Recent observations of atmospheric carbon dioxide over India

Carbon dioxide (CO_2) plays a significant role in the global biogeochemical carbon cycle. The atmospheric concentration of CO_2 has increased by 40% from a pre-industrial level of 278 ppm in 1750 to 390.5 ppm in 2011, as a consequence of various anthropogenic activities[1]. The atmospheric CO_2 concentration has exceeded levels measured for at least the past 800,000 years, the period covered by ice cores[1]. The radiative forcing of CO_2 is estimated at 1.82 [1.46–2.18] Wm^{-2} and further increase in atmospheric CO_2 concentrations may result in significant climate changes in the future[2]. Networks of surface *in situ* sensors provide precise and accurate measurements of CO_2 concentration; however, their sparse and uneven global distribution results in large uncertainties in the natural carbon cycle for key regions such as tropical or boreal regions[3]. Satellites provide a unique opportunity to study variability of atmospheric CO_2 with large spatial and temporal coverages. In this direction, the National Aeronautics and Space Administration (NASA), USA had launched an Orbiting Carbon Observatory-2 (OCO-2) in July 2014 as an important new tool for studying and understanding the fundamental processes that control the accumulation of CO_2 in the atmosphere at present and in the future[4].

OCO-2 is designed to collect space-based measurements of atmospheric CO_2 with the precision, resolution and coverage needed to characterize the fundamental processes of atmospheric CO_2. OCO-2 orbits the Earth 14.5 times each day in a 705 km, sun-synchronous, 98.2° orbit with a 98.8 min period and 1:30 p.m. equator crossing time. Over each 233-orbit ground-track repeat cycle, it collects about 16,000,000 measurements, with orbit tracks separated by less than 1.5° long. at the equator[4]. This space-based instrument incorporates three co-boresighted, long-slit, imaging grating spectrometers optimized for the O_2 A-band at 0.765 μm and CO_2 bands at 1.61 and 2.06 μm. The OCO-2 mission aims to provide precise space-based retrievals of XCO_2 data with spatial and temporal resolution required to identify and characterize the variability in CO_2 sources and sinks on regional scales as well as seasonal to inter-annual timescales. There are three different observing modes of OCO-2, namely nadir, glint and target modes (Figure 1). Glint observations have much greater signal-to-noise ratio (SNR) over the ocean, which acts as a specular surface, and thus glint estimates are higher than nadir observations. Nadir and glint modes are regular science modes and target observations are conducted over OCO-2 validation sites only, which lie within 61° of the local spacecraft nadir along the orbit track and spacecraft viewing angles between ±20° of the ground track[5].

India extends from 8° to 37°N lat. and 68° to 98°E long. OCO-2 Level-2 (L2) geolocated XCO_2 retrievals based on physical model and retrospective processing of nadir and sunglint mode observations represented as improved 7r algorithms were collected[6]. The nadir observations included 46 passes over the Indian region during 19 March–3 April 2015 and 8 May–2 July 2015. In glint mode, 44 passes during 4–12 April 2015 and 13–19 April 2015 over the Indian region were available. On 27 and 31 March and 2 April 2015, two simultaneous nadir observations were collected, but only one included the footprints falling in the Indian territory. Similarly, in glint mode, on 4, 9 and 11 April 2015, two simultaneous observations over the Indian region were collected, but only one included the footprints falling in the Indian territory. Figure 2 shows the spatial coverage of nadir and glint observations used in the present study. The target observations were not acquired over the study area. The spatial databases of OCO-2 L2 XCO_2 nadir and glint observations over the Indian region were prepared over 0.5° × 0.5° grid.

The spatio-temporal analysis indicated XCO_2 in the range 320–432 ppm during the period 19 March–2 July 2015. The XCO_2 concentration in nadir and glint modes varied from 320 to 426 ppm and 354 to 432 ppm respectively. The mean XCO_2 concentration over India was estimated as 399.73 (±1.89) ppm. The merged gridded 0.5° × 0.5° image of nadir and glint observations over the Indian region was generated and a classified map with administrative boundary coverage of India was prepared in ArcGIS (Figure 3). The spatial pattern indicates that most of the regions in the country have 395–405 ppm CO_2 concentration with few grid points having value more than 410 ppm. It is difficult to precisely attribute the causes for such higher values; however, there could be a few possible reasons like lack of CO_2 sink, point sources like forest fire or biomass burning or an urban source, and gaseous transport from neighbouring regions based on prevailing weather conditions. At grid level, the carbon sinks are higher in terrestrial part compared to ocean region, resulting in higher XCO_2 observed over the oceans. Accuracy of retrieval could also be a possible reason. The retrieval of trace gases by absorption in the atmospheric column also takes into account the a priori knowledge of albedo and other land surface features. Sometimes, this a priori information may not be true, which may possibly lead to error

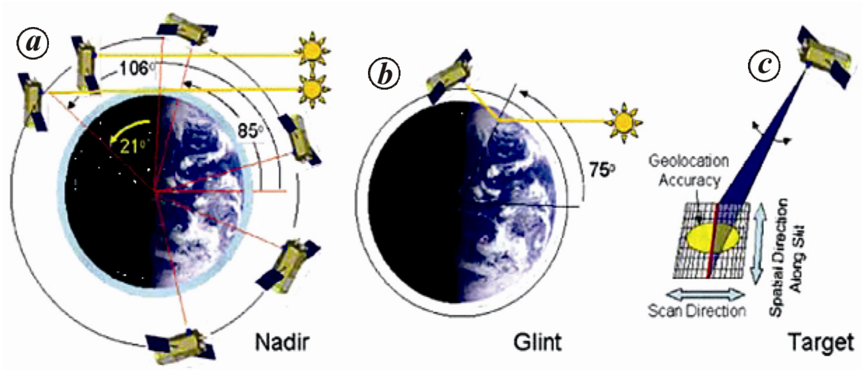

Figure 1. Nadir, glint and target modes of OCO-2. ***a***, Nadir observations acquired over the sunlit hemisphere at latitudes where surface solar zenith angle (SZA) <85°. ***b***, Glint observations at latitudes on the sunlit hemisphere where SZA <75°. ***c***, For target observations, the spacecraft points the instrument at a stationary surface target as it flies over.

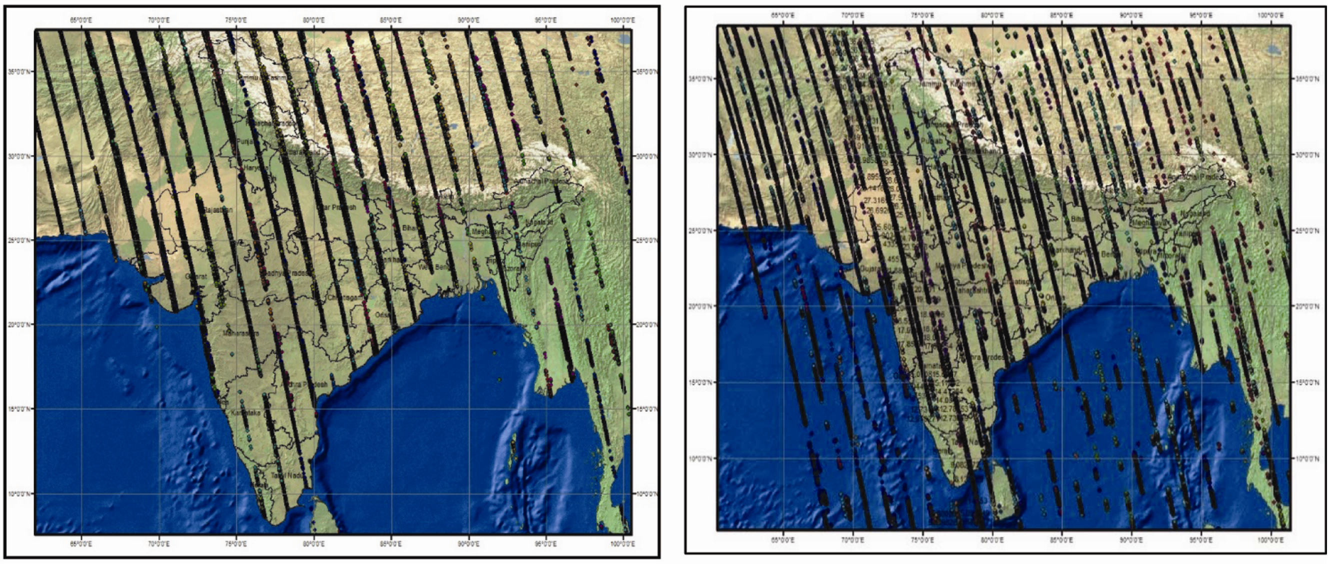

Figure 2. (Left) OCO-2 nadir observations and (right) OCO-2 glint observations over the Indian region.

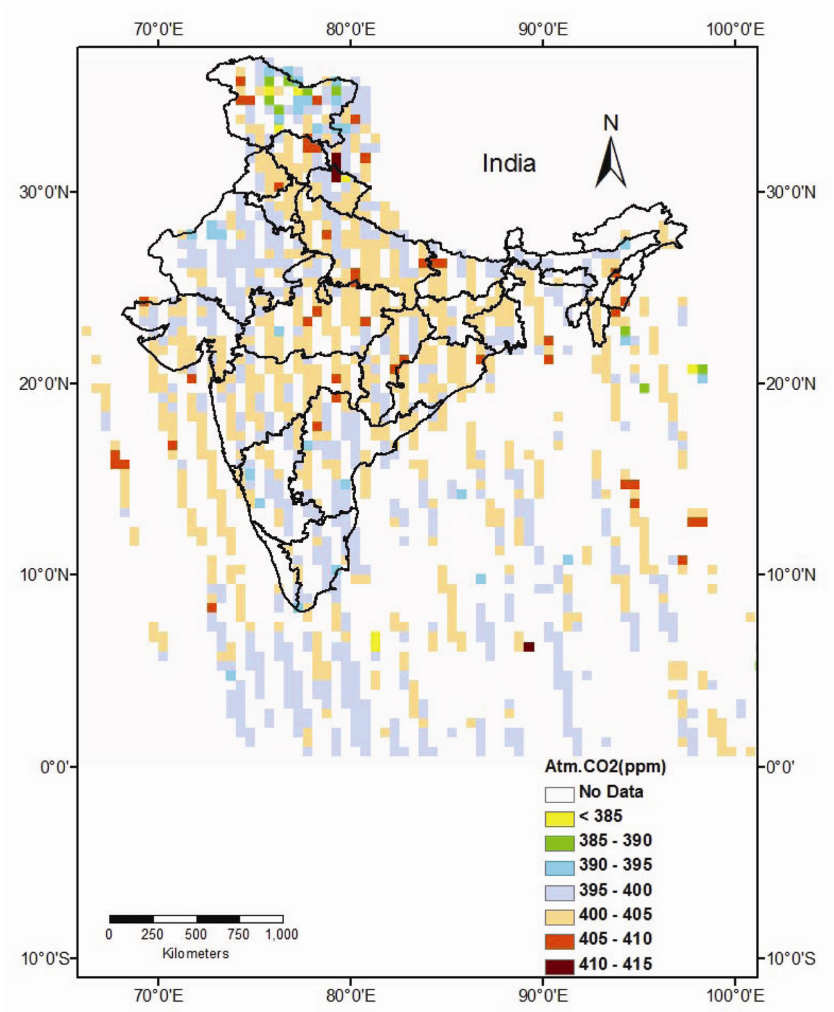

Figure 3. OCO-2 observed atmospheric CO_2 concentration during 19 March to 2 July 2015 over the Indian region mapped over 0.5° × 0.5° grid.

in retrieval estimates. In fact, this is one of the biggest challenges in the retrieval of trace gases concentration.

Cape Rama, a coastal station (lat. 15.08°N, long. 73.83°E) on the west coast of India, is located 80 km south of Panaji, Goa, India. This is a maritime site on a flat rocky terrain about 60 m amsl. During the southwest monsoon period, Cape Rama receives air masses from the sea, whereas during the winter northeast monsoon period it receives winds from landmass of the Indian subcontinent[7]. The CARBONTRACKER_CT2013B available data for the period 2000–2002 and 2009–2012 over Cape Rama were collected to study long-term atmospheric CO_2 concentration over India. These are a combination of an ObsPack Data Product and CarbonTracker simulated data[8]. The available CARBONTRACKER_CT2013B data and recent OCO-2 XCO_2 observations at Cape Rama were fitted using two curve-fitting techniques in order to bring out the seasonal cyclic fluctuations. A linear fit was performed to determine the current rate of increase in atmospheric CO_2 concentration over Cape Rama during 2000–2015 (Figure 4)

$$f(x) = \exp(a + b/x + c*\log e(x)) + d*\sin(e*x + f),$$

where $a = -6.734$, $b = 1331$, $c = 1.229$, $d = 3.716$, $e = 0.9$ and $f = -66.34$. Goodness of fit: $R^2 = 0.9001$ and RMSE = 3.82.

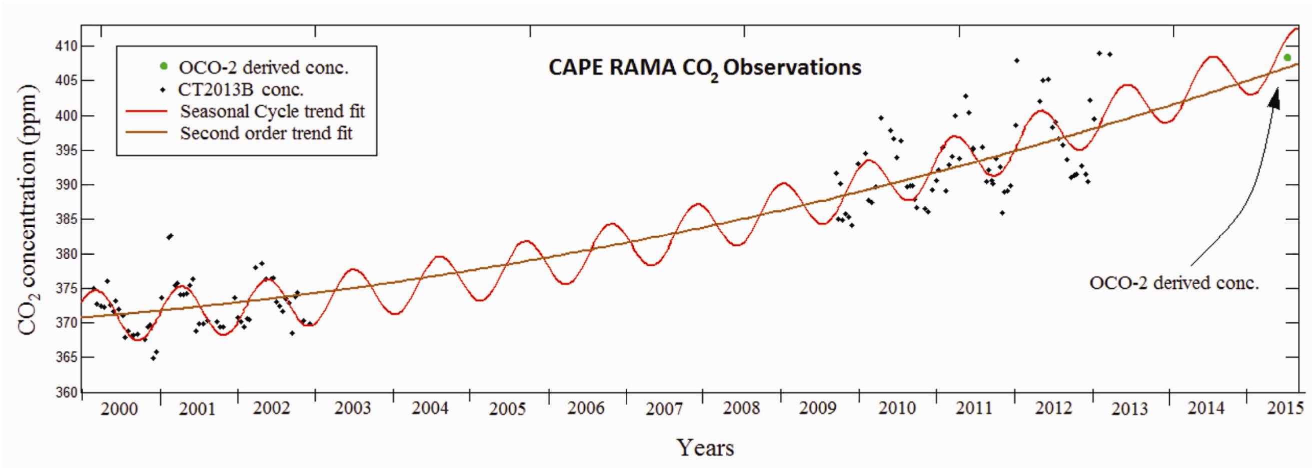

Figure 4. Seasonal cyclic fluctuations in XCO_2 concentration over Cape Rama, India during the period 2000–2015 (data source: CARBONTRACKER_CT2013B and OCO-2).

The long-term data series provides baseline information with an increasing trend in XCO_2 over India for the period 2000–2015. With availability of space-based OCO-2, similar increasing trend was observed at Cape Rama with mean XCO_2 of 408 ppm. The increasing trend in XCO_2 observed in India is comparable to the observed global mean CO_2 growth rate of 2.15 ppm/yr over Mauna Loa, Hawaii, USA during the past decade. Besides, Earth System Research Laboratory, Global Monitoring Division, National Oceanic and Atmospheric Administration (NOAA) has also reported monthly average CO_2 concentration of ~404 ppm measured at Mauna Loa observatory, Hawaii, indicating a global increase of atmospheric CO_2 concentration during the recent period[9].

This study presents an analysis of atmospheric CO_2 concentration over the Indian region based on nadir and glint observations of OCO-2. The present rate of increase in annual mean CO_2 growth rate over Cape Rama has also been studied. With availability of more OCO-2 data, inter-seasonal and inter-annual variabilities in XCO_2 concentration over different land-cover types and their correlation with vegetation indices may be attempted. This study provides useful insights for understanding the present atmospheric CO_2 concentration, an important component of the biogeochemical carbon cycle.

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ABHA CHHABRA*
ANKIT GOHEL

Earth, Ocean, Atmosphere, Planetary Sciences and Applications Area,
Space Applications Centre,
Indian Space Research Organization,
Ahmedabad 380 015, India
**For correspondence.*
e-mail: *abha@sac.isro.gov.in*