Chapter 1:

Introduction

1.1. Background of the Work

The atmospheric carbon dioxide (CO_2) is a vital anthropogenic greenhouse gas. Even though CO_2 exists in trace amount (≈ 400 ppm), it has a huge impact on climate change and global warming and it is highly vulnerable to human activities. The ever-increasing concentration of CO_2 in the atmosphere has drawn the attention of researchers for more than half a century but the true emphasis on the global monitoring of atmospheric CO_2 has raised impetus more recently, during the last two decades when various ground-based, airborne and satellite-based sensors have been developed for CO_2 monitoring at global and local levels.

The physical principle of such sensors is to detect the characteristic absorption features of the atmospheric trace gas on the solar radiation spectra using *hyperspectral remote sensing* technique, which is concerned with high spectral resolution of radiation. The marked difference from common laboratory spectroscopy is that the spectra are derived from images procured by the sensing system so that the process is also known as *imaging spectroscopy*.

The sensing and assessment systems for CO_2 have advanced through the implementation of two distinct modalities, namely global monitoring and detecting local changes or point sources. The following remarkable features are noted in the science and technology of atmospheric CO_2 assessment.

- The high spatial resolution mapping for the CO_2 variation originating from natural disorder, such as volcanic eruption and anthropogenic source, such as power plant has attained significance as a complement of the worldwide monitoring with ground-based and satellite-borne sensors.
- The characteristic absorption of CO_2 at around 2 μm on the solar radiation spectrum is made into wide use for the retrieval of the CO_2 concentration over the atmospheric column.
- The general-purpose imaging spectrometers of orbiting and stationary space-based and airborne sensors have successfully been applied to CO_2 assessment. These sensors are of moderate spectral resolution of the order of 5–10 nm and do not

possess so high spectral resolution as that of the dedicated greenhouse gas sensors, which are, in turn, of coarser spatial resolution.

- Plenty of CO_2-related reports are available on global, regional and local assessments and their comparisons and also a lot of CO_2-related data are publicly available.

Obviously, under such circumstances, the science community does have much scope for further exploring the spectroscopic assessment of CO_2, particularly:

- in connection with different environmental conditions,
- under different resolutions of the sensing and imaging instruments and
- in relation to spatial and temporal changes at local and global levels.

The present work has investigated these aspects of atmospheric CO_2, as introduced in the next section. Absorption spectra of solar radiation at around 2 μm, obtained both from ground-based measurements with spectroradiometer and satellite image-derived spectra are made into use for estimating the gaseous concentration and its spatial distribution.

Atmospheric aerosols are particles suspended in air having both natural and man-made origins. The urban aerosol is a factor closely related to human activity, which is the most serious origin of atmospheric CO_2. Hence, this work has paid attention to urban aerosols also and has contributed two sections of studies on its properties. A method is developed for determining the aerosol optical depth from hyperspectral data using the absorption band of the atmospheric oxygen and the temporal variation of urban aerosols along with that of CO_2 is investigated.

1.2. Objective and Significance

Global warming and the role of anthropogenic CO_2 is a serious issue in climate change. A significant part of the worldwide effort of mitigation is to develop a precise monitoring system for greenhouse gases including CO_2. Many rigorous, useful researches have been carried out in this regard during the last two decades. Some of those are reviewed in Chapter 2 and mentioned in the bibliography at the end of this thesis. It is realized that the radiation absorption features of CO_2 should be re-investigated, especially in the context of the tropical atmosphere of India having wide variation of temperature, pressure and water vapour. Also, these new findings should be validated in the light of high resolution spatial and temporal remotely sensed data. In particular, this work has addressed the following new features.

(A) Spectral Standardization: The actual physical process of radiation absorption is a sub-nanometer level phenomenon whereas the general-purpose moderate resolution imaging spectrometers can detect only an average profile of the absorption spectrum of a trace gas over several nanometers. However, these sensors have better spatial resolution and have the potential of recording the localized changes of CO_2 concentration arising from natural disorder or anthropogenic activity. So, the proper assessment of the CO_2 absorption depth and profile on the spectral radiance curve is of key importance while assessing the gas concentration.

The present work has carried out three types of estimates on the solar radiation absorption by atmospheric CO_2 and compared the absorption profiles. Ground-based measurements of solar radiation spectra over the visible, near-infrared and shortwave infrared wavelengths have been conducted with spectroradiometer with different fields of view and at different environmental conditions. Both radiance and irradiance were included in the ground-based measurement. In the case of image analysis, the radiance spectra for the same range of wavelength were derived from the hyperspectral images of an airborne sensor named *Airborne Visible/Infrared Imaging Spectrometer Next Generation* (AVIRIS-NG) and also a space-borne sensor named *Hyperion*.

(B) Effect of Water Vapour Absorption: The atmospheric Water vapour (H_2O) causes several absorption bands on the solar radiance spectrum and one of those partly overlaps the CO_2 absorption band around 2 μm thereby distorting both its depth and shape. The correct recovery of the CO_2 absorption profile from the spectral radiance curve, is a matter of prime significance. The present work has done this job in two ways.

The first one is based on conventional simulation and fitting technique. The second one is a new method that compares the experimental spectra with an ideal spectral signature free from H_2O absorption. Such a spectrum is achieved from the atmosphere of the planet Mars, which is mostly composed by CO_2 at very low atmospheric pressure and water in the Martian atmosphere exists only in trace amount. The present work suggests a methodology for the proper recovery of CO_2 absorption profile at earth's atmosphere by comparing with Martian atmospheric spectra under possible effects of surface and atmospheric features.

(C) Spatial and Temporal Variations of CO_2: Based on the principles of differential optical absorption spectroscopy (DOAS), this work has developed a new technique, named as *a*-DOAS for assessing the spatial distribution of CO_2 based on weighted averaging the CO_2 absorption depths at different wavebands. Using that technique, the spatial distribution of atmospheric CO_2 is estimated over different places of India with varied natural and man-made components that has revealed several remarkable features.

The places enriched with sequestering agents like vegetation and seas yield not only lower CO_2 values, a larger difference between the maximum and the minimum of CO_2 is noted. Each small region with diversified surface condition with natural and man-made features gets mixed up with the surrounding features and produces an overall uniform condition of emission and sequestration when considered over a larger area. This indeed realizes the equilibrium of CO_2 emission and sequestration in Indian environment. An alarming finding is that the surrounding deep sea regions, supposed to be free from human activities do not always show smaller CO_2 amounts and thus prompt to apprehend the insufficiency of the slow oceanic CO_2 assimilation facing the enhancing global CO_2 level. A linear steady increase is found in the long-term CO_2 change in India. A more or less steady state is noted in the atmospheric CO_2 enhancement of India in both spatial and temporal context. This work also develops a technique for detecting point sources of CO_2 from high spatial resolution, hyperspectral images of AVIRIS-NG and validates it with the spatial CO_2 distributions obtained at a coalfield area that is likely to contain larger amount of CO_2.

(D) Seasonal Variation of CO_2: The general trend of the time variation of atmospheric CO_2 comprises a continuous increase with time and an oscillating seasonal change superimposed to the monotonic enhancement. The extent of the annual fluctuation is generally found to be more enhanced in the northern hemisphere than that of the southern hemisphere. Such seasonal variation of CO_2 concentration is a well-known phenomenon and an explanation, supposed to be well-accepted for such occurrence is the seasonal growth of terrestrial vegetation causing different extents of consumption and release of CO_2 over the seasons. Nevertheless, such well known topic has achieved renewed interest because of several interesting features related to the CO_2 concentration, such as the occurrence of the maximum and the minimum of the concentration at two different seasons for northern and southern hemispheres, semiannual fluctuation and the effects of atmospheric turbulences like *El Nino* on the CO_2 concentration. The reported links between CO_2 and climate variability, such as rainfall and sea surface temperature indicate that the role of vegetation is not sufficient.

Taking the above findings into consideration, the present work has addressed several questions regarding the seasonal variation of CO_2. The actual nature of the periodic change is not well defined or affirmed mathematically. A reasonable quantification is put forward. The trend of the seasonal periodic change of CO_2 is studied both in time domain and in frequency domain, so as to find out the key factors for the variation. It studies the effect of atmospheric pressure on the annual variability of CO_2 column average and develops a mathematical model for interpreting the seasonal phenomena in terms of vertical redistribution of CO_2 molecules.

(E) Global Change of CO_2: Orbiting Carbon Observatory-3 (OCO-3) is the recent-most space-borne sensor meant for CO_2 observation at a global level launched by the National Aeronautics and Space Administration (NASA). It is actually a newer version of its forerunner Orbiting Carbon Observatory-2 (OCO-2) with some distinctions in respect of the global span, the observing platform and the observing mode. OCO-3 started acquiring data in August 2019 and has thus completed more than half of its nominal mission lifetime of three years. The point of concern is that an absolutely uncalled for situation of global lockdown and restricted fossil fuel burning has prevailed during the COVID-19 pandemic for majority of the above-mentioned period and it is totally unprecedented how the atmospheric column average of carbon dioxide (xCO_2) is modified.

The present work has explored the suitability of OCO-3 data for estimating the annual change of atmospheric CO_2 at global level using the OCO-2 records as reference. A comparative analysis is carried out for xCO_2 and solar induced fluorescence (SIF), a related parameter, from both OCO-3 and OCO-2 database for urban and unpopulated regions of various global locations. The similarities and the differences in the annual variation trends are analyzed and a wavelet transform technique is suggested for estimating the deviation from the usual annual variation of xCO_2 obtained from OCO-3 database.

(F) Aerosol Parameters: In addition to CO_2, the present work has studied the spatial and temporal distribution of urban aerosol and investigated if this atmospheric parameter can be correlated with human activity. A simple method is put forward for estimating the aerosol optical depth from the absorption band of atmospheric oxygen. The technique is validated with the results obtained from Hyperion hyperspectral images. The seasonal variation of urban aerosols is compared with that of CO_2.

1.3. Outline of the Thesis

The aforementioned studies compiled in this thesis are divided into eight chapters. This introductory chapter (Chapter 1) presents a cursory look over the entire work and highlights the objective and significance of the work.

Chapter 2 reviews the relevant researches reported earlier. It put up a brief narration on hyperspectral remote sensing and the related ground-based spectroradiometry, the main ingredients of this work. The importance of the studies on atmospheric CO_2 as greenhouse gas, a brief account of the implementation of hyperspectral imaging to the assessment of CO_2 at global and local level and the related instrumentations, the seasonal variations of CO_2, especially in Indian context and the recent global scenario of atmospheric CO_2 are reviewed in detail.

Chapter 3 introduces a new technique, termed as *a*-DOAS, developed in this work for assessing atmospheric trace gas using radiation absorption spectroscopy and has applied the same to the assessment of the atmospheric column average of CO_2 from AVIRIS-NG images procured for the first time in the tropical atmosphere of India. The technique is based on averaging the absorption depths as weighted linear sum of radiance at the absorbing and non-absorbing wavelengths. The spatial variation of atmospheric CO_2 concentration are estimated from AVIRIS-NG images for urban areas of India. It has been able to distinguish the CO_2 concentrations of vegetated and non-vegetated regions.

Since water vapour is a significant atmospheric component is a tropical country like India, this work has developed two different techniques for the correction for water vapor absorption while calculating the CO_2 absorption depth. One of the techniques is based on the fitting of simulated radiance ratio for CO_2 absorption bands. The other one is based on the comparison of the terrestrial radiance spectra with that of the atmosphere of planet Mars where CO_2 is the main ingredient and H_2O is negligible. The radiance spectra of Mars is used as a natural laboratory. The gradual change from ‘earth-like’ to

'Mars-like' radiance spectra with CO_2 absorption features are explained with MODTRAN6 atmospheric simulator and are compared with the actual findings.

Chapter 4 illustrates the spatial retrieval of air-mixed CO_2 utilizing the airborne hyperspectral images of AVIRIS-NG and applying the technique developed in Chapter 3. The results are compared with the contemporary database of global CO_2 sensor Orbiting Carbon Observatory-2 (OCO-2). An equilibrium of emission and sequestration caused by the mixing up of diversified surface features is inferred. It is also realized that the large extent of vegetation distributed throughout India can compensate for the man-made emission and maintain a steady state in the increase of CO_2. The long-time change of CO_2 in India is studied with the data obtained from two independent open sources and a steady increase rate of the average CO_2 concentration over the major portion of Indian atmosphere is noted. This chapter also put forward a useful technique to estimate the spatial distribution of atmospheric H_2O, an important component of tropical climate like that of India. Applying the *a*-DOAS technique to the AVIRIS-NG image and utilizing its high spatial resolution property, the present work has been able to distinguish CO_2 point sources and has validated the finding with the images of a coalfield area.

Chapter 5 presents a method developed in this work for assessing spatial distribution of aerosol optical depth using the atmospheric oxygen absorption depth of solar radiation at around 760 nm. The measured radiance spectrum itself works as the source of information on the relative absorption no other reference for calibration, such as the extraterrestrial radiation is needed. The proposed method is validated with field spectroradiometry and Hyperion hyperspectral image analysis for urban aerosols. It is found to be suitable for comparing the aerosol loading at places under similar atmospheric conditions.

Chapter 6 re-explores the seasonal change of atmospheric CO_2, a subject of renewable interest, in both time and frequency domains. The annual variability of CO_2 dry-air mole fraction derived from OCO-2 database for a specific region was found to increase in summer, decrease in winter and to exhibit an increasing tendency at the end of the year. The trends of variation were cross-checked with the long-time gross variations of CO_2 and related parameters, such as vegetation activity, atmospheric pressure and the temperature at surface level over a large region using NASA-Giovanni database. Field measurements were carried out for ground level and column averaged CO_2 concentrations.

Based on all the findings, an atmospheric model is developed for vertical redistribution of CO_2 molecules under the influence of changed temperature and pressure causing a changed atmospheric path for radiation absorption and an apparent change in the gas concentration at a certain altitude.

Chapter 7 had the initial target of exploring the feasibility of estimating the annual change in CO_2 from the database of Orbiting Carbon Observatory-3 (OCO-3), the latest sensor launched for global CO_2 monitoring. Immediately after OCO-3 started data procuring in late 2019, the unanticipated global lockdown scenario broke forth in connection with the novel coronavirus (COVID-19) pandemic. A condition of restricted human activity, hence limited fossil fuel burning evolved out of that situation, which was likely to distort the atmospheric CO_2 column at global level. This posed some questions to the research problem and reoriented it.

In the light of the global fossil fuel constraining, the present study validates the applicability of OCO-3 data for tracing the actual annual change in CO_2 column average. A comparative analysis of OCO-3 data with its forerunner OCO-2 is carried out in this chapter and a reduction in the CO_2 column average is found at global level, especially in the urban regions. The presence and absence of human activity differentiated by comparing the results obtained at heavily populated metropolitan areas and sparse, unpopulated regions indicate a notable fall in the urban areas, indicating a clear relationship with the sudden decline in global human activity. A wavelet coherence technique is suggested for quantifying the temporary reduction and it is expected that in future, a similar technique would be beneficial to OCO-3 data for self-comparison with its own yearly statistics.