CO_2$ and soil nutrients | Nutrient's availability | Beneficial to legumes, N-dilution |
| | Temperature, precipitation and elevated $CO_2$ | Plant productivity, water use efficiency (WUE), N-deposition, yield, biomass | Variable response in plant productivity, more beneficial for C3 |
| **Soil** | Extreme rainfall | Nutrient run-off/soil erosion/loss of topsoil | Rainfall intensity |
| | GHG exchange and carbon sequestration | Soil health | Changes in organic carbon |
| | Precipitation | Soil nutrients, soil water content and infiltration | Water availability for plant production |
| | Temperature | Soil health | Loss in organic carbon and microbial biomass |
| **Weeds** | Temperature | Plant phenology | Changes in onset of phenological development, e.g. bud break, first flower |
| | | Good biomass and establishment | Higher stand |
| | | | Crop zoning |
| | Elevated $CO_2$ | Stimulate photosynthesis, modified water, nutrient cycles | Higher weed abundance |
| | Temperature, precipitation and $CO_2$ | Plant productivity, yield, biomass | Variable response in plant productivity |
| **Livestock** | Extreme events (hot and cold) | Animal productivity | Temperature humidity index, climate index |
| **Pests** | $CO_2$-temperature interactions | Plant productivity | More attacks |
| | Temperature/humidity | Insect or disease pressures | Pressures of insects/diseases |
| | Temperature/precipitation | Weed pressures | More weed distribution |
| **Disease** | Climate extremes | System productivity | Promote plantdisease and pest outbreaks |
| **Economics** | Extreme events | Declined productivity | Insurance |

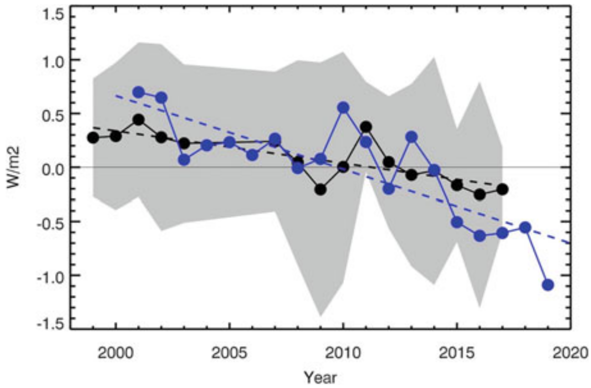



**Fig. 1.20** Earth dimming due to climate change. (Source: Goode et al. 2021)

## 1.9 Conclusion

Climate change is a major environmental concern for the people in all fields of life starting from researchers to policymakers. It is a real phenomenon happening, and its rising impacts cannot be denied. Natural (solar variability, volcanic activity and plate tectonics) and anthropogenic drivers (greenhouse gas emissions, water vapours, ozone, aerosols, land use change and contrails) are the major reasons of accelerated climate change. Another factor includes urbanization, which is the main cause of urban climate change. Since IPCC in AR5 reported that global average surface temperature has increased by 0.85 °C (1880–2012), 0.3–0.7 °C (2016–2036 in comparison with 1986–2005) and 0.3–4.8 °C (end of century in comparison with 1986–2005). Thus, it is essential to use climate change information and adopt measures to control the drivers responsible for this increased climate change. If swift measures will not be taken, these climatic drivers will be responsible for higher possibilities of extreme events, issues of food security, increased weed pressures and occurrence of pest and disease attacks. Climate models are good tools that can give accurate prediction to design adaptation and mitigation strategies for different systems. For example, consider agriculture systems which provides food fuel and fibre to human being is strongly affected by climate change could be managed by using different climate models. The data obtained from these models could be used to understand the relationship between agriculture and climate. The information generated could be used afterwards to improve agricultural systems by adopting different adaptation measures, which can reduce GHG emissions, enhance soil organic carbon and bring sustainability in the system.

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