4 Observations and Modeling of GHG Concentrations and Fluxes Over India

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Key Messages

- The surface CO_2 concentration observed at Sinhagad site, located in the western part of India, shows higher seasonal cycle amplitude as compared to the observations at Mauna Loa in the Pacific region (Fig. 4.1). The higher amplitude is caused by strong local–regional biospheric activity.
- The surface CO_2 concentration amplitude in the western Indian region is increasing with time, likely driven by the enhanced biospheric activities as well as the changes in nearby oceanic fluxes. To ascertain the driving mechanism behind this as well as long-term variability at country scale, a strategically designed network of long-term surface CO_2 concentration and associated flux observations is essential over India.
- Recent studies using flux tower measurements show that the carbon fluxes in Indian forests vary widely across the ecosystems. The Kaziranga forest in Northeast India sequesters maximum carbon during pre-monsoon season, whereas the forests in Haldwani and Barkot in northern India sequester maximum carbon during the summer monsoon season. The forests in Betul in central India, mangroves in Sundarbans in east India and forests in Kosi-Katarmal in north India sequester maximum carbon during post-monsoon, whereas mangroves in Pichavaram in the east coast of south India sequester maximum carbon during the winter season (Fig. 4.5).
- Satellite-derived vegetation indices indicate increasing vegetation productivity over India during recent decades.
- Modeling studies show that even though the Indian terrestrial ecosystem has not historically been a strong source or sink of carbon, it is behaving as a carbon sink since the 1980s. The terrestrial carbon sink is maintained primarily by the carbon fertilization effect aided to some extent by forest conservation, management, and reforestation policies in recent decades (Sect. 4.4.1).
- Surface GHGs measurement sites in India are sparse in nature. In the absence of long-term observational records and a comprehensive modeling of biogeochemical processes, there is a limited understanding of the dynamics of GHGs variability in India. Expansion of observational network as well as development of process-based biogeochemical and coupled climate–carbon models may fill this knowledge gap. Such expanded capabilities would help improve the assessments of the mitigation potential of Indian ecosystem in the future (Sect. 4.5).

Box 4.1 Preamble

In order to study the effect of primary drivers of climate change, observational data of at least a few decades ("climate timescale") are required. Such knowledge is also useful for a meaningful interpretation of a reliable estimate of future projection of the drivers. The primary drivers of climate change in the industrial era are the greenhouse gases (GHGs) which absorb the terrestrial radiation strongly. It is now well established that increase in the GHGs concentrations during the past century has been due to the anthropogenic activities, such as the fossil fuel consumption and land use land cover changes. The largest instrumental data of CO_2 concentration, reported as dry-air mole fraction, are available since the international geophysical year (1957–1958) from South Pole and Mauna Loa, Hawaii. The latter is considered as a reference to global-mean CO_2 concentration. In India however, the longest CO_2 record is available only for a couple of decades. Thus, most studies are limited to

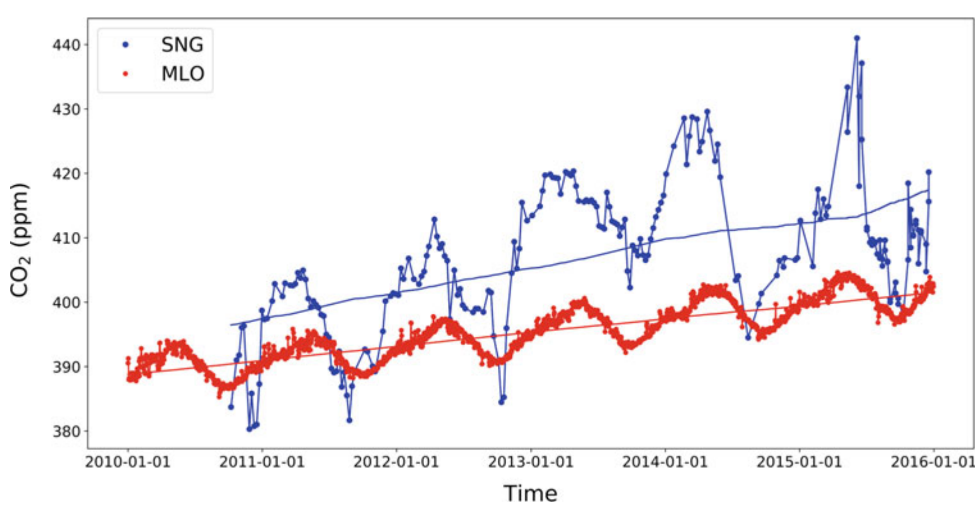

Fig. 4.1 Seasonal variation of CO_2 mixing ratio at two tropical sites. The amplitude of CO_2 mixing ratio variability at Sinhagad, India (blue line), is much higher than that observed at a comparable latitudinal range (18.3–19.4° N), Mauna Loa in the Pacific region (red line). The data were obtained from Tiwari et al. (2014) re-plotted and extended till 2015

short-term changes that span over diurnal to inter-annual timescale. The lack of robust observational records is a severe constraint to make a reliable assessment of the trends in GHGs fluxes. In this chapter, we provide an overview of the measurement of a few GHGs concentration, how carbon is sequestered in natural ecosystems as determined by the eddy covariance technique and some model-based results for India. The chapter provides a summary assessment of GHGs (mainly CO_2, CH_4 and N_2O)-related research in India. Other trace gases, such as ozone, SO_2 and CFCs, have been discussed in Chap. 5. A brief discussion on the upper ocean carbon cycle in the Indian Ocean has been presented in Chap. 10.

4.1 Introduction

There is a general scientific consensus that radiative processes associated with increasing concentrations of greenhouse gases (GHGs) and related feedback processes are responsible for the global warming and climate change (IPCC 2013). The important GHGs in the earth's environment are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons and ozone in the lower atmosphere. The concentrations of CO_2, CH_4 and N_2O have significantly increased since the beginning of the industrial era (Ciais et al. 2013). Among the GHGs of anthropogenic origin, the increase of atmospheric carbon is of primary concern because CO_2 has a long lifetime in the atmosphere ($\sim$100 years). The concentration of atmospheric CO_2 was ca. 280 ppm during the pre-industrial period. This has exceeded 400 ppm in recent time (https://www.esrl.noaa.gov/gmd/ccgg/trends). The average growth rate has been estimated at 2.11 ppm per year during the last decade, and a value of 410 ppm was observed in 2018 (https://www.esrl.noaa.gov/gmd). However, the CO_2 mixing ratio shows considerable variability on local to regional scale. For example, the amplitude of CO_2 variations observed in the west peninsular India ($\sim$25 ppm) was much higher than that observed in the Mauna Loa observatory in the Pacific region ($\sim$6 ppm) (see Fig. 4.1), though both the sites are situated within a narrow latitude band (Sinhagad: 18.35° N; Mauna Loa: 19.4° N). The measurement in India is likely affected by regional terrestrial biospheric processes and marine sources (Tiwari et al. 2014).

The concentration of CH_4 has increased from 700 to 1857 ppb and that of N_2O from 270 to 321 ppb since pre-industrial era (IPCC 2007). Although the concentrations of CH_4 and N_2O are small compared to that of CO_2, their global warming potential (GWP) in terms of radiative forcing is several times (28 and 265 for CH_4 and N_2O, respectively, to 100-year time horizon) higher than that of an equivalent amount of CO_2. Residence time of CO_2 in the atmosphere is $\sim$100 years, whereas that of CH_4 and N_2O is about 10 years and 120 years, respectively. The increase in CH_4 concentration is mainly dominated by agricultural and animal husbandry operations, and that of N_2O is due to agricultural practices (Liu et al. 2019).

4.2 Observational Aspects of GHGs Research in India

In India, there are very few research organizations involved in the observational aspects of GHGs research with a long-term perspective. One of the earliest attempts was made by a group at the National Institute of Oceanography (NIO) in Goa and Physical Research Laboratory (PRL) in Ahmedabad, which took a major initiative in measuring GHGs at a coastal site in western India, Cabo de Rama, also known as Cape Rama (acronym CRI: 15.08° N, 73.83° E, 50 m ASL) in association with the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia (Bhattacharya et al. 2009). The CRI site is located closer to the shoreline, free from any major vegetation and away from habitation (Tiwari et al. 2011). Routine measurement of the concentrations of CO_2, CH_4, CO, N_2O and H_2 was carried out at the bimonthly time intervals. Additionally, carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopic ratios of CO_2 were also measured. The observational record is available for about a decade (1992–2002) and also for a period of 2009–2013.

In the next phase of the carbon cycle study in India, the Indian Space Research Organisation (ISRO) started the National Carbon Project (NCP) under the auspices of the ISRO Geosphere-Biosphere Program (IGBP) in the early phase of the 2010s. The NCP endeavors to understand the GHGs dynamics and estimate their budget by means of a robust observational network across the country (Chanda et al. 2013, 2014; Sharma et al. 2013, 2014; Patel et al. 2011; Mahesh et al. 2014, 2016, 2019; Sreenivas et al. 2016, 2019; Jha et al. 2013, 2014; Rodda et al. 2016). At about the same time, another GHGs observational program (CO_2 and CH_4) at a semi-urban hilly site near Pune, called Sinhagad (SNG), was initiated by the Indian Institute of Tropical Meteorology, Pune, under the patronage of the Ministry of Earth Sciences (MoES), Government of India. The SNG site is 200 km east of the Arabian Sea (73.75° E, 18.35° N, 1600 m ASL) situated over the Western Ghats mountainous terrain of southwestern peninsular region of the Indian subcontinent. The location is relatively free from major vegetation and local habitation disturbances for GHGs measurement on a long-term perspective. Routine air sampling at SNG, from a 10 m meteorological tower at weekly intervals, has been operational since November 2009 (Tiwari et al. 2014). The main objectives were (a) to investigate the GHGs transport mechanisms pertaining to the Indian subcontinent, (b) to understand the causes behind the seasonality of atmospheric CO_2 concentrations and (c) to develop a modeling framework (forward and inverse) for estimations of carbon sources and sinks over the Indian domain.

Among other studies, significant effort was made by the CSIR Fourth Paradigm Institute, Bengaluru (formerly CSIR Centre for Mathematical Modeling and Computer Simulation), in collaboration with a few other national and international research organizations, such as Laboratoire des sciences du climat et de l'environnement (LSCE) in Paris, France; National Institute of Ocean Technology in Chennai and Port Blair; and Indian Institute of Astrophysics, Bengaluru. Scientists from these institutes reported GHGs monitoring results at three sites Hanle (32.78° N, 78.96° E, 4500 m ASL), Pondicherry (11.91° N, 79.81° E, 6 m ASL) and Port Blair (11.62° N, 92.72° E, 17 m ASL) during the period 2007–2011 (Lin et al. 2015). Hanle is a high-altitude site and is considered as northern hemispheric midlatitude representative location. Pondicherry and Port Blair are coastal and oceanic sites, respectively, located at similar latitudes. Measurements were based on weekly flask sampling, and the flask samples were analyzed at the LSCE, France, under the Indo-French collaborative project. The observed concentration of CH_4 at Hanle peaked during the summer monsoon months, in contrast to the seasonal cycle at other sites including Pondicherry and Port Blair. High CH_4 concentration during monsoon could be due to enhanced biogenic emissions from wetlands and rice fields.

Sreenivas et al. (2016) presented CO_2 and CH_4 measurements over Shadnagar (17.03° N, 78°18 E) at Telangana India. But unlike the Hanle observations, these authors found minimum CH_4 during Indian summer monsoon and maximum during post-monsoon, indicating spatial heterogeneity in methane emissions and hence concentrations across the country. Maximum CO_2 occurred during pre-monsoon in conformity with the other observations, such as SNG (Tiwari et al. 2014; Metya et al. 2020). The Physical Research Laboratory in Ahmedabad has also made significant contributions in this regard, especially in analyzing the GHGs dynamics in an urban environment of India. For example, Chandra et al. (2019) observed low concentration of CO_2 at Ahmedabad during the monsoon season in conformity with the result obtained by Tiwari et al. (2014) for the Sinhagad station.

4.2.1 Carbon Dioxide (CO_2)

Tiwari et al. (2014) presented a detailed account of the SNG record. According to these authors, the regional source contributions at SNG and also at CRI arise from the horizontal flow within the planetary boundary layer. Greater

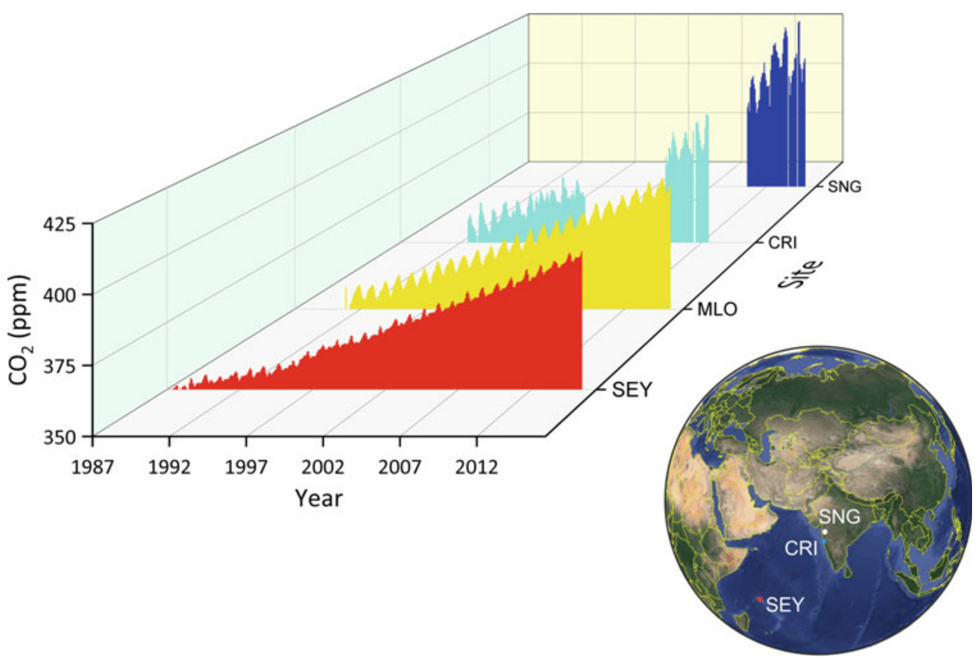

Fig. 4.2 Long-term records of CO_2 (ppm) concentration variability observed in the western peninsular region of India and selected global background locations. The Indian observing sites Sinhagad (SNG) and Cape Rama (CRI) CO_2 records are shown in blue and cyan bars, respectively. The CO_2 record of an Indian Ocean island site Seychelles (SEY) is shown in red, and the Mauna Loa (MLO) CO_2 record is shown in yellow. These are to compare the Indian CO_2 record with that of the global "background" record. The three sites (SNG, CRI, SEY) are also shown separately on the globe (globe credit: Google Earth)

CO_2 variability, >5 ppm, is observed during winter, while it is reduced nearly by half during the summer (Tiwari et al. 2014). Unlike the long-term Mauna Loa observational records, the Indian GHGs record, as mentioned earlier, is short. Bose et al. (2014) developed a fractionation model and used it to reconstruct the CO_2 variability using carbon isotopic analysis of tree rings from a western Himalayan region. These authors demonstrated that the tree ring-derived CO_2 record for the last one hundred year had a good match with the ice core records of CO_2 variability. Considering these observational records, we attempt to make a composite diagram of the CRI and the SNG CO_2 records to examine the regional features of the CO_2 variability in the Indian context. Figure 4.2 shows the CO_2 concentration variability approximately for the timescale of 1992–2013 with an intermittent gap from October 2002 to July 2009.

The CRI record is shown in cyan, while the blue bars represent the variability for the SNG site. The CRI and the SNG data show close resemblance, though a small difference is apparent. The CO_2 amplitude in the case of the SNG site is slightly higher than the CRI site. In case of CRI, the sampling was done once in two months, whereas in case of SNG, the sampling was done on weekly time interval. Since samples collected at lower temporal resolution impart a smoothing effect, the variability is expected to be subdued in the case of the CRI site compared to the SNG site which had a sampling frequency of about eight times higher than the CRI site. Nevertheless, we may assume the combined dataset as a representative of the CO_2 for this region and since there is no other known similar observational dataset available from the Indian region, we may call it as the "Indian CO_2 record."

When this record is compared with the Mauna Loa CO_2 (MLO) variability (see Fig. 4.2), one distinct feature is apparent. The Indian record shows higher amplitude, which has also been discussed earlier and illustrated in Fig. 4.1. In the earliest record, during the 1990s and 2000s, the CRI CO_2 data also show slightly larger amplitude than the MLO record. But, in the second phase of measurement during the early 2010s, this amplitude in the case of the Indian record shows an increasing trend. The amplitudes are larger than that observed during the 1990s and 2000s, and much larger than the Mauna Loa record. As mentioned earlier, Bhattacharya et al. (2009) also measured $\delta^{13}C$ of CO_2 during 1993–2002 and observed a strong inverse correlation between CO_2 and $\delta^{13}C$. This anti-correlation suggests a land biospheric control rather than the oceanic modulation on the seasonal behavior of CO_2 in this region. But according to a recent study, high-frequency (1 Hz) measurements of CO_2 and CH_4 concentrations using a laser-based GHG analyzer at SNG reveal that the oceanic emission of CO_2 and/or background CO_2 transported from the distant marine environment may also be playing a moderate role in determining the seasonal pattern of CO_2 in this region (Metya et al. 2020). Though the marine influence needs to be further investigated to ascertain its role, the increasing amplitude may be attributed to enhanced land biospheric activities. It is important to mention that Barlow et al. (2015) observed similar behavior at a high latitude region, namely Barrow (71.3° N, 156.6° W) in Alaska. They argue that the observed change in amplitude is partially due to an increase in "peak respiration" (contributes to increase the maxima in CO_2 value) and a larger increase in "peak uptake" (contributes to extend the minima in CO_2 value). Since respiration and photosynthetic uptake are by and large driven by vegetation, an increased vegetation cover seems to be the most likely reason for increased CO_2 amplitude. One of the reasons could be that the vegetation and/or the forest cover are probably increasing, at least in the western part of India. In the last twenty years, the surface characteristics may have changed significantly, and interestingly, the forest cover has increased in India (MoEFCC 2015, 2018). On the contrary, some studies show that the Indian forest cover has been decreasing, at least for the last couple of decades (Meiyappan et al. 2017). Needless to say that an accurate estimate of Indian forest cover and its characteristic behavior for different climatic zones/geographical locations in terms of its carbon sequestration potential are essential in order to better understand the carbon dynamics. For example, the Northeast Indian region is characterized by high forest cover (ca. 64%; Jain et al. 2013) but its carbon dynamical characteristics are quite different from the rest of the country. Firstly, it shows a very different characteristic in terms of the timing of the maximum CO_2 uptake on a seasonal scale compared to the rest of India (discussed later), and secondly it shows a large CO_2 variability. Deb Burman et al. (2017) reported large amplitude of the CO_2 concentration in a deciduous forest at Kaziranga in Assam (380–460 ppm) during the year of 2016. Though one year of data may not be generalized as representative values, it may be indicative of distinct spatial characteristics of CO_2 seasonal pattern of different ecosystems in India. Analysis of such records provides useful information on the amplitude and phase of the time series by means of spectral decomposition technique (Barlow et al. 2015). Additionally, tree-ring based measurement of radiocarbon activity of the atmospheric air on sub-seasonal timescale would provide information about the fossil fuel component (Chakraborty et al. 2008) of the CO_2 emission and may help to partition the CO_2 emitted by the agricultural practices (Berhanu et al. 2017).

4.2.2 Methane (CH_4)

Methane is the second most important anthropogenic GHG after atmospheric CO_2 (on the scale of radiative forcing, which is about +0.48 Wm^{-2}; Stocker et al. 2013). The pre-industrial CH_4 concentration has been estimated as 700 ppb, but increased anthropogenic activities, such as the agricultural practices and industrial activities, have resulted in a steady increase of atmospheric CH_4, up to 1803 ppb in 2011 (Dlugokencky et al. 2011; Etheridge et al. 1998). It also plays an active role in tropospheric chemistry. CH_4 is mainly lost by reaction with the OH radical, and hence it directly contributes to stratospheric water vapor increase (Keppler et al. 2006). CH_4 emissions from the anthropogenic sources in India have grown from 18.85 to 20.56 Tg yr^{-1} during 1985–2008 (Garg et al. 2011). Patra et al. (2013) made a comprehensive analysis to estimate CH_4 emission from the entire South Asian region which turned out to be 37 ± 3.7 TgC-CH_4 yr^{-1} during the 2000s. Unlike CO_2, CH_4 has a relatively short lifetime of 9–10 years. Shorter lifetime, compared to CO_2, N_2O or CFCs, is potentially useful for its sources and sinks to achieve a steady state or even a decline, thus reducing its impact on global climate change. A quasi-steady state was observed in the late 1990s and the first half of the 2000s (Dlugokencky et al. 2011). But increased emission of CH_4, driven by the anthropogenic activities, later perturbed the equilibrium state (Rigby et al. 2008; Patra et al. 2016). The source and sink mechanism of CH_4 is complex, and several components of its budget remain poorly constrained. Surface observation of CH_4 in India is limited to a very few places, and those too provide only sporadic data; long time measurement is mostly absent. The CRI data provide one of the first long-term measurements of CH_4 in India. Figure 4.3 shows the time series of the methane concentration at CRI (1993–2002; in cyan) in comparison with the MLO (in yellow) and the Seychelles site (SEY, an island in the equatorial Indian Ocean; in red). The data were obtained from the published results of Bhattacharya et al. (2009). It is noted that the seasonality in CH_4 is much stronger at CRI than at MLO and SEY as shown in the inset. Another feature is that the CH_4 mixing ratios at MLO were higher compared to the CRI values during the SW monsoon season (July–August; Fig. 4.3-inset). This provides a strong evidence of seasonality in CH_4 fluxes in the Indian Ocean sector than in the Pacific (Bhattacharya et al. 2009; Patra et al. 2009). Analysis of the high-frequency data at the Sinhagad site also revealed a strong correlation between the CO_2 and CH_4 mixing ratios during the monsoon season but weak correlation in other seasons (Metya et al. 2020), indicating that the concentrations of both these gases during the monsoon season are also controlled by the monsoon circulation that originates in the Indian Ocean.

Methane shows distinct diurnal- and seasonal-scale variations (Sreenivas et al. 2016), which, unlike CO_2, is characterized by a large variation on spatial domain. The seasonality of CH_4 is found to be varying differently over different parts of India due to the complex interaction between the surface emissions and monsoonal transport patterns (Patra et al. 2009). For example, the eastern Himalayan station Darjeeling (27.03° N, 88.26° E, 2000 m ASL) captures episodes of increased CH_4 concentrations throughout the year (Ganesan et al. 2013), but a north-western Himalayan station Hanle experiences high values during summer monsoon season (Lin et al. 2015).

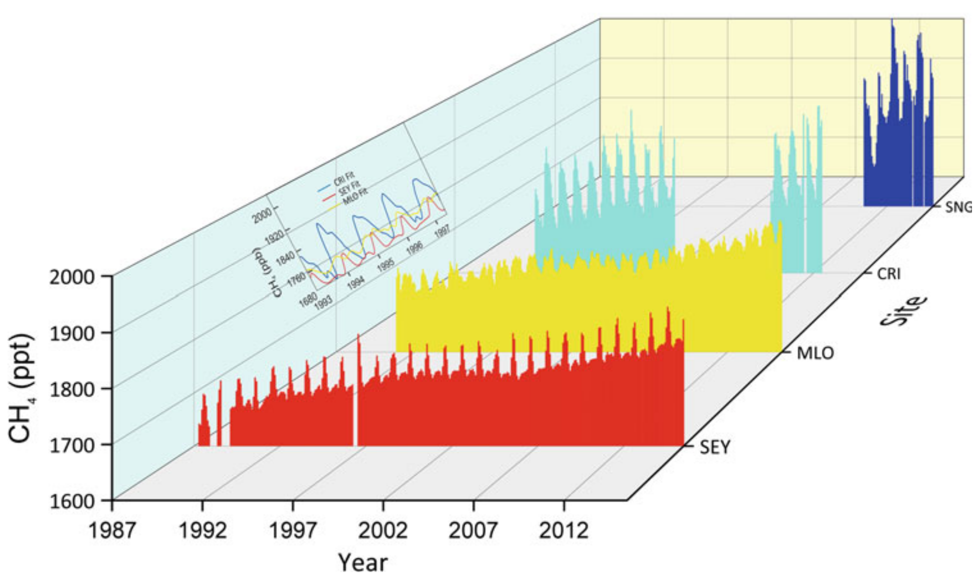

Fig. 4.3 CH_4 mixing ratio in air samples observed at SNG (deep blue) and CRI (since 1993, cyan). The Mauna Loa (yellow) and the SEY data (red) have also been shown for comparison. The inset shows a zoomed version of the CRI data emphasizing the seasonal cycles. The data are available in Bhattacharya et al. (2009) and redrawn with modification

Darjeeling experiences highest CH_4 values during October–November, while Pondicherry at the southeastern coastal site and Port Blair in Andaman Islands register comparatively lower values (Lin et al. 2015). A dense observational network is required for understanding the spatial and temporal variations of CH_4 over India, in particular the central Indian region which is characterized by sparse and intermittent observational network. Chandra et al. (2017) studied the variability of column dry-air mole fractions of methane (XCH_4) over India using GOSAT satellite retrievals. The satellite observation of the XCH_4 is an integrated measure of CH_4 densities at all altitudes from the surface to the top of the atmosphere. The Indian region was divided into eight subregions, and relationship between XCH_4 variability from surface to the upper troposphere with the surface emissions was discussed. More often, the XCH_4 variabilities are strongly linked with the transport of air mass from outside the domain of interests and monsoon anticyclone in the middle–upper troposphere. Variations of XCH_4 are controlled by both surface emissions and atmospheric transport largely driven by the monsoonal dynamics. Various observational techniques have been used to make estimates of top-down CH_4 emissions in India (Schuck et al. 2010; Ganesan et al. 2013; Parker et al. 2015). It was shown that there is a little growth in the CH_4 emissions in India during the period 2010–2015. The reported emissions in Ganesan et al. (2017) are 30% lower than the bottom-up global inventory Emission Database for Global Atmospheric

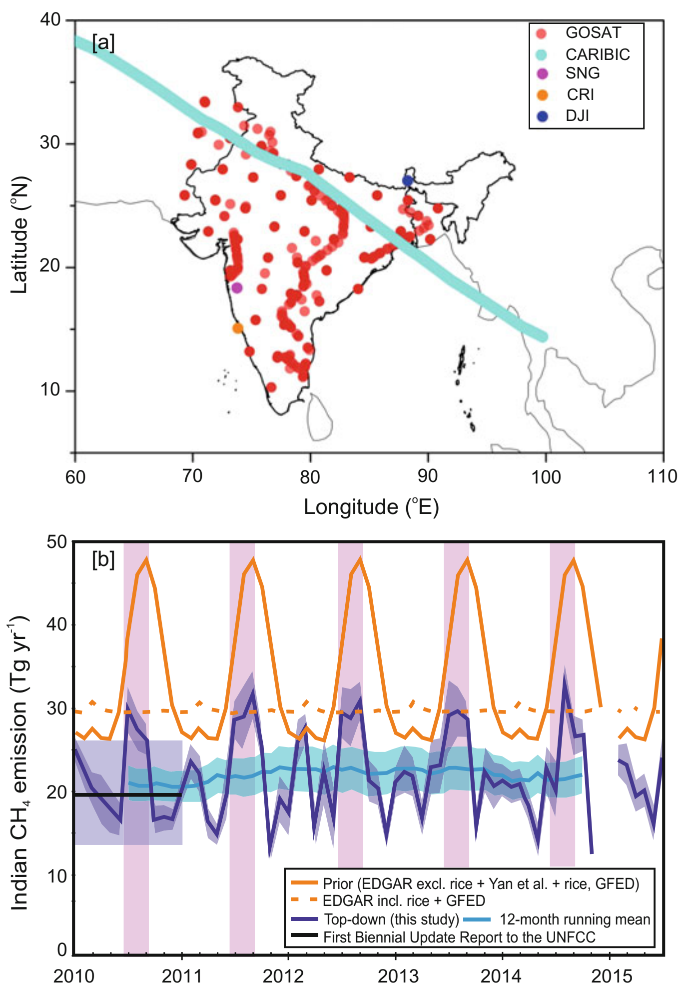

Fig. 4.4 **a** Map of observations used in top-down CH_4 emission estimations. Typical monthly coverage from GOSAT satellite retrievals (red), CARIBIC aircraft's flight path (light blue), surface sites Darjeeling, India (dark blue), Cape Rama (CRI) Goa, India (orange), Sinhagad (SNG), Pune, India (purple). **b** Monthly Indian emissions estimated by EDGAR (orange line), EDGAR2010 including rice, GFED and natural emissions (dashed orange line), top-down CH_4 estimations presented in Ganesan et al. (2017) (dark blue line) and 5th–95th percentile range (dark blue line shading), 12-month running mean along with the 5th–95th percentile range of the running mean from this study (light blue line and shading, respectively), 2010 emissions submitted to the UNFCCC by Government of India (solid black line and uncertainties as shaded line). Ref: Ganesan et al. (2017); the figure is reproduced through an open license

Research (EDGAR) during the same period (Fig. 4.4) and consistent with the emissions reported by India to the UNFCCC (NATCOM BUR-1 and BUR-2). The data used in Ganesan et al. (2013) are XCH_4 based on the CO_2 proxy method from the GOSAT satellite; flask-based measurements of dry-air CH_4 mole fraction from Sinhagad (73.75° E, 18.35° N, 1600 m ASL), Cape Rama, India (73.83° E, 15.08° N, 60 m ASL), in situ measurements from Darjeeling, India (88.25° E, 27.03° N, 2200 m ASL); and upper-atmospheric in situ measurements from the CARIBIC aircraft (Fig. 4.4a). Further, the Lagrangian particle dispersion model, Numerical Atmospheric dispersion Modeling Environment (NAME), was used to provide a quantitative relationship between atmospheric mole fractions and emissions. However, the observation of Ganesan et al. (2017) is subjected to further verification for certain reasons. It is well known that the inverse modeling results depend strongly on the selection of chemistry transport model and treatment of atmospheric measurements. In particular, the regional transport and inverse models for long-lived gas simulation suffer from the use of boundary conditions; e.g., a recent study shows the emission estimates based on observations over Siberia are greatly affected by the trends in emissions of CH_4 over Europe and Asia (Sasakawa et al. 2017). Accurate estimation of emission trends requires uninterrupted long term atmospheric observations from the region. Although Ganesan et al. (2017) used multiple streams of in situ data over India, none of the measurement locations continuously measured CH_4 during the period of their analysis (2010–2015). The remote-sensing measurements from GOSAT do not retrieve XCH_4 for the regions covered by clouds at any thickness, leading to a seasonal bias in inverse model calculation. To overcome these limitations, a well-structured GHGs long-term observational network is to be set up across India (Nalini et al. 2019).

Apart from the above activities, a few aircraft-based GHGs measurements have also been carried out over the Indian subcontinent for the vertical profiling of CO_2 over Bhubaneswar, Varanasi and Jodhpur in order to study the spatiotemporal distribution of CO_2 mixing ratio and inter-comparison with the satellite-derived products (Sreenivas et al. 2019). Out of these three places, Varanasi showed a strong gradient in CO_2 mixing ratio (ca. 3.12 ppm/km), while in the other two cities the gradient was much smaller (<2 ppm/km). Varanasi region being in the Indo-Gangetic Plain is characterized by strong anthropogenic loading, which has resulted in a relatively steep vertical gradient. The Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) Project of the Indian Institute of Tropical Meteorology also carried out similar observations during the Indian summer monsoon months of 2014, 2015 and 2018, 2019 over India and adjacent oceanic regions. The vertical profiling of methane mixing ratio revealed a strong peak at about 4.5 km. It is believed that this kind of mid-tropospheric peak occurs due to strong convective activities (Chandra et al. 2017). Among other work, uptake of winter time carbon by the agricultural practices around Delhi has been discussed in Umezawa et al. (2016).

4.3 Greenhouse Gas Flux Measurements in Natural Ecosystems

GHGs fluxes are monitored over India primarily by two major measurement networks that corroborate efforts from multiple research institutes, universities and government organizations. Two important GHG components, viz., CO_2 and CH_4, are being monitored by the chamber-based or eddy covariance (EC) systems along with the other scalar fluxes including water vapor and energy.

Estimated CO_2 flux from these measurements is subsequently used to calculate net ecosystem exchange (NEE), gross primary productivity (GPP) and total ecosystem respiration (TER) using various process-based biogeoscientific models. These parameters are the different components of the ecosystem carbon cycle. Some definitions are as follows:

NEE: The net amount of carbon exchanged (in the form of CO_2) between the land biosphere and the atmosphere at a given location over a particular period of time; negative and positive values of NEE denote uptake and release of carbon by the land biosphere, respectively.

NEP: Net Ecosystem Productivity; opposite of NEE i.e. positive and negative values of NEP denote carbon uptake and loss by the biosphere, respectively.

NBP: Net biospheric productivity. NEP–disturbance fluxes (fire, etc.).

GPP: The total amount of carbon exchanged between the land biosphere and the atmosphere, through the process of photosynthesis.

NPP: Net primary productivity; GPP - autotrophic respiration.

TER: A part of the gross carbon uptake is lost through autotrophic, heterotrophic, microbial and soil respiration, often clubbed together as TER.

The larger value of GPP signifies greater carbon assimilation by the ecosystem; however, the net carbon uptake is defined by the NEE. In general, the carbon sequestration potential of an ecosystem depends on climatological conditions, soil moisture, texture and nutrient content, and vegetation type. Hence, for a regional or country-scale estimation of carbon budget, GHGs fluxes must be measured over different ecosystems scattered across the length and breadth of the region or the country.

4.3.1 Carbon Dioxide Fluxes and Net Ecosystem Exchange

Several micrometeorological flux towers were erected for the long-term monitoring of GHGs fluxes over different ecosystems in India by the Indian Space Research Organisation (ISRO) as part of the Geosphere-Biosphere Program. These sites include a mixed deciduous teak forest in Betul over central India (Jha et al. 2013); a mangrove forest in Sundarbans on the east coast of India, flanked by the Bay of Bengal (Jha et al. 2014; Rodda et al. 2016); a mixed deciduous forest in Haldwani over north India (Watham et al. 2014; Ahongshangbam et al. 2016); and a tropical moist deciduous sal forest in Barkot over north India (Watham et al. 2017; Pillai et al. 2019).

Being deciduous in nature, the carbon exchange at the Betul forest is observed to be strongly influenced by the availability of the leaves. It is seen to act as a sink in winter with a maximum value of NEE being −300 μgC m^{-2} s^{-1} in the daytime. However, the sink strength is drastically reduced to −24 μgC m^{-2} s^{-1} in the dry months of summer due to leaf dehiscence. Annual NEE, GPP and TER of the Betul forest were not available at the time of writing this report.

The Sundarbans mangrove acted as a net sink of CO_2 with annual NEE of −249 ± 20 gC m^{-2} y^{-1}. Soil–CO_2 emission from this ecosystem was found to vary between 18 and 28 μgC m^{-2} s^{-1}. It remains positive throughout the year with a close dependency on the soil temperature (Chanda et al. 2014). Annual GPP and TER of this ecosystem were 1271 gC m^{-2} y^{-1} and 1022 gC m^{-2} y^{-1}, respectively. Sink strength varied widely between −72 μgC m^{-2} s^{-1} in summer and −120 μgC m^{-2} s^{-1} in winter.

The 9-year-old man-made mixed forest at Haldwani acted as a net CO_2 source during the leafless months of winter, quite contradictory to Betul and Sundarbans (Watham et al. 2014). Subsequently, it transformed into a sink during the growing months from April to September. The monthly mean daily total NEE of this ecosystem was 0.35 gC m^{-2} d^{-1}, in January. It became slightly negative at −0.38 gC m^{-2} d^{-1} in February and grew farther negative continuously to −5.74 gC m^{-2} d^{-1} in September. The annual NEE of this ecosystem was unavailable at the moment to quantify the yearlong total carbon exchange. The GPP of Barkot forest was observed to vary from 5.38 gC m^{-2} d^{-1} in December to 12.42 gC m^{-2} d^{-1} in September. This shows the gross carbon exchange to be stronger in monsoon compared to winter. The annual mean daily GPP of this ecosystem was 7.98 gC m^{-2} d^{-1}. However, annual NEE is required for estimating the actual carbon sequestration by this ecosystem. Based on a three-year-long EC measurement during 2014–2016, the mixed forest at Kosi-Katarmal, Almora (20.05° N, 79.05° E, 1217 m amsl), acted as a net sink of atmospheric CO_2 with the average daily NEE being −3.21 gC m^{-2} d^{-1} (Mukherjee et al. 2018). In another study, CO_2 exchange of a wheat field was measured by an EC system at Modipuram, north India, by the ISRO (Patel et al. 2011). Maximum daytime uptake and nighttime release of CO_2 by this ecosystem were observed to vary markedly during different stages of the crop growth. During the anthesis stage of the crop, maximum midday uptake and nighttime release were −26.78 gC m^{-2} d^{-1} and 3.45 gC m^{-2} d^{-1}, respectively. Due to reduced leaf area index (LAI), midday uptake drastically reduced to −19.00 gC m^{-2} d^{-1} in the senescence stage. However, the nighttime release remained unaltered. Subsequently, in the mature stage daytime uptake further plummeted below −11.22 gC m^{-2} d^{-1}. The annual estimates of NEE, GPP and TER will be required to draw conclusion on the actual carbon sequestration of this wheat field.

The Indian Institute of Tropical Meteorology (IITM), Pune, also established a few flux towers over different ecosystems under the aegis of the MetFlux India project, initiated and funded by the Ministry of Earth Sciences (MoES), Government of India. These sites include a semievergreen moist deciduous forest in Kaziranga National Park over Northeast India (Deb Burman et al. 2017, 2019; Sarma et al. 2018), a mangrove forest in Pichavaram (Gnanamoorthy et al. 2019) on the southeast coast of India by the Bay of Bengal and an evergreen coniferous forest over the eastern Himalayan range in Darjeeling (Chatterjee et al. 2018) in Northeast India. In addition to the GHG fluxes, CO_2 concentration in seawater and atmosphere is also measured in two islands, in Agatti in the Lakshadweep Islands over the Arabian Sea (Kumaresan et al. 2018) and Port Blair in the Andaman and Nicobar Islands over the Bay of Bengal as part of the MetFlux India network. The ecosystem at Kaziranga has an annual GPP of 2110 gC m^{-2} y^{-1} with a prominent seasonal variation primarily governed by the plant leaf phenology (Deb Burman et al. 2017). It is also reported that cloudiness during the Indian summer monsoon months drastically reduces the availability of the photosynthetically active radiation at this ecosystem which in turn affects its carbon sequestration activity negatively (Deb Burman et al. 2020b). The mangrove forest of Pichavaram in Tamil Nadu registered a NEE maximum (ca. −11.40 gC m^{-2} d^{-1}) during the month of January. Annual GPP and ecosystem respiration (TER) were estimated to be 1466 gC m^{-2} y^{-1} and 1283 gC m^{-2} y^{-1}, respectively (Gnanamoorthy et al. 2020). Based on a two-month observation at a high-altitude Himalayan evergreen forest near Darjeeling, Chatterjee et al. (2018) estimated springtime CO_2 flux for the year 2015. These authors observed a maximum NEE reaching up to −10.37 gC m^{-2} d^{-1}.

The analysis of the available annual NEE data from across the country reveals that the maximum carbon uptake (maximum negative NEE value on a diurnal scale) takes place typically in monsoon to early winter in most of the places, except in the Kaziranga forest in Northeast India. This site is characterized by maximum uptake (large negative NEE values) during the pre-monsoon time, while the minimum values typically occur in the winter. Kosi-Katarmal in north India sequesters maximum carbon during the late monsoon, though significant amount of carbon is also sequestered during the pre-monsoon time. The reason for this unusual behavior is thought to be arising partly due to the leaf phenology and partly driven by the regional climate variability. For example, the northeast region of India receives a significant amount of rainfall (driven by nor'westers) during the early summer and high sunshine (compared to the cloudy days during the monsoon time) days resulting in the increased uptake of carbon by the vegetation. The kharif (rainfed) sesame crop cultivated at Barkachha, Uttar Pradesh, in the Indo-Gangetic Plain over north India sequesters maximum CO_2 during monsoon, whereas the sequestration activity is seen to be severely affected by the drought (Deb Burman et al. 2020a).

4.3.2 Methane Fluxes

The Sundarbans mangrove forest acted as a net source of atmospheric CH_4 with average daily flux being 150.2 ± 248.9 mg m^{-2} d^{-1} (Jha et al. 2014). Methane source was enhanced at Sundarbans during summer months due to the elevated temperature and moisture contents. Another study by Mukhophadhya et al. (2001) estimates the CH_4 source from Sundarbans mangroves to lie within 4.5–8.9 µg m^{-2} s^{-1}. The methane flux has also been measured in the Pichavaram mangrove forest. Purvaja and Ramesh (2001) used static chamber and reported methane emission in the range of 47.2–324.5 mg m^{-2} d^{-1}.

Methane flux from Indian rice paddy fields is reported to vary from 2.4 to 660.0 mg m^{-2} d^{-1} (Parashar et al. 1991; Lal et al. 1993; Adhya et al. 1994). Total CH_4 emission from an irrigated rice paddy field in New Delhi was reported to be 0.275–0.372 g m^{-2}. Fertilizers such as urea, ammonium sulfate and potassium nitrate increased the CH_4 emission, while dicyandiamide helped reduce it (Ghosh et al. 2003). Intermittently irrigated rice paddy fields were seen to emit less CH_4 compared to the continuously flooded fields (Jain et al. 2000). A dry land rice cultivation in Varanasi, north India, was reported to be a sink of CH_4 with an average growing season uptake of 8.4 mg m^{-2} d^{-1} (Singh et al. 1997). According to these authors in dry tropical ecosystems, N availability is remarkably low, and this may be the reason for high CH_4 uptake rates in these ecosystems. Furthermore, these dry soils are well drained and permeable, and it has been clearly demonstrated that CH_4 consumption is diffusion-limited (Dörr et al. 1993). A recent study showed potential for CH_4 emission by changing rice cultivation practice from conventional transplanting (CT) to system of rice intensification (SRI) in India (Oo et al. 2018). Inland water bodies such as lakes, ponds, open wells, rivers, springs and canals are known to emit CO_2 and CH_4 to the atmosphere. Total CH_4 flux from multiple such ecosystems in India measured using flux chambers ranged from 0.16 to 834 mg m^{-2} d^{-1} (Selvam et al. 2014). Additionally, the CO_2 flux from these systems was measured to lie between 0.34 and 3.15 gC m^{-2} d^{-1} (Selvam et al. 2014).

4.3.3 Carbon Inventory of the Indian Forests

The total carbon stored in Indian forests, including forest soil, is estimated to be in the range of 8.58–9.6 PgC (Ravindranath et al. 2008). According to Chhabra and Dadhwal (2004), 3.8–4.3 PgC is stored as Indian forest phytomass, approximately 10% of the global forest phytomass carbon pool. Several studies assessed the influence of land use change on forest carbon (Ravindranath et al. 1997; Kaul et al. 2009). Kaul et al. (2009) estimated that net carbon flux attributable from land use change decreased from a source level of 5.65 Tg C yr^{-1} during 1982–1992 to a sink level of 1.09 Tg C yr^{-1} during 1992–2002. It indicates that Indian forests became a sink of atmospheric carbon due to the regeneration and afforestation efforts.

4.3.4 Agricultural Ecosystem

Apart from the natural vegetation, agricultural ecosystems also contribute significantly to the GHGs fluxes. Specifically, the rice paddy fields are known to emit significant amounts of CH_4 owing to the anaerobic conditions prevalent during the times when the fields are inundated with potentially warm water (Adhya et al. 2000). Moreover, the net emission from the agricultural ecosystems depends strongly on the agricultural practices such as applications of fertilizers, manure, pesticides, crop residue, straw and flooding of the agricultural field (Debnath et al. 1996; Singh et al. 1996; Bhatia et al. 2005). Indian Agricultural Research Institute (IARI) has several flux measurement systems across India for measuring the emissions from different agricultural fields.

4.3.5 Other Observations

Several satellites provide derived values of GPP, NEE and TER from space observations. Such products have also been compared with the ground-based estimates (Dadhwal 2012). Using SPOT VEGETATION 10-day NPP composites, Chhabra and Dadhwal (2004) estimated the total net carbon uptake by the Indian landmass to be 2.18 PgC y^{-1}. Bala et al. (2013) studied the trends and variability of the terrestrial net primary productivity over India for the period of 1982–2006 using the Advanced Very-High-Resolution Radiometer (AVHRR)-derived data. These authors found an increasing trend of 3.9% per decade over India, indicating an increased rate of carbon fixation by the terrestrial ecosystems during the past two decades. NPP estimates based on Dynamic Land Ecosystem Model for the 1901–2000 period also show an increasing trend, from 1.2 to 1.7 PgC yr^{-1} (see Sect. 4.4.1). These observations also support our hypothesis of increasing CO_2 amplitude due to increasing biospheric activity (discussed in Sect. 4.3.1). According to Watham et al. (2017), the MOD17 product by MODIS is a severe underestimation of the actual GPP calculated from both surface measurements and remote-sensing-driven models. Deb Burman et al. (2017) showed that MODIS LAI fails to capture the seasonality in the leaf phenology which can lead to significant error in the GPP estimate if used as input in process-based models. Ground observations over different ecosystems and satellite products are combined together for a countrywide estimate of carbon sequestration by Nayak et al. (2013). According to their study, broadleaf evergreen forests are the largest contributor to the annual carbon storage followed by broadleaf deciduous forests. Annual NEE of these ecosystems is -1057 gC m^{-2} y^{-1} and -658 gC m^{-2} y^{-1}, respectively. Additionally, this upscaling study also reports an estimated growth rate of 0.005 PgC y^{-1} in the annual carbon sequestration over the Indian region.

Apart from the surface flux measurements, satellite observations are also used to estimate the GHGs fluxes. Valsala et al. (2013) studied the intra-seasonal oscillations in

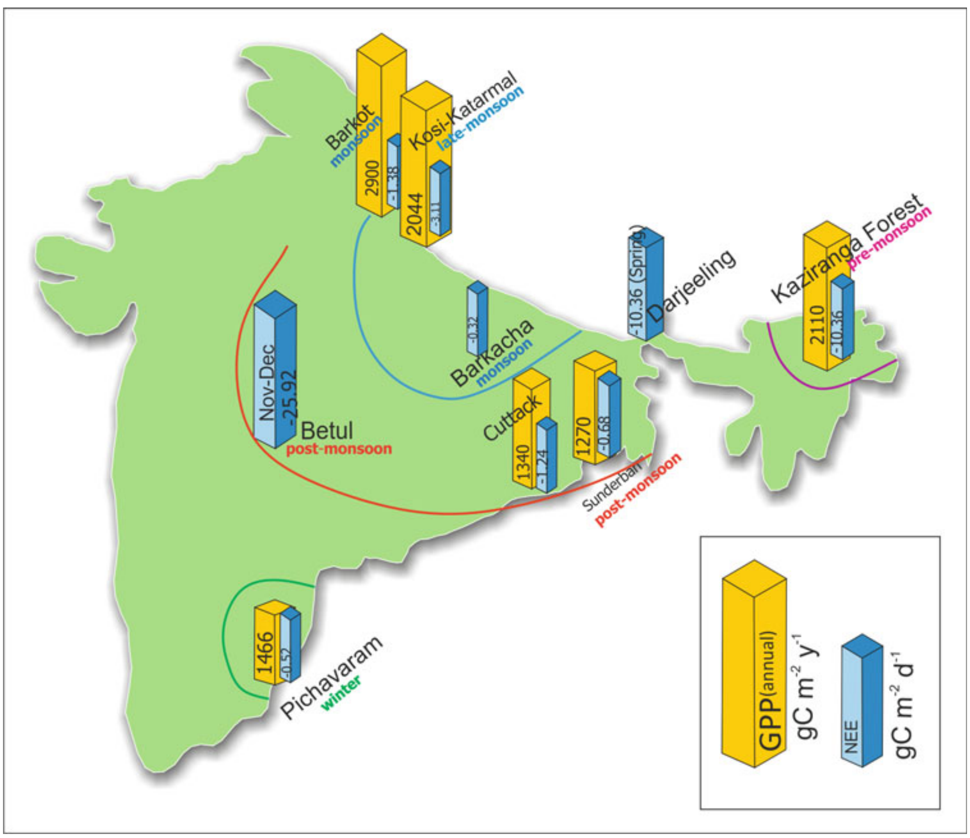

Fig. 4.5 A schematic representation of CO_2 fluxes measured by the eddy covariance technique across the different ecosystems over India. The blue bars depict the maximum CO_2 uptake by the vegetation on the diurnal timescale averaged for a particular season as mentioned in the figure (unit: gC m^{-2} d^{-1}). The yellow bar represents the GPP value for a particular ecosystem on an annual timescale (unit: gC m^{-2} y^{-1}). Maximum carbon sequestration varies greatly with season and geography: the northeast during the pre-monsoon (represented by magenta), the Gangetic plains in monsoon (shown in blue), the north, central and east India during post-monsoon (shown in orange) and the east coast of south India during the winter (shown in green). The curved lines very approximately show the geographical variation of carbon uptake for the specific season. No data are available for the whole of the western region. The total carbon uptake by the Indian landmass is estimated to be 2.18 PgC yr^{-1} (Chhabra and Dadhwal 2004)

terrestrial NEE during the Indian summer monsoon. These authors showed that while the terrestrial ecosystems act as a net source of CO_2 during June and July, they transform into the net CO_2 sink during August and September. However, due to spatial variability in GHGs distribution and dynamics, this characteristic feature may differ in specific regions. For example, the eddy covariance-based results show that the deciduous forest (Kaziranga in Assam) in the Northeast India acted as a strong sink of carbon during the pre-monsoon period (May–June; Sarma et al. 2018). On the other hand, as mentioned earlier, most of the forests in mainland India sequester significant carbon in the monsoon but maximum carbon during the post-monsoon to early winter. Hence, the study by Valsala et al. (2013) points out the limitations of satellite measurements (GHG column concentrations) in illustrating the GHGs dynamics in the Indian landmass. However during monsoon season and due to cloud cover, GHG absorption bands are obscured; hence, ground-based direct measurements of GHG are also necessary to complement the satellite measurements.

Figure 4.5 schematically shows the carbon sequestration by some Indian forests measured by means of the eddy covariance technique. The blue bar represents the maximum value of the net ecosystem exchange on the diurnal timescale for a particular month as indicated. The height is proportional to the amount of carbon uptake by the vegetation having a unit of gC m^{-2} d^{-1}. The gross primary productivity (expressed in gC m^2 yr^{-1}), available only for a few ecosystems, is shown as yellow bar.

4.3.6 Nitrous Oxide Fluxes

Another potent GHG is N_2O, which is produced in the natural biological processes occurring in soil, ocean and inland water by the microbes (Thomson et al. 2012; Davidson and Kanter 2014). Various anthropogenic activities such as agriculture, energy production, heavy industries and waste management also contribute to the rising N_2O flux into the atmosphere (Wassman et al. 2004; Malla et al. 2005; Datta and Adhya 2014). Prasad et al. (2003) studied N_2O emissions from India's agricultural sector between 1961 and 2000 and suggested that the total N_2O emission had increased approximately 6 times over 40 years. Presently, agricultural activities alone account for more than 90% of the total anthropogenic N_2O emissions in India, with 65% of the total N_2O emission being attributable to the chemical fertilizers. In a study done by Ghosh et al. (2003) over an upland rice ecosystem grown during the summer monsoon months in New Delhi, N_2O fluxes were found to vary within 4.32–2400 μg m^{-2} d^{-1}, whereas seasonal N_2O loss by the ecosystem varied between 0.037 and 0.186 kg ha^{-1}. An agricultural denitrification and decomposition model was calibrated for predicting the crop yield and GHG emissions and validated for Indian conditions by Pathak et al. (2005). According to their study, continuous flooding of rice fields results in annual net emissions as follows: 21.16–60.96 TgC in the form of CO_2, 1.07–1.10 TgC in the form of CH_4 and 0.04–0.05 TgN in the form of N_2O, whereas intermittent flooding changes the emissions to 16.66–48.80 TgC in the form of CO_2, 0.12–0.13 TgC in the form of CH_4 and 0.05–0.06 TgN in the form of N_2O. Noticeably, the agricultural practice of intermittent flooding of the rice paddy field had opposite effects on carbon and nitrogen emissions. An analysis using atmospheric observations and models suggests acceleration in N_2O emission per unit of nitrogen fertilizer use, thus a global emission factor of $2.3 \pm 0.6\%$, which is significantly larger than the IPCC default for combined direct and indirect emissions of 1.375% (Thompson et al. 2019).

4.4 Model Simulation of GHGs

4.4.1 Biogeochemical Model Study

Biogeochemical models are widely used to simulate the life cycles of GHGs. These models adopt a bottom-up approach to simulate the concentrations and fluxes of GHGs within and between various reservoirs such as the atmosphere, biosphere, pedosphere, geosphere and hydrosphere using mathematical representations of various biogeochemical, as well as biogeophysical, processes that affect the storage and transport of GHGs. Hence, they are able to simulate composite fluxes such as NEP and NBP that include soil dynamics as well as disturbances such as fire and land use/land cover change (Watson et al. 2000). Hence, these are more appropriate measures of the carbon source/sink status of a reservoir than GPP and NPP obtained using typical empirical methods.

Studies with biogeochemical models are very limited in the Indian context and confined to the carbon cycle in terrestrial ecosystems. Some studies have conducted simulations over India (Banger et al. 2015; Gahlot et al. 2017), while others have extracted India-specific information from global-scale biogeochemical simulations (Cervarich et al. 2016; Gahlot et al. 2017; Rao et al. 2019). Banger et al. (2015) used the Dynamic Land Ecosystem Model (DLEM) to estimate NPP patterns for the 1901–2000 period. They found that it has increased from 1.2 to 1.7 PgC yr^{-1} during this period. Using an ensemble average of nine different dynamical vegetation models, Cervarich et al. (2016) found NEP and NBP values for India to be in the 200.6 ± 137.7 TgC yr^{-1} and 185.9 ± 145.6 TgC yr^{-1} range, respectively, for the 2000–2013 period. These values are much larger than other estimates. Gahlot et al. (2017)

Table 4.1 Comparison of net biome productivity (TgC yr^{-1}) for the terrestrial ecosystems of India estimated using different approaches based on Gahlot et al. (2017)

Decade	1980s	1990s	2000s
Process-based models	1.04 ± 46.75	34.65 ± 54.16	18.50 ± 48.40
Inverse models	–	45.22 ± 69.53	42.12 ± 67.40
ISAM	27.17	34.39	23.70

conducted a comprehensive study using the Integrated Science Assessment Model (ISAM). They found that the NBP in India changed from 27.17 TgC yr^{-1} in the 1980s to 34.39 TgC yr^{-1} in the 1990s to 23.70 TgC yr^{-1} in the 2000s indicating that the terrestrial ecosystems of India are a net carbon sink but the magnitude of the sink may be decreasing in recent years. Their estimates are comparable with results from the models involved in the TRENDY (Trends in net land carbon exchange) project (Table 4.1). Very importantly, their results show that there is a large uncertainty between different estimates of the terrestrial carbon sink.

Banger et al. (2015) and Gahlot et al. (2017) also conducted numerical experiments to quantify the impacts of various natural and anthropogenic forcings on the dynamics of the carbon cycle. They found that the net positive carbon sink is maintained mostly by the carbon fertilization effect, aided to some extent by forest conservation, management and reforestation policies in the past decade. In an idealized modeling study, Bala et al. (2011) showed that CO_2-fertilization has the potential to alter the sign of terrestrial carbon uptake over India. They found that modeled carbon stocks in potential vegetation increased by 17 GtC with unlimited fertilization for CO_2 levels and climate change corresponding to the end of the 21st century. However, the carbon stock declined by 5.5 GtC when fertilization is limited at 1975 levels of CO_2 concentration. Thus, the benefits from CO_2 fertilization could be partially offset by land use/land cover change and climate change (Bala et al. 2011). Further, the model simulations of Bala et al. (2011) also implied that the maximum potential terrestrial sequestration over India, under equilibrium conditions and best-case scenario of unlimited CO_2 fertilization, is only 18% of the twenty-first-century SRES A2 scenario emissions from India. The limited uptake potential suggests that reduction of CO_2 emissions and afforestation programs should be top priorities for India.

The broader trends, variability and drivers of the carbon cycle dynamics over India were comprehensively addressed by Rao et al. (2019) using the multi-model dataset TRENDY for the period 1900–2010. Their analysis showed that the TRENDY multi-model mean NPP shows a positive trend of 2.03% per decade over India during this period which is consistent with a global greening in the last two decades (Chen et al. 2019) and other studies such as Bala et al. (2013) which showed an NPP increase of about 4% per decade during the satellite era. Rao et al. (2019) also analyzed the trends in water-use efficiency (WUE) of ecosystem in India and found that WUE has increased by 25% during the period 1900–2010. Further, it was found that the inter-annual variation in NPP and NEP over India is strongly driven by precipitation, but remote drivers such as El Nino–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) may not have a strong influence. The multi-model-based estimate of the cumulative NEE is only 0.613 ± 0.1 PgC during 1901–2010, indicating that the Indian terrestrial ecosystem was neither a strong source nor a significant sink during this period. Among other studies, Chakraborty et al. (1994) used proxy-based atmospheric and surface ocean radiocarbon records to estimate the CO_2 exchange rate in the coastal region of Gujarat. Using a box model approach, these authors have estimated CO_2 exchange rate in the tune of 12 mol m^{-2} yr^{-1}.

4.4.2 Greenhouse gases Emission and Projections

In this chapter, we present projections of future changes based on the SSPs (Shared Socioeconomic Pathways)—a suite of future forcing scenarios being used for the latest generation of climate model (CMIP6) experiments. The SSPs describe five possible future emissions trajectories based on different narratives of socio-economic developments in the future. It may be noted that the future forcing scenarios used by the previous generation of climate models (CMIP5) were based on the Representative Concentration Pathways (RCPs; see Chap. 1).

The future projection of GHGs emissions may be understood in light of the shared socioeconomic pathways (SSPs) by climate change researcher community, which takes an account of qualitative and quantitative trends in population growth, economic development, urbanization and education leading to future development of nations. The narratives of these are discussed in detail in O'Neill et al. (2017). These SSPs are developed using integrated assessment models. These are considered to be new scenarios designed under 5 pathways, namely SSP1, SSP2, SSP3, SSP4 and SSP5 out of which SSP1, SSP3, SSP4 and SSP5 are based on different levels of challenges to climate adaptation and mitigation while SSP2 is a median pathway considering a moderate challenge to both (O'Neill et al. 2014, 2017). Briefly, these SSPs are named and understood as:

SSP1: Sustainability, in which the world gradually shifts toward a more sustainable path where the development happens considering the environmental boundaries.
SSP2: Middle of the road pathway, where social, economic and technological developments follow a historical trend, leading to uneven progress among the countries and slowly attaining sustainable goals.
SSP3: Regional rivalry, where there is increased competitiveness among the countries to attain development and policies are mostly oriented toward empowering national securities and local issues.
SSP4: Inequalities, where uneven investments and policies enhance the inequalities among and within the countries' increase. Energy demand increases so as the consumption of carbon as well as low-carbon energy sources.
SSP5: Fossil-fueled development; investment in technological progress and human capital is considered a way to achieve sustainable development. To cater the increasing energy demand for achieving economic development, this world still primarily relies on the fossil fuel resources.

Further details about these SSPs can be found in Calvin et al. (2016), Fricko et al. (2016), Fujimori et al. (2016), Hasegawa et al. (2018), Kriegler et al. (2016), van Vuuren et al. (2016). Emission projections are made using these SSPs in MAGICC6 (Model for the Assessment of Greenhouse Gas-Induced Climate Change) climate model and are available as 9 CMIP6 emission scenarios, 4 of which are in line with the radiative forcings of 2.6, 4.5, 6.0 and 8.5 W m^{-2} of RCPs of CMIP5 projections as SSP1-2.6, SSP2-4.5, SSP4-6.0 and SSP5-8.5. The 5 additional intermediate scenarios cover vivid possibilities of forcing targets during emergence of these scenarios in future as SSP1-1.9, SSP3-7.0, SSP3-low near-term climate forcing (LowNTCF), SSP4-3.4 and SSP5-3.4 Overshoot (OS). Out of these, SSP3-7.0 and SSP5-8.5 are baseline scenarios, considering no additional policies are brought into the action to mitigate GHGs emission other than the existing policies. Considering the base year as 2015, all these scenarios were then harmonized for smooth transition between the historical data and these projections and downscaled at country level (Gidden et al. 2018).

Future projections for India's GHG emissions, primarily CO_2 and CH_4, under different SSPs up to the year 2100 are shown in Fig. 4.6 where CO_2 emissions span over a large range of 2–16 Gt-CO_2 yr^{-1} under different scenarios and CH_4 emissions span over 10–90 Mt yr^{-1}. The data were sourced from Riahi et al. (2017). In India, emission projections under four SSPs and a total of 8 scenarios are available, SSP1-1.9, SSP1-2.6, SSP3-7.0, SSP3-LowNTCF, SSP4-3.4, SSP4-6.0, SSP5-3.4 OS and SSP5-8.5. SSP1-1.9 is considered a greener world where energy consumption is based on more green and renewable energy sources, restricting the radiative forcing to 1.9 W m^{-2} which is in accordance with the recent Paris Agreement. Trajectories represent the immediately decreasing CO_2 emissions. In SSP1-2.6 which also implies a greener world, but the radiative forcing reaches a level of 2.6 W m^{-2}, CO_2 emission tends to decrease, but slightly less than that of SSP1-1.9 in the future due to investment in green energy. India's CO_2 emissions are projected to peak by the year 2030 and gradually decrease thereafter. CH_4 emissions are projected to decrease gradually by the year 2100 to its lowest value hovering around one-third of present emission. India's (intended) nationally determined contribution under the Paris Agreement commits to reduce the emission intensity of its GDP by 33–35% by 2030 from 2005 level and to achieve about 40% cumulative electric power installed capacity from non-fossil fuel-based energy sources by 2030. These SSP projections are in line with the green and sustainable world with least GHGs emissions from India as well in such scenario.

In SSP3-70 and SSP3-LowNTCF, there is a consistent increase in CO_2 emissions till the end of the century at almost the same rate. For CH_4, there is an increase in SSP3-70 scenario, but in the SSP3-LowNTCF scenario, where the policies are to reduce the forcing due to short-lived species, a sharp decrease after 2020 and then a slight increase are projected till the end of the century. CO_2 increase is attributed to the increased power consumption to meet the growing energy demand mostly by relying on fossil fuels and carbon-based energy sources along with the change in land use, whereas CH_4 emissions are dominated by agriculture (cultivation and livestock) as of now, also contributed by energy sector and waste management. Under the SSP3-70 scenario while CO_2 emission tends to increase about four times the present emission, increase in CH_4 emission is projected to rapidly increase after 2020 and shall be tripled by the end of the century; in fact, CH_4 emissions are seen to reach higher values in this scenario among all the cases.

SSP4 projection is in the world of unequal development. In SSP4-6.0, where radiative forcing is restricted to 6 W m^{-2}, India's emission of both CO_2 and CH_4 is projected to peak around the middle of the century, after which it stabilizes and shows a decreasing tendency around the year 2060 probably due to the inclusion of investments in better technologies and sustainable energy sources in the future. While CO_2 emissions tend to stabilize toward the end of this century around today's emission rate, CH_4 emissions are on the higher side, even after an anticipated decline in emission in the latter half of the century. In SSP4-3.4, CO_2

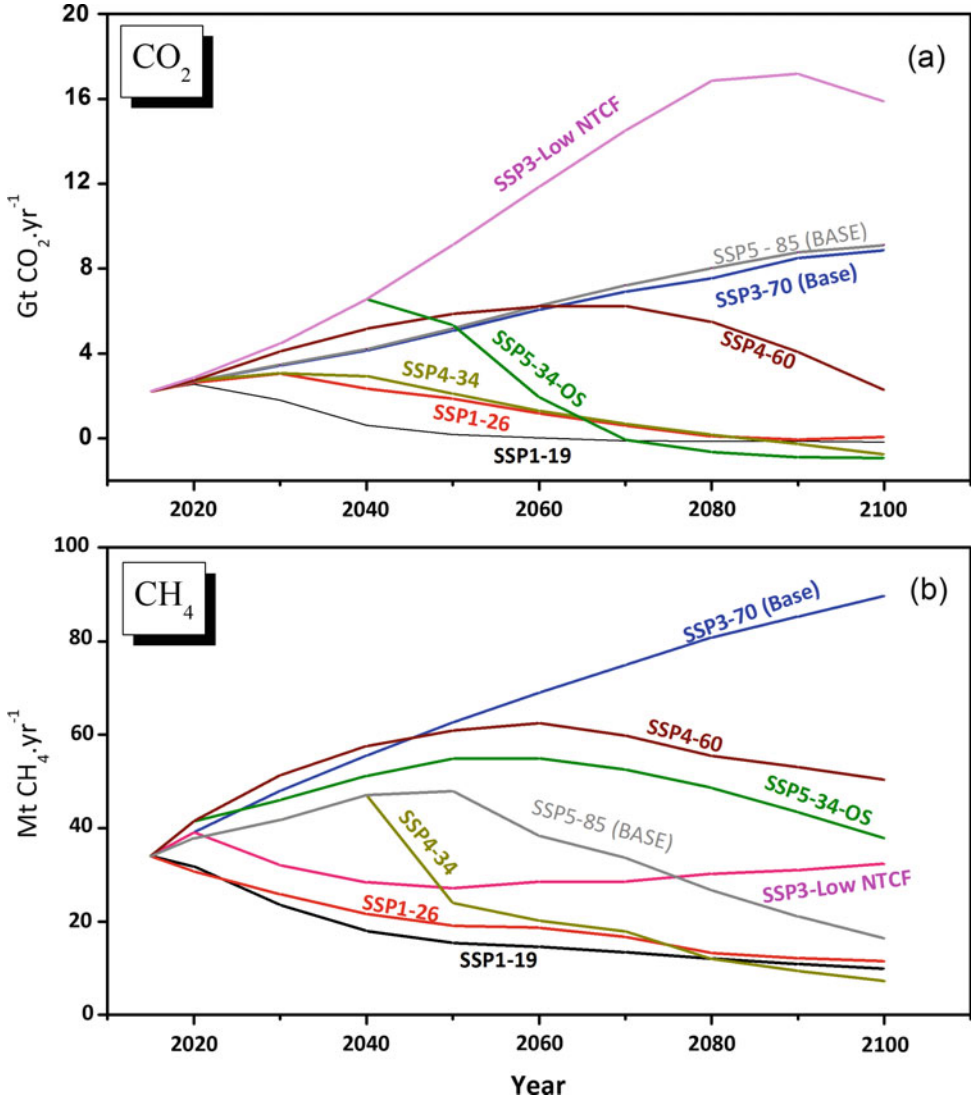

Fig. 4.6 Emission trajectories of (**a**) CO_2, and (**b**) CH_4 for India under different CMIP6 emission scenarios

emission trajectories are toward decreasing trend in the near future and CH_4 emission trajectories following slightly lesser than the SSP4-6.0 trend.

In SSP5, CO_2 emissions are projected to follow an increasing trend for the next few decades and stabilize itself around the year 2080. It then slightly decreases by 2100, but yields the highest emission of CO_2 as a result of socioeconomic development powered by fossil fuel. Projected emissions hover at the highest rate of 16,000 Mt CO_2 yr^{-1}. CH_4 emission is projected to increase till 2040 and stabilize itself in a decade, and by 2050 it starts decreasing and ends up to the values near the emission values as projected in SSP1. This decrease in CH_4 emission may be attributed to better agriculture practices, livestock management and land usage as a result of investment in technologies.

4.5 Knowledge Gaps

The seasonal-scale atmospheric CO_2 concentrations typically show high amplitude in the high latitude region and low in the tropical areas. Despite being a tropical country, the Indian CO_2 variability shows unusually large seasonal cycle and an increasing trend in the CO_2 values. So, whether the natural and/or the anthropogenic emission of carbon is controlling the CO_2 amplitude needs to be properly understood.

A lack of long-term record and sparse observational data limits our ability to comprehensively assess the biogeochemical cycle of carbon over India. The eddy covariance-based data of NEE are available only for a few forested and agricultural environments. It is also believed that trees emit significant amount of methane, especially in forested environment; no study to ascertain and quantify the plant-derived methane emission exists in India. This poses a serious constraint in making an accurate estimation of the net ecosystem productivity and in turn the carbon sequestration potential of the Indian forests. A large amount of vapor is generated through the process of transpiration, but their role in modulating the monsoon processes remains largely unknown. Apart from insufficient observational data, there are no significant studies for Indian region to quantify this effect by climate modeling. Development and use of coupled climate–carbon models could help identify the sources and sinks of both carbon dioxide and water vapor fluxes. Inverse models have been shown to reliably estimate the sources and sinks of the GHGs, but insufficient observed data pose a serious challenge to achieve the task in the Indian context. Likewise, the role of the oceanic GHG emission on the terrestrial carbon cycle also remains poorly constrained.

One of the important parameters is the carbon isotopic values of certain GHGs, such as CO_2 and CH_4, which are known to provide valuable information about the sources, but their use in the Indian context is almost nonexistent. With the advent of new technology (i.e., laser-based cavity ring-down spectroscopy), real-time in situ monitoring of GHGs concentrations and their isotopes are possible (Mahesh et al. 2015; Chakraborty et al. 2020). Use of outputs from such instruments would greatly enhance our capability to characterize the GHGs source and sink patterns on a higher temporal and regional scale.

With increasing population and rapid industrialization, energy demand for the country is increasing at a rapid pace resulting in more GHGs emissions. But there is no network of observations available to monitor these emissions and to have a better understanding of sources and sink pattern over the country. In this context, there is an urgent need to develop a countrywide surface GHGs concentration observational network and their fluxes at all the major ecosystems and urban hotspots.

Other issues, such as the sensitivity of the photosynthetic sink and the respiration-driven sources of carbon to increased warming, relation between the CO_2 and other green house gas fluxes with the intra-seasonal variation of rainfall across the ecosystems, need to be investigated.

The scope of research needs to be expanded using process-based modeling of carbon cycle to quantify the role of different natural and anthropogenic factors. These models do not rely on the remote-sensing data and hence can be used to study the pre-satellite era as well as develop future scenarios. Development of a coupled climate and GHG cycle model constrained and validated by an extensive observational network would strengthen the effort in unraveling the regional sources and sinks of the GHGs and develop realistic projections of the future.

4.6 Summary

The observational records of CO_2 and CH_4 concentration are available from a West Indian location (Sinhagad) for the last several years. This is one of the very few flask-based measurements that is currently underway in India on a long-term perspective.

The observation shows that the amplitude of CO_2 mixing ratio has been increasing progressively for the past several years. The mechanism responsible for producing such variability is not fully understood, but is likely to be linked to the changes in vegetation and forest cover.

Reports available on Indian forest cover expansion (contraction) are not coherent. Systematic efforts are required to address these issues. The measurement of surface CO_2 concentration over a wide geographical area must be carried out on a long-term basis. Analysis of such kind of records has been proven to be an effective means to assess the biospheric activity.

Use of satellite-derived vegetation indices (proxy of terrestrial biosphere) indicates an increasing trend (ca. 4% per decade) during the last two decades in India. Also, the NPP estimates based on Dynamic Land Ecosystem Model for the 1901–2000 period show an increasing trend, from 1.2 to 1.7 $PgC.yr^{-1}$.

The available surface GHGs concentration observations, albeit from a limited area, indicate the role of marine processes, especially during the summer monsoon season, in determining the seasonal pattern of CO_2 and CH_4 fluxes. However, quantification of this process needs to be done for a better understanding of the GHGs dynamics.

The atmosphere–biosphere exchange of CO_2 tends to be active during summer monsoon and maximum during post-monsoon seasons of India. However, the Kaziranga forest in Northeast India appears to sequester maximum carbon during the pre-monsoon season.

The net ecosystem exchange (NEE) of carbon derived from satellite retrievals gives only a gross estimate over a wide region. Considerable differences exist with the eddy covariance-based in situ observations at several places.

A robust network of eddy covariance-based observations consisting of a large number of micrometeorological tower setup over the diverse ecosystems across the country can lead to a better understanding of the biogeochemical cycles.

CO_2 and CH_4 projections for the Indian environment have been made under different CMIP6 emission scenarios. Without rapid mitigation policies, atmospheric CO_2 and CH_4 loading will continue to increase for the next several decades.

However, with more sustainable approaches using green technologies these rising trends can be controlled.

Carbon cycle study in India using the biogeochemical models is still in its infancy. Process-based modeling of GHGs cycle coupled with general circulation models should be developed to estimate the sources and sinks, and identify the transport of the GHGs contributed by different natural and anthropogenic factors. This could be carried out in association with the radiocarbon analysis of atmospheric CO_2 in order to partition the emission due to fossil fuel burning and agricultural practices and/or natural processes.

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