

Table of Figures

Figure 2. 1. Samples of radiance spectrum for the solar radiation reflected from a typical vegetation derived from AVIRIS-NG hyperspectral image (solid line) and measured with ground-based spectroradiometer (dashed line).	14
Figure 2. 2. Working principle of a spectroradiometer	15
Figure 2. 3. Comparison of spectroradiometric and imaging spectra: (a) Samples of solar radiance spectra measured with ground-based spectroradiometer. (b) Samples of image-derived hyperspectral radiance variation for densely populated urban regions. The thick line marked as ‘AV’ denotes the radiance spectrum derived from AVIRIS-NG image and the thin lines represent the similar radiance spectra obtained from Hyperion images for monsoon (H1) and winter (H2) seasons.	16
Figure 3. 1. Variation of MODTRAN6 simulated absorption depth $\tau(z)$ (hollow circles) fitted with Eq. (3.4) (dashed line). The transition point of the ground surface is indicated by the solid line.	51
Figure 3. 2. Sample solar radiance spectra for a typical urban site measured with ASD spectroradiometer for narrow and wide-angle fields-of view. The inset shows an enlarged view around CO ₂ absorption bands (1 & 2). The water vapor (H ₂ O) and oxygen (O ₂ -A) absorption bands are indicated on the spectra.	53
Figure 3. 3. A sample of AVIRIS-NG image-derived hyperspectral radiance variation over 0.4 to 2.4 μm for densely populated urban region.	54
Figure 3. 4. Samples of field measured surface reflectance spectral curves for three different surface features, namely grass, soil and concrete; the inset showing an expanded view for the CO ₂ absorption bands.	58

Figure 3. 5. Wavelength dependence of the reflected radiance over the CO ₂ absorption bands for different surface features, namely Waterbody, Vegetation and Concrete derived from AVIRIS-NG image: (a) Original condition in DN value and (b) After normalizing with Eq. (3.3).....	58
Figure 3. 6. (a) A segment of AVIRIS-NG image containing distinct waterbody (W), vegetated region (V) and non-vegetated urban zone (U) and (b) the corresponding spatial distribution of CO ₂ concentration (ppm) estimated from CO ₂ -2 band.	59
Figure 3. 7. (a) MODTRAN6 simulations of CO ₂ absorption bands for tropical urban atmosphere with different water vapor concentrations (g cm ⁻²) indicated against the curves. Atmospheric profile: tropical urban, assumed CO ₂ concentration 400 ppm, surface reflectance 10%, Lambertian and sensor altitude 6 km. (b) Spatial distribution of CO ₂ concentration (ppm) estimated from CO ₂ -1 absorption band for the AVIRIS-NG image of Figure 3.6(a) using the same a-DOAS algorithm of section 3.1.3 and including 9% increase for water vapor effect on the absorption depth.....	60
Figure 3. 8. Spatial spreading of CO ₂ concentration (ppm) assessed from (a) CO ₂ -2 and (b) CO ₂ -1 absorption band for the AVIRIS-NG image segment of Figure 3.6(a) by the conventional image-derived CIBR technique using MODTRAN6 simulated model parameters.	62
Figure 3. 9. Radiance spectra for Mars derived from CRISM images at different seasons indicated against the curves. Three CO ₂ absorption bands designated as CO ₂ -1, CO ₂ -2 and CO ₂ -3, respectively are visible on the radiance spectral curves.	66
Figure 3. 10. Terrestrial atmospheric radiance spectra derived from AVIRIS-NG images for vegetation, waterbody and urban regions. The CO ₂ -1 and CO ₂ -2 absorption bands are visible.....	66
Figure 3. 11. MODTRAN simulated radiance spectra illustrating: (a) absorption due to different H ₂ O concentrations (gcm ⁻²) with 400 ppm of CO ₂ concentration, (b) overlapping of CO ₂ absorption with zero H ₂ O (solid lines) and H ₂ O absorption with zero CO ₂ (dashed lines), radiance ratio (L ₀ /L _a) of CO ₂ -1 and CO ₂ -2: (c) in the same scale and (d) in individual scales.	67

Figure 3. 12. (a) Variation of CO ₂ -1 to CO ₂ -2 absorption depth ratio \otimes with CO ₂ (ppm) and H ₂ O (g cm ⁻²) concentrations simulated with MOdTRAN6 for tropical atmosphere of the earth with two different surface features: urban (solid line) and grassland (dashed line). (b) The corresponding percentage deviation in R from that with zero water vapor (symbols are same as those of Figure 3.12(a)).....	68
Figure 3. 13. (A) and (B) are AVIRIS-NG image segments of densely populated areas. The corresponding CO ₂ concentration (ppm) distributions are derived in (C) and (D), respectively using CO ₂ -2 absorption depth. The CO ₂ distributions for the same two regions retrieved from CO ₂ -1 absorption depth are given in \otimes and (F), respectively. The distributions retrieved from CO ₂ -1 with H ₂ O correction are given in (G) and (H), respectively.	71
Figure 3. 14. Binned scatter plot of CO ₂ values estimated from CO ₂ -1 and CO ₂ -2 band of (a) Figure 3.13 \otimes vs (C) and (b) Figure 3.13(F) vs (D).....	72
Figure 4. 1. Google earth map showing the boundaries (green) of the five overlapping rectangular regions enclosing a major portion of India and the locations of the nine Indian sites specified in Table 4.1.....	80
Figure 4. 2. Monthly average CO ₂ mole fraction (ppm) obtained from NASA-Giovanni online environment for regions 1 through 5 (Table 4.1): (a) for years 2003–2011 and (b) for years 2010–2016.	82
Figure 4. 3. RGB false colour composite for the surface features of sites A through I (Table 4.1) obtained from AVIRIS-NG images.	84
Figure 4. 4. The spatial distribution of CO ₂ corresponding to the surface features of the sites of Figure 4.3, retrieved from AVIRIS-NG images using the CO ₂ -2 absorption band by the method outlined at section 2.2.	85
Figure 4. 5. Histogram distribution of CO ₂ by the number of pixels corresponding to the sites of Figure 4.4.....	86

Figure 4. 6. Temporal changes of the CO ₂ daily data for the period of 2016-19 over 1°×1° (≈ 100 km × 100 km) area surrounding each of the sites A through I , (a) fitted with straight lines and (b) the slopes indicating the linear increasing rate (ppm/year).	88
Figure 4. 7. CO ₂ concentration (ppm) at urban sites (Jaduguda, Jodhpur, Kakinada and Kolkata), plotted and fitted (white circles, solid line) along with that for deep sea (black circles, dashed line) for years 2016 to 2019.	90
Figure 4. 8. Atmospheric water vapour (H ₂ O) concentration derived from the ratio (R) of the two CO ₂ absorption bands: (a) The influence in R-values of CO ₂ and H ₂ O change in grey mesh across vast ranges simulated using MODTRAN6 is shown in black dots, (b) the original H ₂ O distribution supplied with the AVIRIS-NG image.	92
Figure 4. 9. Spatial distribution of H ₂ O (g cm ⁻²) retrieved for all nine sites using the CO ₂ and R values derived from AVIRIS-NG images.	93
Figure 4. 10. Three separate sections of the coal field area (a), (b), and (c) with (1) the matching Google Earth picture, (2) the AVIRIS-NG false colour image segment, and (3) the corresponding spatial distribution of CO ₂ concentration (ppm).	95
Figure 4. 11. Two separate locations (a) and (b) of the coalfield's (Figure 4.9) surrounding urban area are depicted with (1) the matching Google Earth picture, (2) the AVIRIS-NG false colour image segment, and (3) the related spatial distribution of CO ₂ concentration (ppm).	96
Figure 4. 12. CO ₂ difference (ppm) between the coal field region [Figure 4.10(a)] and the surrounding urban area [Figure 4.11(a)].	96
Figure 4. 13. Exact delineation of high CO ₂ zones (white regions) utilising picture post processing and a threshold value of 10% higher than the world CO ₂ average, rounded to 450 ppm. Figures 4(a), (b), and (c) correspond to Figures 1(a), (b), and (c).	97
Figure 4. 14. The xCO ₂ values procured by OCO-2 in 2018 for the regions around the coal field (Jharia) and the Kolkata-Howrah metropolitan areas.	98

Figure 5. 1. Relative optical depth generated with Eq. (5.6) and its change with various extents of aerosol path radiance (L_{pa}). The relative contributions of two reference wavelengths (756 nm and 772 nm) to path radiance are accounted for by q_1 and q_2 , respectively.....	109
Figure 5. 2. Hyperion images of Kolkata dated (a) July 27, 2002 and (b) January 6, 2010. The vegetated regions are denoted by ‘A’ and ‘B’ and waterbodies are denoted by ‘C’ and ‘D’.	110
Figure 5. 3. Spatial variation of relative optical depth [Eq. (5.6)] determined for: (a) Figure 5.2(a) 0.95 to 1.02 and (b) Figure 5.2(b) 0.64 to 0.69. The O_2 -A band is band-41 (762.6 nm) and the two reference wavebands on either sides are band-40 (752.4 nm) and band-42 (772.8 nm).	110
Figure 6. 1. Twenty-five urban places of India in relation to section 6.2.1 for procuring CO_2 monthly average data from NASA- Giovanni online environment. The sites are: 1. Ahmedabad, 2. Bhopal, 3. Bhubaneswar, 4. Bilaspur, 5. Delhi, 6. Dhanbad, 7. Indore, 8. Jabalpur, 9. Jaipur. 10. Jalpaiguri, 11. Jamnagar, 12. Jamshedpur, 13. Kolkata, 14. Lucknow, 15. NTPC Dadri, 16. Patna, 17. Raipur, 18. Rourkela, 19. Ujjain, 20. Vadodara and thermal power stations of 21. Mundra, 22. Rihand, 23. Sipat, 24. Talcher, 25. Vindhyachal.	118
Figure 6. 2. xCO_2 (ppm) variation throughout the year for (a) 2017, (b) 2018 retrieved from OCO-2 database for coordinate range 22° N to 23° N and 86° E to 89° E.	127
Figure 6. 3. Annual CO_2 (ppm) variation for the year 2016 extracted from AIRS database for the region 22° N to 23° N and 86° E to 89° E.	128
Figure 6. 4. Annual fluctuation of solar induced fluorescence ($Wm^{-2}m^{-1}sr^{-1}$) retrieved from the OCO-2 database for the years (a) 2017 and (b) 2018 for the area between 22° N and 23° N and 86° E and 89° E.....	130

Figure 6. 5. For the years 2017 and 2018, annual variations in (a) and (b) surface pressure (hPa) and (c) and (d) air temperature (K) were taken from the OCO-2 database for the area between 22° N and 23° N and 86° E and 89° E.	131
Figure 6. 6. Annual variation of CO ₂ concentration over the period of year 2010 to 2017 for four randomly selected places of Figure 1, namely (a) Ahmedabad (No. 1), (b) Bhopal (No. 2), (c) Delhi (No. 5) and (d) Rourkela (No. 18), obtained from NASA-Giovanni database specified in Table 6.1.....	132
Figure 6. 7. Annual variation of (a) CO ₂ concentration, (b) seasonal fluctuation over the initial value of CO ₂ concentration, (c) NDVI, (d) surface pressure and (e) surface air temperature for the period of year 2010 to 2017, each parameter averaged over the twenty-five urban areas of Figure 6.1, obtained from NASA-Giovanni database specified in Table 6.1.....	133
Figure 6. 8. Fourier transform spectra for (a) CO ₂ , (b) NDVI and (c) surface pressure for the regions specified with Figure 6.7. The arbitrary units indicate the proportional variations of the parameters.	135
Figure 6. 9. Theoretical curves generated with equations (6.1), (6.4) and (6.8) demonstrating the change in CO ₂ vertical concentration profile due to change in air temperature from 300 K (solid line) to 320 K (dashed line) and the consequent air pressure in presence of different extents of vertical transport component: (a) 10%, (b) 10%, (c) 25% and (d) 50% of ground level concentration and other changed parameters indicated in the figures.	138
Figure 7. 1. Seasonal fluctuations in xCO ₂ from 2018 to 2020 for the nine metropolitan areas (Table 7.3), computed from all OCO-2 measurements. Symbol with corresponding line: 2018 is a square with a red solid, 2019 is a triangle with a blue dot, and 2020 is a circle with a black dash. (N = the number of excellent data points discovered during a three-year period.).....	153
Figure 7. 2. Seasonal fluctuations in xCO ₂ for the nine metropolitan areas (Table 7.3) from 2018 to 2020, calculated from OCO-2, 2018 & 19 with OCO-3, 2020. Symbol with corresponding line: 2018 is a square with a red solid, 2019 is a triangle with a blue dot,	

and 2020 is a circle with a black dash. (N = the number of excellent data points discovered during a three-year period.).....	154
Figure 7. 3. Quantification of the drop time (day) and slope (ppm/day) for the xCO ₂ yearly changes acquired from OCO-2, 2018 to 2020 (upper panels) and OCO-2, 2019 & 20 and OCO-3, 2020 (lower panels) for all of the metropolitan regions shown in Figure 7.1.	155
Figure 7. 4. Seasonal fluctuations in SIF (Wm ⁻² nm ⁻¹ sr ⁻¹) from 2018 to 2020 for the nine metropolitan areas (Table 7.3), based on OCO-2, 2018, 19, and 20. Symbol and fitting line are the same as in Figure 7.1.	156
Figure 7. 5. Seasonal fluctuations in SIF (Wm ⁻² nm ⁻¹ sr ⁻¹) from 2018 to 2020 for nine metropolitan areas (Table 7.3), calculated from OCO-2, 2018 & 19, and OCO-3, 2020. Symbol and fitting line are the same as in Figure 7.1.	157
Figure 7. 6. Seasonal fluctuations in xCO ₂ from 2018 to 2020 for nine unpopulated locations (Table 7.3), determined from OCO-2, 2018, 19, and 20. Symbol and fitting line are the same as in Figure 7.1.	158
Figure 7. 7. Seasonal fluctuations in xCO ₂ from 2018 to 2020 for nine unpopulated areas (Table 7.3), calculated from OCO-2, 2018 & 19, and OCO-3, 2020. Symbol and fitting line are the same as in Figure 7.1.	159
Figure 7. 8. An example of wavelet coherence of the xCO ₂ yearly fluctuation obtained from OCO-2, 2019 and OCO-3, 2020 (Los Angeles).	161
Figure 7. 9. Comparison of the wavelet phase difference and drop time differences of the fitted xCO ₂ curves of (i) OCO-2, 2019 and OCO-3 2020 (top) and (ii) OCO-2, 2019 and OCO-2 2020 (bottom) for the urban locations abbreviated in the same order as in Figure 7.3.	161

List of Tables

Table 2. 1. Comparison of Hyperion and AVIRIS-NG.....	13
Table 2. 2. Several reports on the investigation of atmospheric CO ₂ during the last six decades.	17
Table 2. 3. Overview of several studies on the sudden decrease of CO ₂ emissions and the resulting changes in column averaged dry-air mole fractions of CO ₂ (xCO ₂) during the worldwide lockdown caused by the COVID-19 outbreak.	23
Table 2. 4. A brief sketch of several well-known methods of assessing aerosol optical depth.....	26
Table 3. 1. AVIRIS-NG band numbers for calculating mean radiance at absorbing (λ_a) and non-absorbing (λ_s and λ_l) wavelengths of the CO ₂ -1 and CO ₂ -2 absorption bands	48
Table 3. 2. Comparison of the absorption maxima for atmospheric carbon dioxide (CO ₂ -1 and CO ₂ -2) obtained from ground-, air- and space-based spectra.....	55
Table 3. 3. Comparison of non-absorbed and absorbed radiance ratio for narrow and wide angle ground measurements at four independent urban sites calculated for CO ₂ -2 band.	56
Table 3. 4. Comparison of R-values for synthetic (MODTRAN simulated) and AVIRIS-NG spectra.	69
Table 4. 1. The extents of five rectangular regions enclosing a majority of India, as well as the locations of nine Indian sites with contrast environments and expected contrast CO ₂ components related to vegetation/biosphere (Bio) and air-sea (Ocean) exchanges, as well as man-made (MM) fossil fuel combustion and fire emission.....	80

Table 4. 2. Time variation of CO ₂ concentration in India obtained from Figure 4.2 compared with earlier reports.	82
Table 4. 3. Comparison of present results with earlier reports on the change of column-averaged mixing ratio of CO ₂	89
Table 6. 1. Specification of parameters downloaded from NASA Giovanni online environment.....	116
Table 6. 2. Land use land cover information for the states containing the 25 places of Figure 6.1 for obtaining CO ₂ monthly average data (Source: calculated from the statistics of 2015 to 2016 provided by Bhuvan, Indian Geo-Platform of Indian Space Research Organization, National Remote Sensing Centre, India (https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php)).	117
Table 6. 3. Comparison of CO ₂ abundance and fluorescence response	129
Table 6. 4. CO ₂ concentration measured at ground level (with GCH-2018 CO ₂ meter) and estimated for atmospheric column average (from ASD spectroradiometry) at different types of sites. Climatic conditions: full sun, temperature 33 to 34 °C, humidity 44%, pressure 1007 mbar, wind SW 9 km hr ⁻¹	137
Table 6. 5. Some comparisons of the extent of CO ₂ seasonal variation with the possible change due to temperature fluctuation according to Equation (6.11).	139
Table 7. 1. Comparative view of the characteristics of OCO-2 and OCO-3 platforms.....	147
Table 7. 2. Locations of crowded urban and unpopulated natural regions selected around the globe, each of 2°×2° span.....	149