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Research Article
Assessment of Troposphere Carbon Monoxide Variability and Trend in Iraq Using Atmospheric Infrared Sounder During 2003-2016

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Abstract
Background and Objective: Tropospheric Carbon Monoxide (CO) is indirect greenhouse gas and one of the most significant air pollutant produced from the biomass burning, combustion of fossil fuels and the oxidation of methane (CH_4) by hydroxyl radicals (OH) or other carbonaceous gases. The aim of this study was to analyze the spatial and temporal variations of CO and to estimate its long term-trends over study area. **Materials and Methods:** Results of the retrieved monthly CO volume mixing ratio (VMR) obtained from Atmospheric Infrared Sounder (AIRS) data, included on the EOS Aqua satellite, from January, 2003-December, 2016 over Iraq were employed. In order to better assess the CO distribution, trend analysis used for seven stations dispersed across Iraq: Mosul, Sulaimaniyah, Rutba, Baghdad, Nukhayb, Nasiriyah and Basra. The spatial distribution analyses of the CO maps were generated employing Kriging interpolation technique. **Results:** The results showed a considerable variability of monthly CO in spatial and temporal scale, the monthly mean and the standard deviation of CO was 0.125±0.02 ppm for the entire period. The maximum values (0.158 ppm) were over Northern and Northwestern regions (Mosul and Rutba) in February and March and the minimum values (0.096 ppm) over Southern regions (Nasiriya and Basra) in October. The CO values during winter were higher than its values in summer season and Northern area have the highest values of CO throughout the year due to the meteorological conditions and geographic features. Trend analysis showed a negative trend for the months of the year overall selected stations refer to a considerable decreasing of CO values reached to -0.0026 ppm/year which represent about 2% of the mean value. A stagnation and stability feature was obvious from annual trend analysis during 2003-2007 and decreased in 2008 till 2016. **Conclusion:** The AIRS observation efficiently showed the spatial and temporal variations of CO for the considered study area.

Key words: Carbon monoxide, CO volume mixing ratio (VMR), satellite, remote sensing, greenhouse gases, AIRS

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Chemically reactive trace gas CO, indirect greenhouse gas (GHG's), is one of the primary air pollutants cause a significant deterioration in air quality. The CO gas can pose threats to human health, as stated by EPA criteria. The CO has an affinity for hemoglobin about 200 times greater than carbon dioxide (CO_2)[1,2]. Carbon monoxide forms during the biomass burning and combustion of fossil fuels and from the oxidation of CH_4 by OH radicals or other carbonaceous gases. Recently, most of the CO in the troposphere is from anthropogenic .The global CO emissions for the past decade range from 1504 TgCO (in 2007) to 1318 TgCO (in 2009) due to biomass burning, anthropogenic emissions and climate factors[1,3,4].

Due to the main vibration-rotation band is not at the spectral maximum of Earth's long wave radiation, CO has a little contribution to the greenhouse effect. Nevertheless, CO presence in high concentrations can enhance the concentrations of GHG's, such as CH_4, ozone (O_3) and CO_2, by removing the OH which would otherwise destroy them. Thus, affects the oxidizing capacity of the atmosphere. Also, modify its chemical, physical and climatologically properties[5,6]. In addition, CO lifetime of about 2 months in the atmosphere makes it a good tracer for atmospheric motions and wildfire smog propagation[7,8].

During the 21st century, several studies[3,4,9] shows decreasing in the global tropospheric CO emissions. A more comprehensive study was carried out by NOAA (National Oceanic and Atmospheric Administration) network, calculated the long-term trends to be about 0-2% per year in the lower tropospheric CO over the globe[10]. The seasonal cycle of CO in the Northern Hemisphere (NH) at mid-latitudes, showed maximum levels in late winter and early spring, but minimum levels in summer, that are due to lower OH concentrations (which are the primary CO sink) in winter compared with summer season[11].

The industrial development, political turmoil, climate change and wars have left health effects and environmental problems in the past century. Like the rest of the world, Iraq is one of middle East countries, also contributed significantly to economic growth due to the industrialization, reconstruction and traffic growth. The heaviest pollution are emitted from industrial sources, increase in the number of residences and buildings, manufacturing facilities and a dramatic elevations in vehicles numbers. Also Iraq affected by pollutants, including CO, from Turkey and the Southeast of the Mediterranean sea brings by the Northwestern winds and from the Indian subcontinent by the Southwest winds, in addition, the natural resources, anthropogenic emissions and burning agricultural waste. It is very important to monitor and document the changes in pollutants and atmosphere parameters to assess their impacts on health and environment. During the past three decades, the abundances of the atmosphere gases and parameters acquired by many ways such as balloons, airplane and sparsely distributed measurement sites[12].

These are not able to provide continuous, large-scale regional or global coverage as well as strenuous efforts and cost a lot of money[13] . The observations from space, in the absence of cloud, only allows for such measurements to get the reasonably short time period. The satellite observations have very good global coverage, increase our ability to analyze the impact of human activities on the climate change and chemical composition of the atmosphere. In addition, it can provide the quantitatively data with good spatial and temporal resolution. Furthermore, the free download satellite data provided by the AIRS become a useful space instrument for observing the earth's atmosphere, as in this paper. Troposphere CO concentrations is easily obtainable from a large number of satellite instruments at infrared wavelengths, such as SCIAMACHY, MOPITT, IASI, AIRS and TES[14]. The AIRS has very high capacity for daily global observations of varied atmospheric parameters. Hence, AIRS is particularly promising for studying pollution transport and CO emission[15].

The objective of this study was to analyze the regional hotspots emissions and monthly distribution of CO VMR and estimate its long term-trends over Iraq using satellite (AIRS) data for the period 2003-2016. The CO satellite data were estimated and analyzed over seven stations: Mosul, Sulaimaniyah, Rutba, Baghdad, Nukhuyb, Nasiriya and Basra for trend analysis.

MATERIALS AND METHODS

Study area: Iraq is one of the middle East countries located Southwest of Asia with an area of about 437,072 km^2. Centrally located between 39-49°E longitudes and 29-38°N latitudes and is bordered by Turkey to the North, Iran to the East, Kuwait to the South, Saudi Arabia to the Southwest and Syria and Jordan to the West as shown in Fig. 1. Topographically, Iraq has high ramp mountains along its border with Iran and Turkey. Iraq is formed as a basin divided into four main regions: Desert areas in the West and Southwest; highlands in the North and Northeast: Alluvial plain in the central and Southeast parts and rolling upland area between upper Euphrates and Tigris river[16]. The terrain of Iraq is largely broad plains with reedy marshes in the South.

Table 1: Locations, mean of annual, maximum, minimum and trend of CO estimated by Mann-Kendall for the period (2003-2016) significance of change at 0.001 level of confidence

Stations	Latitude (N°)	Longitude (E°)	Mean of annual CO (ppm)	Maximum CO (ppm)	Minimum CO (ppm)	Standard deviation CO (ppm)	Trend CO (ppm/year)	Statistic Z-test	Significance level
Mosul	36.21	43.06	0.130	0.153	0.114	0.011	-0.0024	-4.16	0.001
Sulaimaniyah	35.33	45.26	0.129	0.150	0.116	0.008	-0.0025	-4.05	0.001
Baghdad	33.20	44.20	0.123	0.145	0.109	0.011	-0.0026	-4.38	0.001
Rutba	33.26	40.17	0.128	0.150	0.111	0.011	-0.0022	-4.05	0.001
Nukhuyb	32.20	42.15	0.125	0.145	0.109	0.011	-0.0023	-3.91	0.001
Nasiriya	31.24	46.15	0.119	0.139	0.107	0.010	-0.0022	-3.84	0.001
Basra	30.30	47.78	0.119	0.138	0.107	0.009	-0.0024	-4.16	0.001

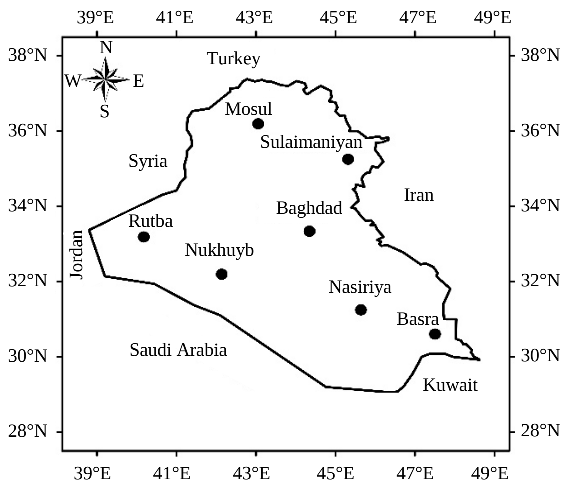

Fig. 1: Geographical features of study area and the main stations

In general, Iraq has a continental, subtropical semi-arid climate, with a Mediterranean climate in North and Northeastern mountainous regions. Subtropical summers climate is prevalent in central and Southern regions and the temperatures up to 50°C. Rainfall is seasonal with mean annual rainfall about 216 mm, it ranges from 1200 mm in the Northeast to less than 100 mm over 60% of the region in the South .Winter months are mild to cool, the day temperature is about 16°C and decline to 2°C at night with a probability of frost. Summer months are dry and hot, with average temperature above 43°Cand frequently exceed 48°C for most region of the country[16].

Data acquisition and methodology: This study has been implementing for 14 years AIRS data sets from January, 2003 to December, 2016. In order to study and analysis the CO distribution and estimate the monthly long term-trends, CO over seven selected stations dispersed across Iraq: Mosul, Sulaimaniyah, Rutba, Baghdad, Nukhuyb, Nasiriya and Basra, as shown in Table 1 and Fig. 2. Using Kriging interpolation technique, the average monthly mean CO maps of spatiotemporal distribution patterns were generated to analyze the CO distribution along the study period as shown in Fig. 3 and 4. The trend analysis was conducted by using MAKESENS 1.0 software to analyze the monthly and annually trend over the seven stations. Generally, 168 monthly granules were downloaded to obtain the desired output. Extract the ascending AIRX3STM version 6 (V6) Level-3 (L3) data product's files from the AIRS website and saves in HDF-EOS4 files, which is a convenient file extension that easily take out data from it and arrange in table using MS Excel. The monthly data basis for the study period including the corresponding time and location along the satellite track were in a Hierarchical Data Format (HDF).

The AIRS is a unique hyper spectral thermal IR radiometer, designed by NOAA and NCEP's research programs to improving numerical weather prediction and to support climate-related studies. Compose the complete atmospheric sounding to observe the entire atmospheric column from the surface to the top of the atmosphere[17,18]. It was launched successfully on 4 May, 2002 aboard the aqua spacecraft into polar sun-synchronous orbit of 705 km altitude and an orbital period of 98.8 min. The AIRS equatorial crossing time is 01:30 ascending (in the morning) and 01:30 descending (in the afternoon), with a 1650 km cross track scanning swath and ground track repeatability of +/- 20 km, complete global coverage twice per day[19]. The AIRS infrared spectrometer acquires 2378 spectral channels at high spectral resolution ($\lambda/\Delta\lambda$ =1200) and low noise, covering the main spectral features of carbon trace gases CO_2. CH_4, O_3 and CO. Practically AIRS supply global distributions of CO in real time using radiances around 4.58 and 4.50 µm (2183–2220 cm^{-1}) of region spectra in the 1-0 vibration-rotation CO fundamental[7,20].

The AIRS V6-L3 consist of three products: Standard daily product (AIRX3STD), 8 day standard product (AIRX3ST8) and monthly standard product (AIRX3STM), each product provides separate ascending (day time) and descending (night time) portions of the orbit besides 24 standard pressure levels for volume mixing ratio (VMR) and spatial resolution 1×1° grid cells for all standard level 3 products. The level 3 files contain geophysical parameters that have been averaged and then binned into 1×1° grid cells. Grid coordinates range from

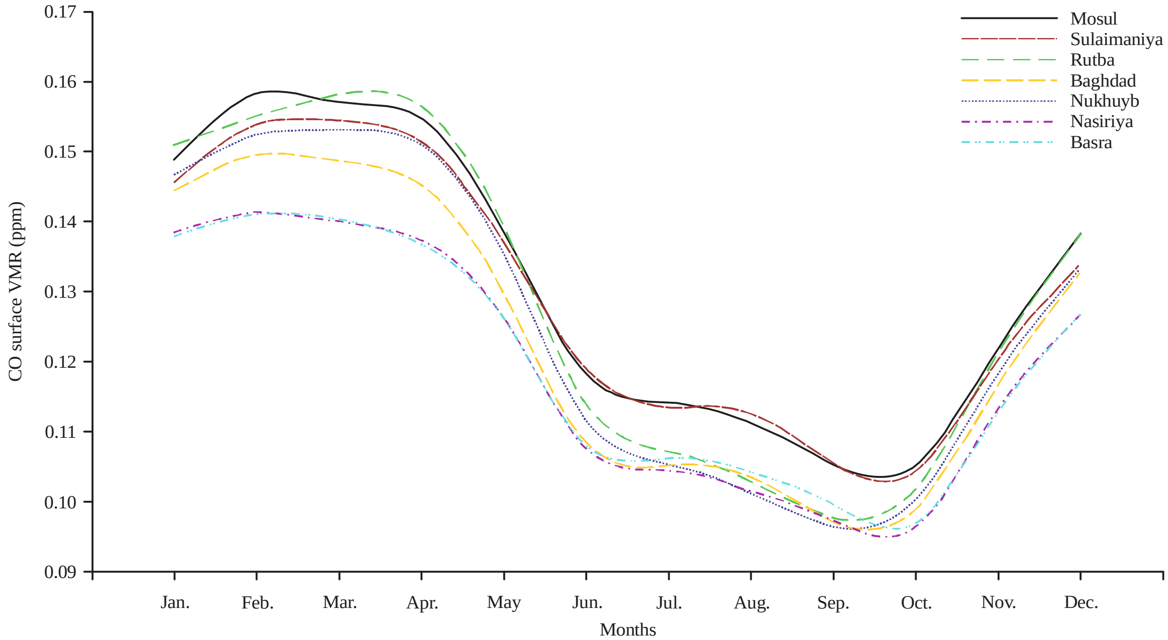

Fig. 2: Average monthly CO for Mosul, Sulaimaniyah, Rutba, Baghdad, Nukhuyb, Nasiriya and Basra stations during January, 2003-December, 2016

-90.0° to +90.0° in latitude and from -180.0° to +180.0° in longitude. The AIRS standard CO products were derived from the IR stage of the combined IR/MW retrieval[18].

Trend analysis by Mann Kendall test: In order to determine the trends of CO values MAKESENS 1.0 freeware had been employed in present study, MAKESENS 1.0 which developed by Finnish Meteorological Institute 2002 for detecting and estimating trends in the time series of values of atmospheric chemical components concentration. The monthly CO data utilized to analysis and to estimate the monthly trend for the period 2003-2016. The procedure was based on the nonparametric Mann-Kendall test for the magnitude of the trend. The Mann-Kendall test was applicable for the detection of a monotonic trend of a time series with no seasonal or other cycle. All tested data values were compared to all subsequent data values[21,22]. The Mann-Kendall test statistic S was calculated using the equation:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \quad (1)$$

where, x_j and x_k are the time series values in years j and k, j>k, respectively and:

$$\begin{aligned} \operatorname{sgn}(x_j - x_k) &= 1 \text{ if } (x_j - x_k) \succ 0 \\ \operatorname{sgn}(x_j - x_k) &= 0 \text{ if } (x_j - x_k) = 0 \\ \operatorname{sgn}(x_j - x_k) &= -1 \text{ if } (x_j - x_k) \prec 0 \end{aligned} \quad (2)$$

The absolute value of S was compared directly to the theoretical distribution of S derived by Gilbert[23]. In MAKESENS 1.0 the two-tailed test was used for four different significance levels (α) (0.1, 0.05, 0.01 and 0.001). At certain probability level, H_0 was rejected in favour of H_1 if the absolute value of S equals or exceeds a specified value $S_{\alpha/2}$, where, $S_{\alpha/2}$ was the smallest S which has the probability less than α/2 to appear in case of no trend. A positive (negative) value of S indicated an upward (downward) trend.

The variance of S was computed by the following equation which takes into account as following:

$$VAR = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right] \quad (3)$$

where, q is the number of tied groups and t_p is the number of data values in the p_{th} group. The values of S and VAR(S) were used to compute the statistic Z-test as follows:

$$\begin{aligned} Z &= \frac{S-1}{\sqrt{VAR(S)}} \text{ if } S \succ 0 \\ Z &= 0 \text{ if } S = 0 \\ Z &= \frac{S+1}{\sqrt{VAR(S)}} \text{ if } S \prec 0 \end{aligned} \quad (4)$$

The presence of a statistically significant trend was evaluated using the Z value. A positive (negative) value of Z

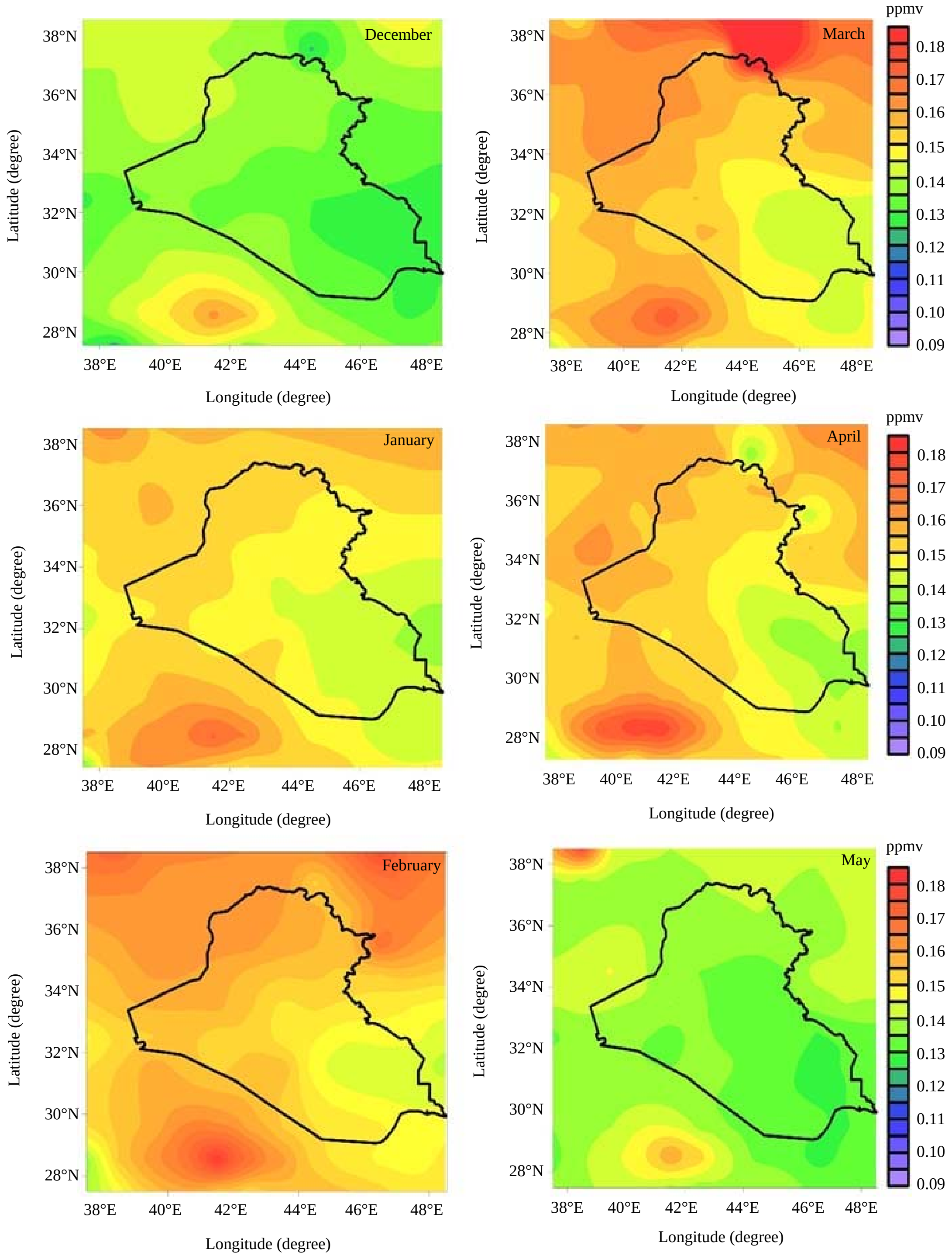

Fig. 3: AIRS average monthly coverage from the retrieved CO surface VMR, over Iraq for winter and spring seasons (December, 2003-May, 2016)

indicated an upward (downward) trend. The Z statistic had a normal distribution. To test for either an upward or downward monotone trend (a two-tailed test) at α level of significance, H_0 was rejected if the absolute value of Z was greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ was obtained from the standard normal cumulative distribution tables.

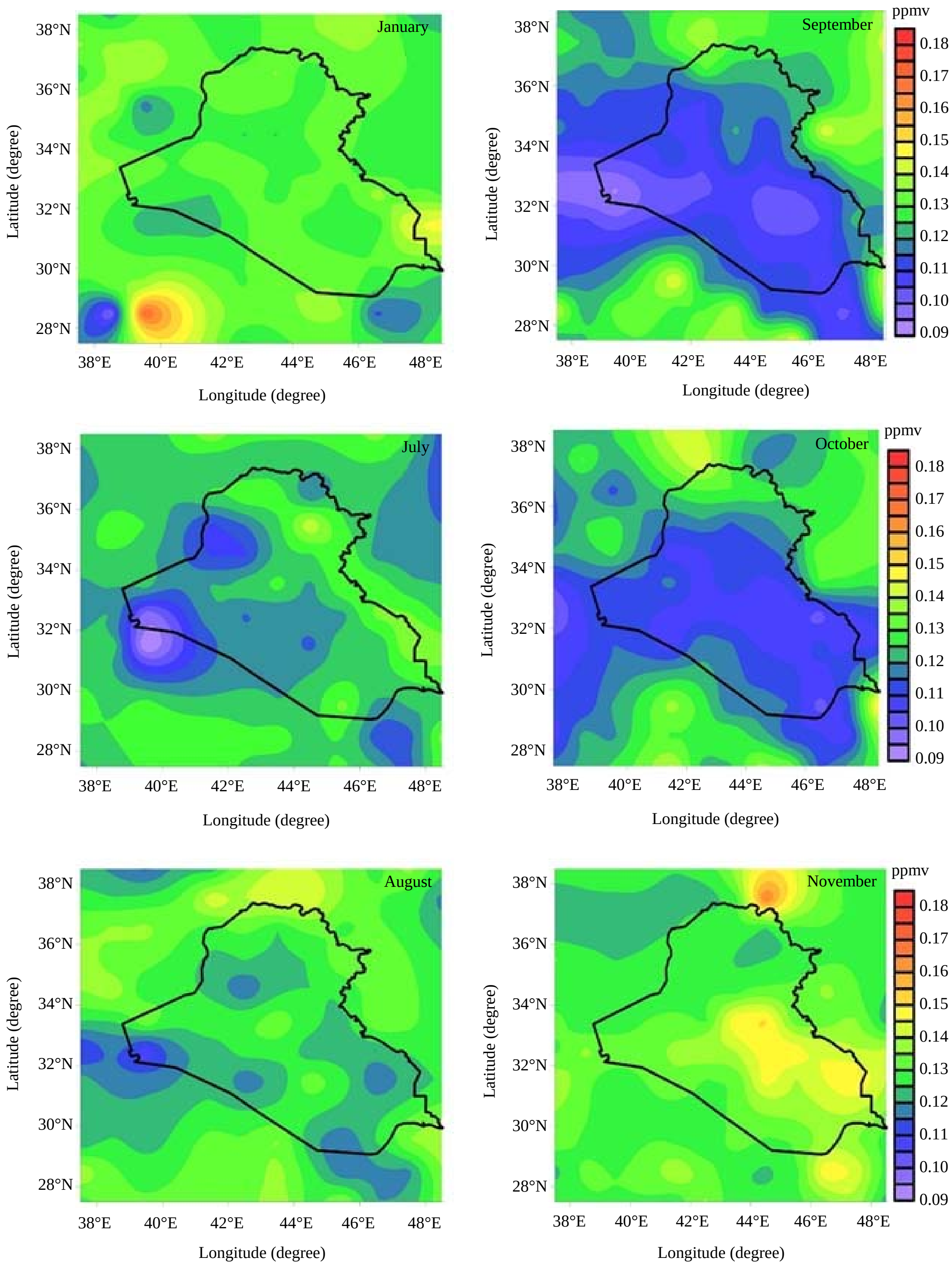

Fig. 4: AIRS average monthly coverage from the retrieved CO surface VMR, over Iraq for summer and autumn seasons (June, 2003-November, 2016)

RESULTS AND DISCUSSION

The average monthly CO VMR during 2003-2016 for all considered stations: Mosul, Sulaimaniyah, Rutba, Baghdad, Nukhuyb, Nasiriya and Basra are shown in Fig. 2. The mean and the standard deviation of CO monthly was (0.125±0.02 ppm) for the study period. Seasonal variation showed in the CO fluctuated considerably between winter and summer seasons. The CO values experience different seasonal variations strongly depending on topography and weather conditions. The higher values of CO that occurred was (0.158 ppm) in February and March over Mosul and Rutba and the lowest value was in October over Nasiriya and Basra (0.096 ppm), this seasonal variance were primarily results from the seasonal photochemical cycle of the OH in the troposphere, where during winter and early spring, in the Northern Hemisphere, coincides with the minimum of OH concentrations and thus a maximum for CO concentrations[11].

Spatiotemporal distribution of CO surface mixing ratio: Figure 3 and 4 illustrated the monthly mean CO VMR acquired from AIRS data base and averaged through the study period from January, 2003-December, 2016. Observed the spatial variation CO values over most parts of Iraq, minor differences in spatial patterns for each season depended on topography and weather conditions. From Fig. 3, showed AIRS coverage retrieved CO VMR for winter and spring seasons (December, 2003-May, 2016, the highest values occurred during the winter and spring season (February-March) at the North and Northeast regions. Also increase over desert environment in Western and Southwest regions near Syria and Saudi Arabia border.

The CO increased to its highest value (0.158 ppm) through the year in February and March over Mosul and Rutba and then it slightly decreased to moderate in April, compare to previous months and low in May. This mostly connected to be a mix of the advection of CO-enriched air masses blowing from neighboring countries like Turkey and Syria driven by active Northwesterly winter shamal winds and different anthropogenic activities during the cold season over Iraq. Normally, winter shamal winds associated with mid latitude disturbances which is progressing from West to East, following cold frontal passages, incursion the cold air from the North into the Arabian Gulf area during the winter (November to March) and the summer (June-August)[24] . The colder climate induce a longer lifetime of CO (leads to lower H_2O and hence, lower OH concentrations)[25]. The lowest value was at the Southern (below the latitude 32°N) regions on May (0.126±0.01 ppm) at Basra and Nasiriya. This fluctuation in the CO values during this period (December-May) due to the difference in geographic nature, human activity and climatic conditions.

The summer and autumn seasons (June-November) are shown in Fig. 4. A reduction in the CO values during June-October, except on July: Sulaymaniyah the Northern region (up to the latitude 34°N) of Iraq, showed enhanced in CO value, due to the extensive biomass burning from the forest fire that have occurred in the adjacent provinces. Whereas, slightly increase to moderate values of CO in November. There was an elevation of CO values in the central and Southeastern region of Iraq, especially over Baghdad and Basra, compared to their values on the rest of the regions during this period.

This was due to increase of industrial activities and oil extraction operations in congested cities with many CO sources. The highest value that occurred in this period was on November at Mosul (0.122±0.02 ppm) and the lowest value (0.096±0.02 ppm) on September and October in the South and Southwestern regions (below the latitude 32°) at Basra, Nasiriya and Nukhuyb, this reduction in CO is mostly connected to large extent marshes in this part of Iraq[16] coupled with solar radiation, thereby enhance (OH) radicals concentration (the mean CO sink).

Overall, CO maximum values occurred during the winter and spring season (February-March) and its values over Northern of Iraq is the highest compared to the rest regions throughout the year, due to meteorological condition and geographic nature of the regions, with subsequent plumes contributed to CO concentrations are from Turkey and Syria bring by Northwesterly winter shamal wind. Whereas, CO emissions gradually decreases during the summer months of June through September due to the summer shamal, or "wind of 120 days" blows almost daily and has great vertical mixing, large scale dynamics over a large horizontal area[26], which can reduce the CO concentrations during these months with CO precursors (especially the reaction between CO and OH radicals)[3]. Elevation in CO values can be observed throughout the year over the capital Baghdad due to its high population, crowded city and large industrial area and anthropogenic emissions.

Monthly long-term CO data trend analysis 2003-2016: The monthly time series for mean CO values calculated over the station; Mosul, Sulaimaniyah, Baghdad, Rutba, Nukhuyb, Nasiriya and Basra from January, 2003-December, 2016, as shown in Fig. 5. The CO emissions have significant Interannual variability with minimum in May-October and maximum in February-April, due to weather conditions and topography. The CO trend analyses for all stations were estimated and have significant negative trend ranged from (- 0.0022) to (- 0.0026) ppm/year over (Rutba, Nasiriya) and (Baghdad), respectively as tabulated in Table 1. The monthly trend analysis showed a stagnation and stability feature as obvious during 2003 until 2007 and began to decreasing in 2008 till 2016. These decreasing trends agree with global CO trend reported by the NOAA (National Oceanic and Atmospheric Administration) network. The surface-CO burden has the same behavior for North America and the entire Northern hemisphere

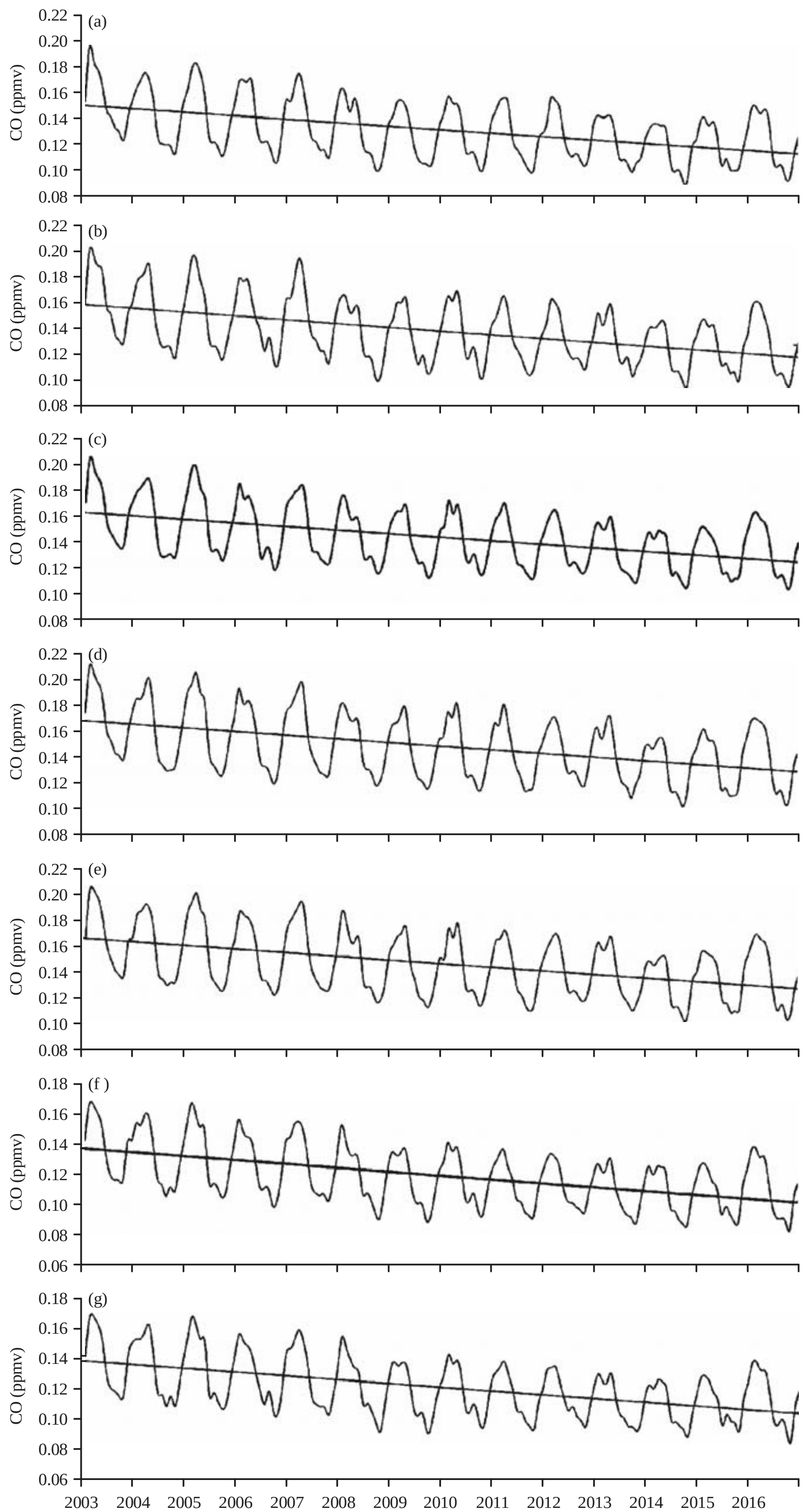

Fig. 5(a-g): Monthly CO value (2003-2016) over (a) Mosul, (b) Sulaimaniyah, (c) Baghdad, (d) Rutba, (e) Nukhuyb, (f) Nasiriya and (g) Basra, respectively mid-latitudes that observed from space by AIRS and MOPITT. These are due to the diminution of the Northern hemisphere CO emission from fossil fuels during the recession of global economic connected with CO-poor air transport from the tropics and climate change[10,20].

CONCLUSION

The investigated of 14 years (2003-2016) AIRS data reveals that weather conditions and topography are strongly affected and correlated with CO values. The monthly distribution shows important spatiotemporal variations of CO VMR with seasonal variations fluctuated considerably observed between winter and summer seasons and standard deviation (0.125$\pm$0.020 ppm) for the entire period. The enhancement of CO values at Northern regions above latitude 34° during winter seasons due to increase of incomplete emissions by combustion of thermal heaters utilized for heating at the cold season and active Northwest winter shamal winds brings a significant plumes of CO from neighboring countries.

The high values of CO over Southeastern region during summer compared to their values at the rest of areas were as result of emissions from the burning of agricultural residues in the paddy fields and oil extraction. The highest CO occurred during February and March at Northern and Western regions (0.158 ppm) and lowest were observed at Southern regions in October (0.096 ppm). The trend analysis shows negative trends at all considered stations throughout the period which refer to a notable reduction of CO which reaches to -0.0026 ppm/year. The CO emissions have important Interannual variability with minimum in May-October and maximum in February-April. Annual trend analyses have an obvious stability feature during 2003-2007 and began to decrease in 2008-2016.

SIGNIFICANCE STATEMENT

This study discovers that the AIRS-Aqua observations shed new light on the processes responsible for CO emission over Iraq in connection with its sources, topography and weather conditions. Also an attempt to assess the spread, distribution and variations of CO values over study area by satellite data in 14 years using mapping and long term-trends methods. The Satellite (AIRS) retrieved observations can be used to observe the variations of the atmosphere parameters and GHG's values over different regions with high spatial and temporal resolution and being able to make continuously monthly regional coverage for daily, monthly and annually reports.

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