

## Spatiotemporal Monitoring of CO<sub>2</sub> and CH<sub>4</sub> over Pakistan Using Atmospheric Infrared Sounder (AIRS)

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**Abstract.** Carbon dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>) are two most potent greenhouse gases and are major source of climate change. Human activities particularly fossil fuels burning have caused considerable increase in atmospheric concentrations of greenhouse gases. CO<sub>2</sub> contributes 60% of anthropogenic greenhouse effect whereas CH<sub>4</sub> contributes 15%. Ice core records also show that the concentrations of Carbon dioxide and methane have increased substantially. The emission of these gases alters the Earth's energy budget and are drivers of climate change. In the present study, atmospheric concentration of CO<sub>2</sub> and CH<sub>4</sub> over Pakistan is measured using Atmospheric Infrared Sounder (AIRS). Time series and time averaged maps are prepared to measure the concentrations of CO<sub>2</sub> and CH<sub>4</sub>. The results show considerable increase in concentration of Carbon dioxide and methane. The substantial increase in these concentrations can affect human health, earth radiative balance and can damage crops.

### 1. Introduction

The major source of changing climate is anthropogenic emission of greenhouse gases such as Carbon dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>) and Nox (N<sub>x</sub>O), where, CO<sub>2</sub> and CH<sub>4</sub> are most potent greenhouse gases [1]. Since 1750, anthropogenic emissions of these greenhouse gases have increased considerably due to human activities [2]. These gasses are affecting the earth's energy balance leading to changes in climate. Primarily, anthropogenic greenhouse effect is contributed by CO<sub>2</sub> with 60% and CH<sub>4</sub> with 15 to 25% [1, 3]. By the year 2065, CO<sub>2</sub> levels in atmosphere will reach the double of pre-industrial levels [4]. Fossil fuel emissions followed by land use changes such as logging and deforestation have been reported as major source of CO<sub>2</sub> with an increase of 29% (8.7 + 0.5 Pg C/yr) from year 2000 to 2008 [5]. Similarly, 60% of CH<sub>4</sub> emissions are from human activities due to fossil fuels, rice paddies, landfill wastes and livestock with an average lifetime of 12 years. Although, concentration of CH<sub>4</sub> in atmosphere is lower than CO<sub>2</sub> but absorbs infrared (IR) radiation much more strongly making it 3.7 times more potent than CO<sub>2</sub> for global warming [6]. CH<sub>4</sub> is produced naturally by thermal, pyrogenic and microbial processes due to dilapidation of organic material under the earth's crust, biomass burning and metabolism of methanotropic bacteria respectively [7, 8, 9]. Therefore, CH<sub>4</sub> can be released in to atmosphere from deep earth, above surface and from lakes etc. This makes mining of fossil fuel, forest fires, landfills, fields of grass, rice and peat as major natural sources. Anthropogenic activities in major cities, in addition to preceding sources, play an important role in spatiotemporal variations in concentration of CO<sub>2</sub> and CH<sub>4</sub>.

Increasing concentration of CO<sub>2</sub> and CH<sub>4</sub> is much more challenging for developing countries especially in Asia which is indirectly affecting the developed world. Developing countries in Asia have less emission controls that dump significant amount of CO<sub>2</sub> and CH<sub>4</sub> in atmosphere which is already very warmer than global mean [10]. In addition, anthropogenic emissions, emissions from enteric fermentation and livestock has placed Pakistan in upper five countries of CH<sub>4</sub> emission [11,

12]. This might be the reason that Pakistan is placed among top ten countries that are highly vulnerable to climate change [13]. According to Environmental Protection Agency (EPA) report (<http://www.epa.gov/methane/sources.html>), Pakistan was ranked on 13th position in 2005 for anthropogenic Methane emissions. Regional emissions also bring challenges at global scales as monsoon meteorology of this region shifts the concentration of these gases to high altitudes [14], whereas, tropical easterly jet transport some of its concentration to Middle east, Africa and Europe as well [15, 16].

Developing countries like Pakistan have inadequate mechanism to even monitor such emissions due to involvement of high cost in deploying ground based monitoring networks. However, with latest developments in the field of atmospheric Remote Sensing (RS), reliable sensors such as Atmospheric Infrared Sounder (AIRS) have made monitoring of CO<sub>2</sub> and CH<sub>4</sub> have become feasible [17, 18]. Closure studies involving RS and in-situ data been very useful for identifying the sources and sinks at regional and global level [19]. Along with loading of CO<sub>2</sub> and CH<sub>4</sub> satellites can provide the additional information of particle size and vertical profile [20]. Xiong et al., (2010) [21] reported maximum error of 1.5 % in retrieval of CH<sub>4</sub> using AIRS. AIRS has been reported more accurate for retrieving CH<sub>4</sub> over tropics and mid latitudes [21, 22]. Although, spatiotemporal resolution hinders the performance of some sensors like Greenhouse Gases Observing Satellite (GOSAT), even then Kort et al., (2012) [23] mapped and quantified the anthropogenic emissions with significant accuracy. Similarly, Rakitin et al., (2015) [24] reported accuracy of AIRS for CH<sub>4</sub> retrieval with strong coefficient of determination ( $R^2 = 0.96$ ) over Russia. A satellite based sensor with reasonable accuracy as discussed earlier can characterize the emission sources for a given region. Sharma et al., (2010) [25] has identified crop residual burning as major source of air pollution in India. Unfortunately, effective use of satellite RS in monitoring of CO<sub>2</sub> and CH<sub>4</sub> for Pakistan is still very rarely reported. Therefore, this study is designed to map the spatiotemporal distribution of CO<sub>2</sub> and CH<sub>4</sub> over Pakistan. Results of this study help in identifying the hotspots for regional CO<sub>2</sub> and CH<sub>4</sub> emissions leading to suggestions for developing low-carbon scenario of Pakistan.

## 2. Data and Methodology

Carbon dioxide and Methane Total Column data is obtained from AIRS NASA Giovanni online data system for the study area of Pakistan [26]. The CO<sub>2</sub> monthly gridded data is obtained on spatial resolution of 2.5° x 2.5°, whereas, the CH<sub>4</sub> data is obtained on spatial resolution of 1° x 1°. The Total Column Methane is the atmospheric density of Methane (CH<sub>4</sub>) in a vertical column of air. The Carbon dioxide parameter is the CO<sub>2</sub> mole fraction. This is a total tropospheric column property, and is in mole fraction units ( $\text{data} \times 10^6 = \text{ppm by volume}$ ) [26]. AIRS on board NASA's Aqua satellite is launched in May 2002 and used for earth's weather and climate related research. The primary purpose of this satellite is to measure the trace greenhouse gases such as ozone, carbon monoxide, carbon dioxide, and methane. Due to its cutting edge IR technology, it develops 3D maps of water vapor, cloud properties, air and surface temperature. The AIRS instrument provides spectral coverage in the range of 3.74 – 4.61  $\mu\text{m}$ , 6.20 – 8.22  $\mu\text{m}$  and 8.8 – 15.4  $\mu\text{m}$  IR wave bands. The concentration of CO<sub>2</sub> is measured in parts per million by volume (ppmv) with peak sensitivity at 400 hPa pressure level. The nadir resolution is 90 km x 90 km. AIRS map global distribution of CO<sub>2</sub> every day due to its broad swath [27]. The concentration of CH<sub>4</sub> is measured in parts per billion by volume (ppbv) with peak sensitivity at 400 hPa. Its algorithm is based on optimal estimation and retrieval is performed for 10 layers. It utilizes an eigenvector regression algorithm for efficient retrieval of atmospheric temperature, moisture and ozone [28]. The 2D raster data of CO<sub>2</sub> and CH<sub>4</sub> were converted into point vector format and IDW (Inverse Distance Weighted) algorithm was applied to interpolate the concentration for assessing the spatial extents. The CO<sub>2</sub> and CH<sub>4</sub> concentration were determined using area-average over entire study for graphical analysis.

### 3. Results and Discussion

Time series and time-averaged maps are analyzed to observe the spatiotemporal changes in concentrations of CO<sub>2</sub> and CH<sub>4</sub>. The observed changes can be attributed to anthropogenic activities mainly based on the spatial extent of each gas. A significant increase in CO<sub>2</sub> concentration is noted from January 2010 to December 2015, where, CO<sub>2</sub> average concentration was 390 ppm in 2010 that increased up to 400 ppm in 2015 leading to an increase of 1.75 ppm/year (Figure 1). This indicates an average CO<sub>2</sub> value of  $395.33 \pm 3.77$  (ppm average  $\pm$  standard deviation) for the whole study period with a significant increase of 3.22%. It is alarming to note that observed increase in the concentration of CO<sub>2</sub> during the study period is equaling to 5.37% per decade which is significantly higher than reported for Pakistan [29]. The CO<sub>2</sub> concentration can be a by-product during combustion of low grade fuel and improper combustion system which can be found in open market due to lack of quality control by the competent authorities. Traffic congestion, road conditions, and industrial exhaust are the major causes of CO<sub>2</sub> concentration and similar results were perceived with Haq et al. (2015) [29] over Pakistan.

Spatial distribution of CO<sub>2</sub> during the study period is found correlated with the locale of anthropogenic emission sources of CO<sub>2</sub> in Pakistan. Major cities of Pakistan except in southern part have high concentration of CO<sub>2</sub>. Although Karachi in Sindh is the biggest city of Pakistan located in southern part but still low to moderate loading of CO<sub>2</sub> is observed similar to coastal line of Sindh and Balochistan. This can be attributed to natural cycle of land and sea breeze in this area that keep on sweeping the portion air pollutants all around the year. Similarly, there is less concentration of CO<sub>2</sub> in extreme north of Pakistan firstly due to no anthropogenic activity and secondly, these areas are located 5000m above sea level and meteorology at these heights cap the pollutants at lower heights. Similarly, time-averaged map of CO<sub>2</sub> shows a large concentration in northern and central Pakistan, especially in industrial and densely populated regions (Figure 2).

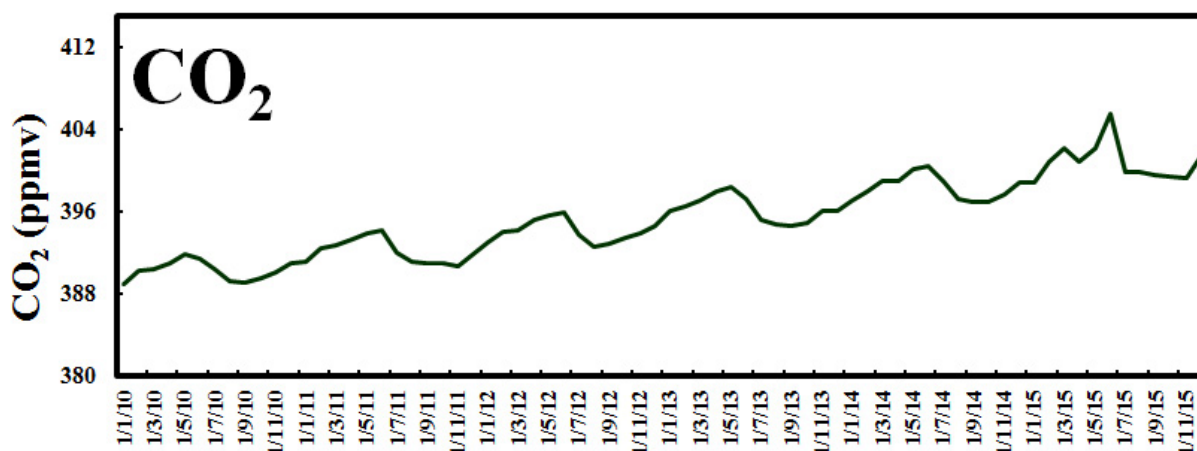


Fig. 1: Time Series Analysis map of CO<sub>2</sub> concentration over Pakistan (2010-2015)

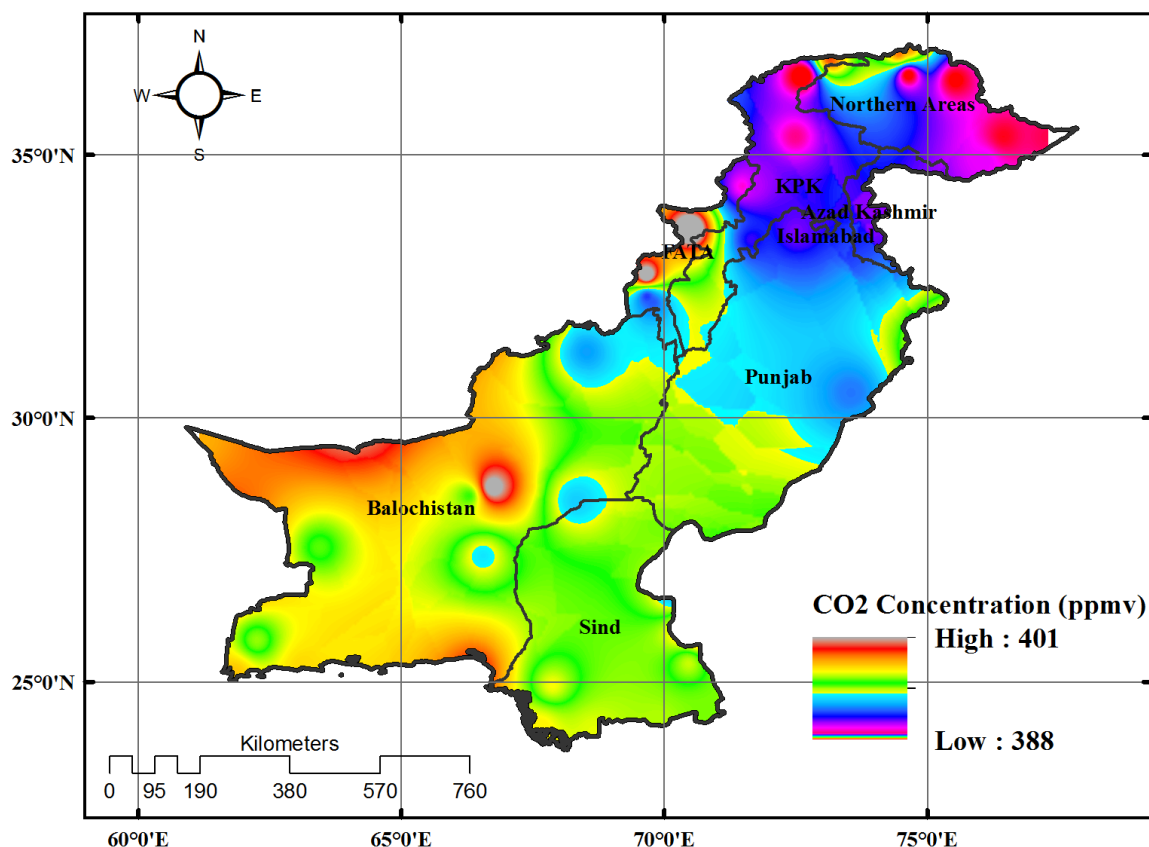


Fig. 2: Time Averaged Map of CO<sub>2</sub> concentration over Pakistan (2010-2015)

Methane total column data was utilized from 1st January 2003 to 31st December 2015 for Pakistan. A significant increase in CH<sub>4</sub> concentration is noted from 2003 to 2015, where, CH<sub>4</sub> average concentration was 1791.09 ppb in 2003 that increased up to 1856.39 ppb in 2015 leading to an increase of 5.02 ppb/year (Figure 1). This indicates an average CH<sub>4</sub> value of  $1823.83 \pm 30.01$  (ppb average  $\pm$  standard deviation) for the whole study period with a significant increase of 3.65%. It is alarming to note that observed increase in the concentration of CH<sub>4</sub> during the study period is equaling to 2.80% per decade. Similar concerns have been reported in the only study available for whole Indo-Gangetic region, Afghanistan and parts of Russia from 1990-2008 using another satellite called Scanning Imaging Absorption SpectroMeter for Atmospheric Chartography (SCIAMACHY) [30]. The comparative analysis between CO<sub>2</sub> and CH<sub>4</sub> were also performed. Figure 5 shows increasing concentration of both the gases approximately with same magnitude.

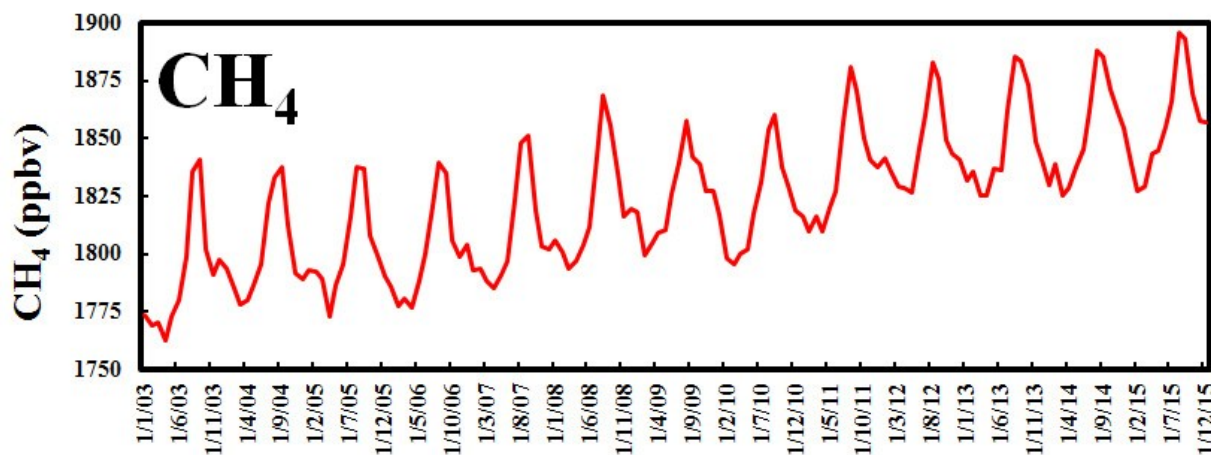


Fig. 3: Time Series Analysis map of CH<sub>4</sub> concentration over Pakistan (2003-2015)

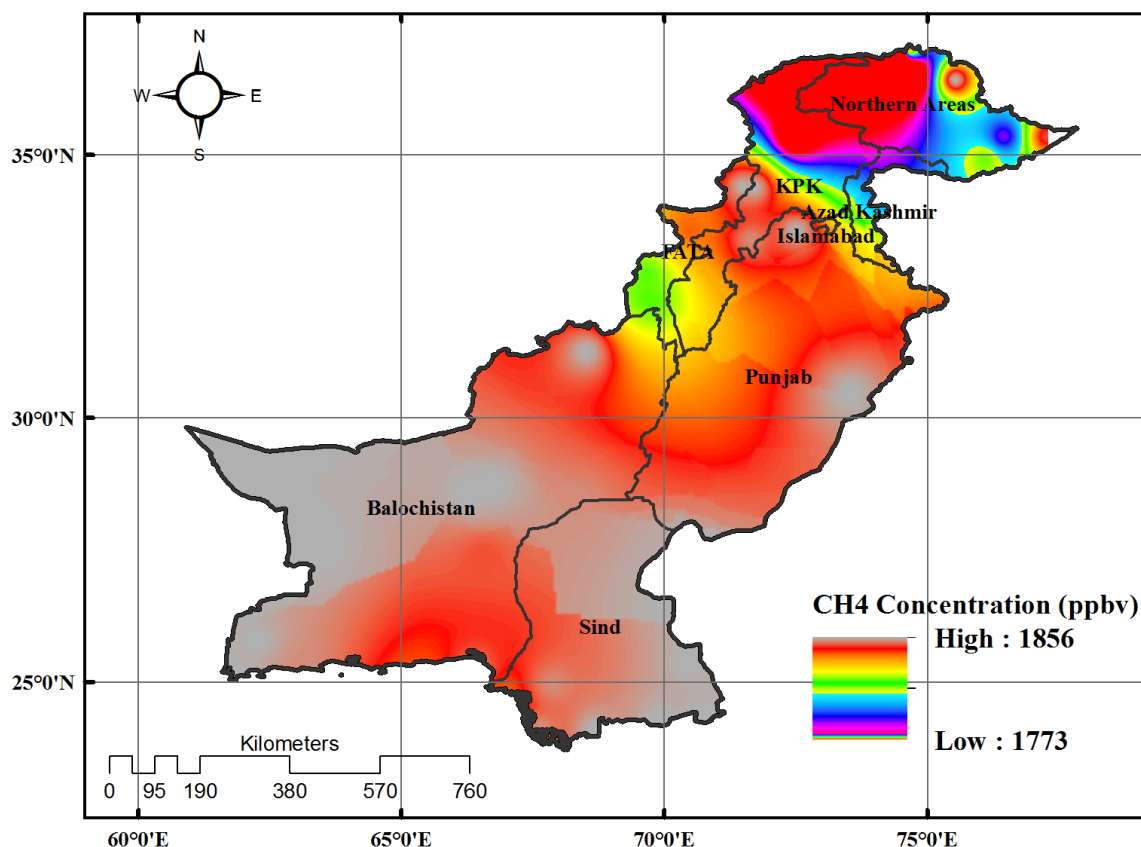


Fig. 4: Time Averaged Map of CH<sub>4</sub> concentration over Pakistan (2003-2015)

Major emission sources of CH<sub>4</sub> are observed from time-averaged map of Methane Total Column (MTC) showing a large concentration of Methane in most parts of Pakistan (Figure 4). However, CH<sub>4</sub> concentration is in acceptable range in Northeastern Pakistan which can be due to same meteorological conditions that inhibit the concentration of CO<sub>2</sub> in this part of Pakistan as described previously. However, the high concentration of CH<sub>4</sub> in some parts of southern Pakistan is in contrast to CO<sub>2</sub> concentration in the same area. This might be due to wet lands in Indus Delta Region along the coastal belt of Pakistan. Areas with high concentration of CH<sub>4</sub> include major cities and industrial locations in Pakistan which are associated with lots of transportation. During past couple of decades, a major portion of the transport, power and industrial sector has shifted on Compressed Natural Gas (CNG i.e. CH<sub>4</sub>) as major fuel. This has triggered increase in extraction from ground and expansion in distribution network of CH<sub>4</sub>. It is still challenging for the authorities to control the quality of distribution network during this rapid increase in demand and supply of CH<sub>4</sub>. This is the reason that leakage during filling of CNG can be attributed as major emission source of CH<sub>4</sub> in different cities. Moreover, the spatial distribution of CH<sub>4</sub> perceived in this study encompasses almost all areas that can be source of CH<sub>4</sub> due to activities such as (1) Thermogenic - largest CH<sub>4</sub> reserves at Sui in Baluchistan, (2) Pyrogenic - industries in Lahore in Punjab, Karachi in Sindh, Biomass burning in Punjab and lastly (3) Microbial - landfills of the major cities that are mostly located in Punjab, Sindh and Khyber Pakhtunkhwa. Western part of Pakistan observe relatively less CH<sub>4</sub> loading may be as most of this region is of barren mountains that can act as sink for CH<sub>4</sub> due to dry soil oxidation [28]. Overall, significant increasing concentration of CH<sub>4</sub> and CO<sub>2</sub> can be observed over Northern Pakistan that can be attributed to the rapid melting of glaciers due to warming of climate possibly liberating a large amount of Methane hydrates and CO<sub>2</sub> stored in permafrost.

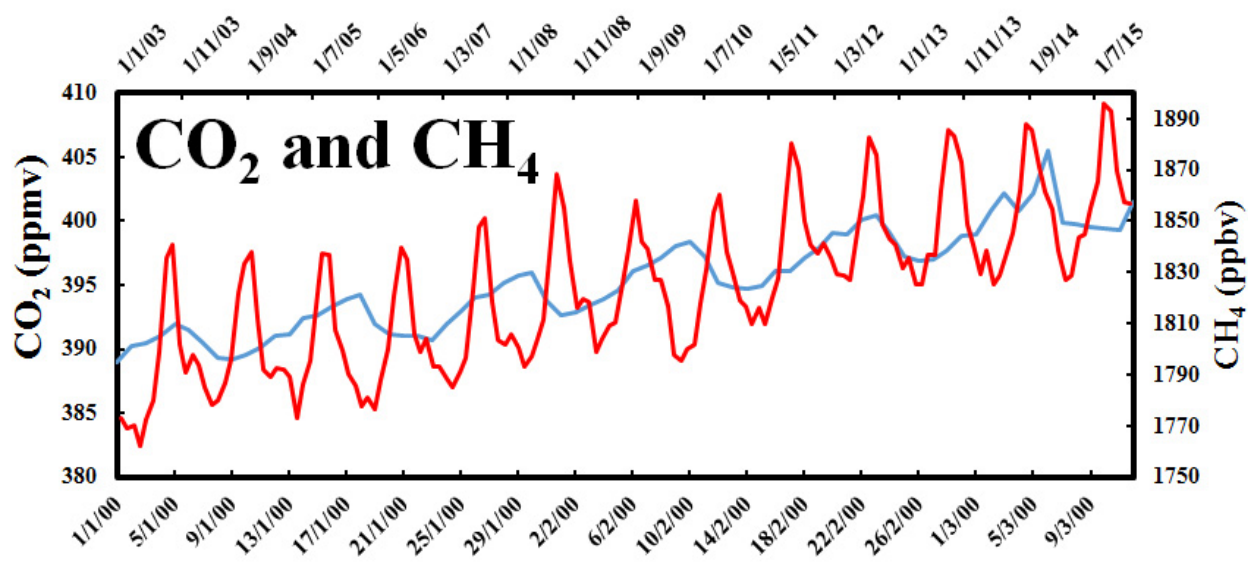


Fig. 5: Comparative analysis of CO<sub>2</sub> and CH<sub>4</sub> for assessing the magnitude of concentration

#### 4. Conclusions

Anthropogenic emission of greenhouse gases builds up in the atmosphere leading up to climate warming. CO<sub>2</sub> and CH<sub>4</sub> data from AIRS shows an increase in concentration of both the gases over Pakistan. Fossil energy consumption is the major cause of increase in CO<sub>2</sub> and CH<sub>4</sub> emissions and is driven mainly by emerging economies. Due to warming of climate, large amount of Methane hydrates and CO<sub>2</sub>, which is stored in permafrost in Northern Pakistan, can be released. Both agricultural production and food quality will be affected by rising levels of CO<sub>2</sub>. Stabilization in concentrations of atmospheric CO<sub>2</sub> and CH<sub>4</sub> is required to control climate change. Agriculture, coalmines, municipal solid waste, natural gas and oil are major contributors of Methane emissions from Pakistan. Results of this study also point toward the opportunities to understand the dynamics for carbon emission in Pakistan in future researches.

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