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Spatiotemporal Analysis of Carbon Monoxide Observed by Terra/MOPITT in the Troposphere of Iran

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ABSTRACT: It has been more than 20 years that the Measurement of Pollution in The Troposphere (MOPITT) mission onboard the NASA Terra satellite keeps providing us CO atmospheric concentration measurements around the globe. The current paper observes CO mixing ratio from the MOPITT Version 8 (MOP03J_V008) instrument in order to study the spatiotemporal analysis of CO (spanning from April 2000 to February 2020) in the Troposphere of Iran. Results indicate that the average CO in Iran's troposphere has been 133.5 ppbv (i.e., 5.5 ppbv lower than the global mean CO). The highest distribution of CO (with an average of 150 ppbv) belongs to the city of Tehran (the capital of Iran) as well as the Caspian Sea coastal area, while the lowest value (with an average of less than 110 ppbv) has been estimated on the Zagros Mountains (southwestern Iran). The highest and lowest CO values have been observed in cold and hot months, respectively. Seasonally speaking, it is also clear that the highest and lowest carbon monoxide values occur in winter and summer, respectively. The vertical profile of MOPITT CO shows the maximum CO concentration at lower levels of the troposphere. It has been expanded up to 150 hPa. The trend is investigated by means of Pearson correlation coefficient statistical method. Overall, long-term monitoring of MOPITT CO in Iran indicates a decreasing trend of tropospheric CO over the 20 years (Y=-0.008X+449.31). Possible reasons for such a decrease can be related to improved transportation fleet, increased fuel quality, plans for traffic control, promotion of heating systems, and promotion of industrial fuels and factories.

Keywords: Air quality, Satellite, MOPITT, CO, Mixing Ratio.

INTRODUCTION

Carbon monoxide (CO) is a primary criteria pollutant, with both natural and anthropogenic sources, and plays an important role in tropospheric chemistry and climate (Ashpole and Wiacek, 2018). It is directly emitted as a product of incomplete combustion from industrial and urban fossil/biofuel burning as well as large-scale biomass burning and to a lesser extent directly emitted by plants and oceans (Buchholz et al., 2017). According to the 4th assessment report (AR4) of the IPCC, methane and carbon dioxide, contribute 1.66 and 0.48 W m^{-2}, respectively, to the total 2.94 W m^{-2} anthropogenic global mean radiative forcing due to gases (Solomon, 2007). CO is a colorless, odorless, and tasteless flammable gas that is slightly less dense than air (Warner and Wei, 2010). It is very toxic to human beings and animals that

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use hemoglobin as an oxygen carrier (both invertebrate and vertebrate) when encountered in concentrations above about 35 ppm (Dekker et al., 2017). CO is not a direct greenhouse gas; however, CO and other pollutants can affect tropospheric ozone, carbon dioxide, and methane (George et al., 2009; Nechita et al., 2016). Measurement of CO is usually done by in-situ stations (Zander et al., 2008), airborne measurement, airborne networks (Aguilar et al., 2005) and by satellites data analysis (Zhang et al., 2019). In the last years, measurements of CO have been performed by a number of satellite platforms; have produced CO distribution in a global view, from the troposphere to the mesosphere (Drummond and Mand, 1996). Satellite observations of tropospheric carbon monoxide are utilized in numeral atmospheric science usages including chemical weather forecasting, characterization of CO emissions through inverse modeling, air quality studies and representing the oxidizing capacity of the troposphere (Deeter et al., 2013). Global monitoring of CO in the last two decades has been facilitated by the deployment of space borne instruments using nadir geometry to measure infrared radiances (Drummond and Mand, 1996). Nadir looking TIR missions currently in operation are the Measurements of Pollution in the Troposphere (MOPITT) onboard TERRA (NASA), the Atmospheric Infrared Sounder (AIRS) onboard AQUA and the Tropospheric Emission Spectrometer (TES) onboard AURA (George et al., 2009). Only MOPITT and AIRS had sufficient data records for trend determination and both show similar decreasing decadal trends in CO total column for both hemispheres and for specific regional averages (Deeter et al., 2013). The new version of the MOPITT CO multispectral (thermal infrared (TIR) and near infrared (NIR) retrievals has enhanced surface sensitivity over many land regions, compared to TIR only retrievals and provides an improved estimate of CO near source locations (Clerbaux et al., 2009). MOPITT instruments provide extensive retrievals of total CO column and vertical profiles. These CO data have been correlated with the biomass burning fires and tropospheric ozone (Bremer et al., 2004). Over the last decade, several studies have performed of tropospheric CO globally data of MOPITT CO sources. Yudin et al. (2004) used the same data assimilation system to optimize CO emissions in MOZART. Arellano Jr et al. (2007) assimilated MOPITT CO, in addition to meteorological conventional observations, in a chemistry/climate model (CESM-CAM-chem) using the ensemble Kalman filter approach of the Data Assimilation Research Testbed (DART). Global MOPITT CO data assimilation started later over Europe with Claeyman et al. (2010) and El Amraoui et al. (2009) where assimilation was performed with a CTM using a 3-D variation data assimilation scheme. Recent studies such as Jiang et al. (2017) assimilated the new multispectral version of MOPITT CO retrievals to study the influence of vertical transport errors on inferred CO sources. Fortems-Cheiney et al. (2009) used MOPITT CO retrievals separately at 700 hPa to estimate CO emissions. Klonecki et al. (2012) assimilated MOPITT CO total columns in a global CTM, and recently, Inness et al. (2013) presented an 8 yearlong reanalysis of the atmospheric composition into a CTM that includes, among other sounders, assimilation of MOPITT CO total columns. Jiang et al. (2017) estimated the change in global CO emissions from 2001 to 2015 using remotely sensed CO measurements from the MOPITT, in situ methyl chloroform (MCF) and the adjoin of the GEOS-Chem model. Zhang et al. (2019) used the GEOS Chem four-dimensional variational data assimilation system to estimate emissions of carbon monoxide (CO) and nitrogen oxides (NOx) in November 2009 and July 2010. According, the aim of this study is to analyze retrievals of CO from the MOPITT satellite instrument to investigate monthly and seasonal variations of CO and evaluation of vertical distribution of CO in Iran.

MATERIAL & METHODS

The Measurement Of Pollution In The Troposphere (MOPITT), as the first EOS sensor to observe tropospheric CO, is on board the NASA Terra spacecraft and is flying in a sun synchronous polar orbit with an altitude of 705 km (Emmons et al., 2009). The MOPITT remote sensor was launched December 1999 and was the first sensor to observe the tropospheric CO which measures the emissions of terrestrial radiation in the thermal and Near-IR region of the electromagnetic spectrum (Yarragunta et al., 2017) . The retrievals of CO from the radiance data are available from 2000 as vertical profiles CO (on 14 altitude levels) and total columns amounts with a horizontal resolution of 22 × 22 km^2. MOPITT retrievals uses the maximum a posteriori optimal estimation method that requires covariance matrix and an 'a priori' CO profile (Deeter et al., 2013). The validation of these retrievals have been done by Emmons et al. (2007) by aircraft in-situ measurements. The results of this research indicate an acceptable coordination between MOPITT and in-situ profiles with an average bias less than 20 ppbv at all levels. An optimal estimation-based retrieval algorithm and a fast radiative transfer model are used to invert the measured A and D signals to determine the tropospheric CO profile. In principle, retrievals of CO may involve up to twelve measured signals (calibrated radiances) in two distinct bands: a near-infrared (NIR) band near 2.3 microns, and a thermal-infrared (TIR) band near 4.7 microns. The TIR radiances are sensitive to thermal emission from the earth's surface as well as atmospheric absorption and emission. The NIR radiances are sensitive to atmospheric CO solely through absorption of solar radiation. Currently, only clear-sky radiances (i.e., radiances uncontaminated by clouds) are fed to the retrieval algorithm. In the present study the latest version, version8 level 3 (MOP03J_L3.008), of monthly retrieved CO data has been used. The MOPITT CO data used here were obtained from the joint (J) retrieval (V8J) of CO from thermal infrared (TIR, 4.7 μm) and near-infrared (NIR, 2.3 μm) radiances using an optimal estimation approach (Bowman, 2006; Worden et al., 2010). In this study, CO retrievals from 1000 hPa to 1hPa (14 levels) levels have used. This research has been carried out for 20 year data from April 2000 to February 2020. In order to evaluate and analyze the CO distribution over the study area, we selected MOPITT CO data across Iran. The MOPITT CO mixing ratio day time products are derived from the near and thermal infrared radiances retrieval. A priori CO mixing ratio profile monthly is produced at 14 levels between 1000 hPa and 1hPa. Data including the corresponding time and location along the satellite track in an HDF (Hierarchical Data Format) and Net CDF format on monthly basis. This study was used CO Surface mixing ratio day time data closed to the earth surface. Generally, 12 monthly Level-3 versions 8 daytime were downloading to obtain the desired output. Extracted the MOP03J_L3.008 product's files from the Satellite using the MOPITT website, and has been evaluated and analyzed using various software such as ENVI 4.5 and ArcGIS 10. This study was conducted in Iran, which is located in the southwest of the Middle East with an area of more than 1,648,000 km^2 (Fig. 1) with over 81 million inhabitants, Iran is the 18th most populous country in the world. Comprising a land area of 1,648,195 km^2, it is the second largest country in the Middle East and the 17th largest country in the world. Tehran is the country's capital and largest city, as well as its leading economic and cultural center. Two main mountain ranges, namely Alborz and Zagros, surround Iran and are located in the northern and western parts of the country, respectively. An important role of these mountains is to block the entry of the Mediterranean moisture into the central and eastern parts of Iran, respectively, and creating intra-annual variations as well as spatial differences in some climate elements, especially temperature (Khosravi and Balyani, 2019).

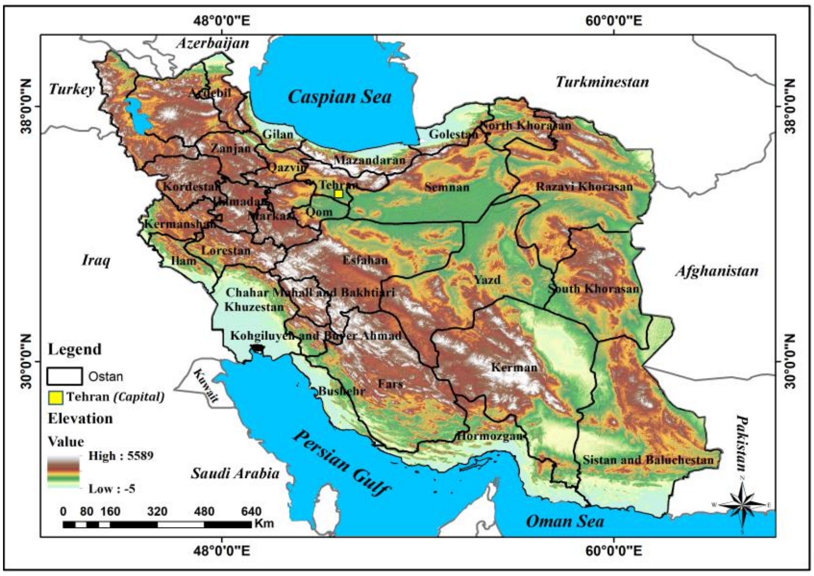


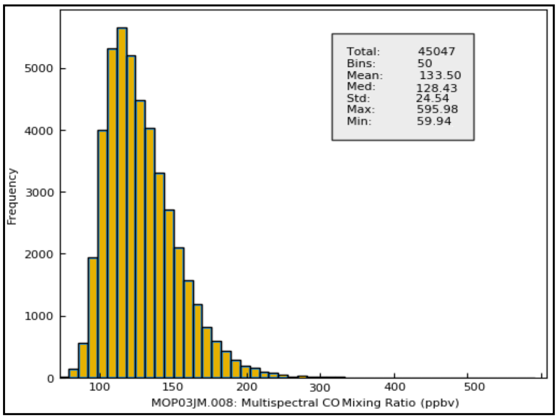
Fig. 1. Location of study area

RESULTS AND DISCUSSION

Fig. 2 (a) shows the parameters of the descriptive statistics of the CO during April 2000 to February 2020 periods for Iran. According to the Fig. 2 (b), the mean yearly distribution of CO in the troposphere of Iran increased from south to north. Nevertheless, the Zagros Mountains have a special condition, while the lowest concentration of CO with a long-term average of less than 110 ppbv is observed in this geographical area. The highest amounts of carbon monoxide is observed in the northern parts of Iran, over Tehran and the Caspian Sea, with a long-term average higher than 150 ppbv. The average of CO during this statistical period in Iran's troposphere was 133.5 ppbv, the highest carbon monoxide value was 595.9 ppbv, its lowest value was 59.9 ppbv and the standard deviation was 24.5. Tehran is the capital of Iran with an area of about 800 km^2 in the southern parts of the Alborz Mountains and one of the most polluted cities in the world. The contribution of CO in pollution of Tehran is higher than other pollutants (Ghodousi et al., 2017). According to the studies, several factors contribute in the pollution of Tehran among which such as topography, climate systems, population, transportation network, industries and so on (Naddafi et al., 2012). Alborz Mountains in the north and east are like a dam in front of the western winds and cause persistence of pollutants in the city of Tehran. The presence of many inversion conditions and the continuous deployment of high pressure systems throughout the year are among the other natural features of the region, which provides the conditions for more air pollution in Tehran. On the other hand, human factors such as large populations (14 million people - 17 percent of the Iran population), high numbers of vehicles (often worn out) and high traffic, the establishment of factories in the city, especially in the west and southwest significantly increase the urban pollution. The northern coastal area of Iran (Mazandaran, Gilan and Golestan provinces) has a population concentration of more than 150 people per square kilometer due to the favorable climate conditions. This has led to an increase in CO levels in this area.

Fig. 3 shows the time series variation of CO and CO_2 over the statistical period (August 2002 to February 2020) using the MOPITT CO and AIRS CO_2 sensors data. The trend was investigated using the Pearson correlation coefficient statistical method. According to this diagram, the CO value had a decreasing trend during the statistical period so; the average CO in Iran's troposphere has risen from approximately 152 ppbv in 2002 to 110 ppbv in 2020. This means that from the years 2002 to 2020, Iran's tropospheric CO has been reduced by 42 ppbv (more than 30%). Based on results, the CO value decreases from the beginning of the statistical period (2002) to the last years of the statistical period (2020). So that its claim the level of CO in 2002 dropped from about 200 ppbv to less than 100 ppbv. This situation well illustrates the decreasing trend of CO levels in Iran's troposphere during the statistical period. Improving the transport fleet, increasing fuel quality, plans for traffic control and promotion of heating systems, promotion of industrial fuels and factories are the reasons for reducing the level of CO. But unlike the declining trend of CO during the study period, CO_2 emissions have been on the rise. So that the amount of CO_2 has increased from 373 ppm in 2002 to 411 ppm in 2020. Accordingly, the average emission of CO decreased by about 42 ppbv during the statistical period, but the rate of emission of CO_2 increased by about 38 ppm. This situation is a good indication of the inverse correlation between the CO and CO_2.

According to the results of statistical analysis of the monthly CO (Fig. 4, 5 and 6), the highest CO value were observed in January, February and March (cold months of the year), and the lowest levels were observed in July, August and September (warm months of the year). According to these figures, value of CO in the other months (April, May, June, October, November and December), is between the value associated with maximum and minimum months. On the basis of CO value in these months, the highest and lowest values are visible in January and February 2001 (higher than 210 ppbv) and the in July and August 2017 and 2018 (lower than 105 ppbv), respectively. Spatially, the distribution of CO in the Iranian atmosphere does not have a homogeneous distribution. So that in the northern regions of Iran, especially in the atmosphere located above Tehran and the coastal area of the Caspian Sea, as well as the atmosphere of the southern coasts of the Persian Gulf and the Sea of Oman, the highest concentration of CO was estimated. On the other hand, the lowest concentration of CO was observed in the Zagros Mountains.



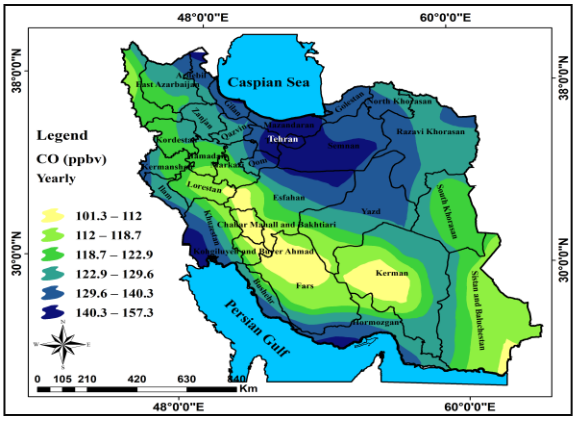


Fig. 2. descriptive statistics of the CO (a) and mean yearly distribution of CO in the troposphere of Iran for 2000-Apr to 2020-Feb (b).

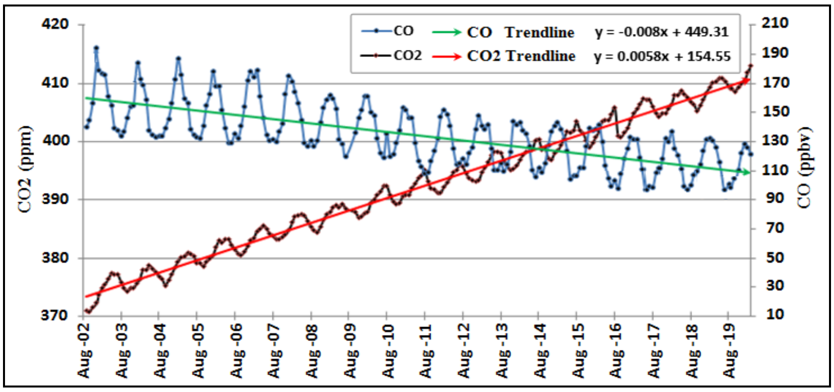


Fig. 3. Time series, Area Averaged of Multispectral CO Mixing Ratio monthly. ppbv for 2002-Aug to 2020-Feb, Iran area.

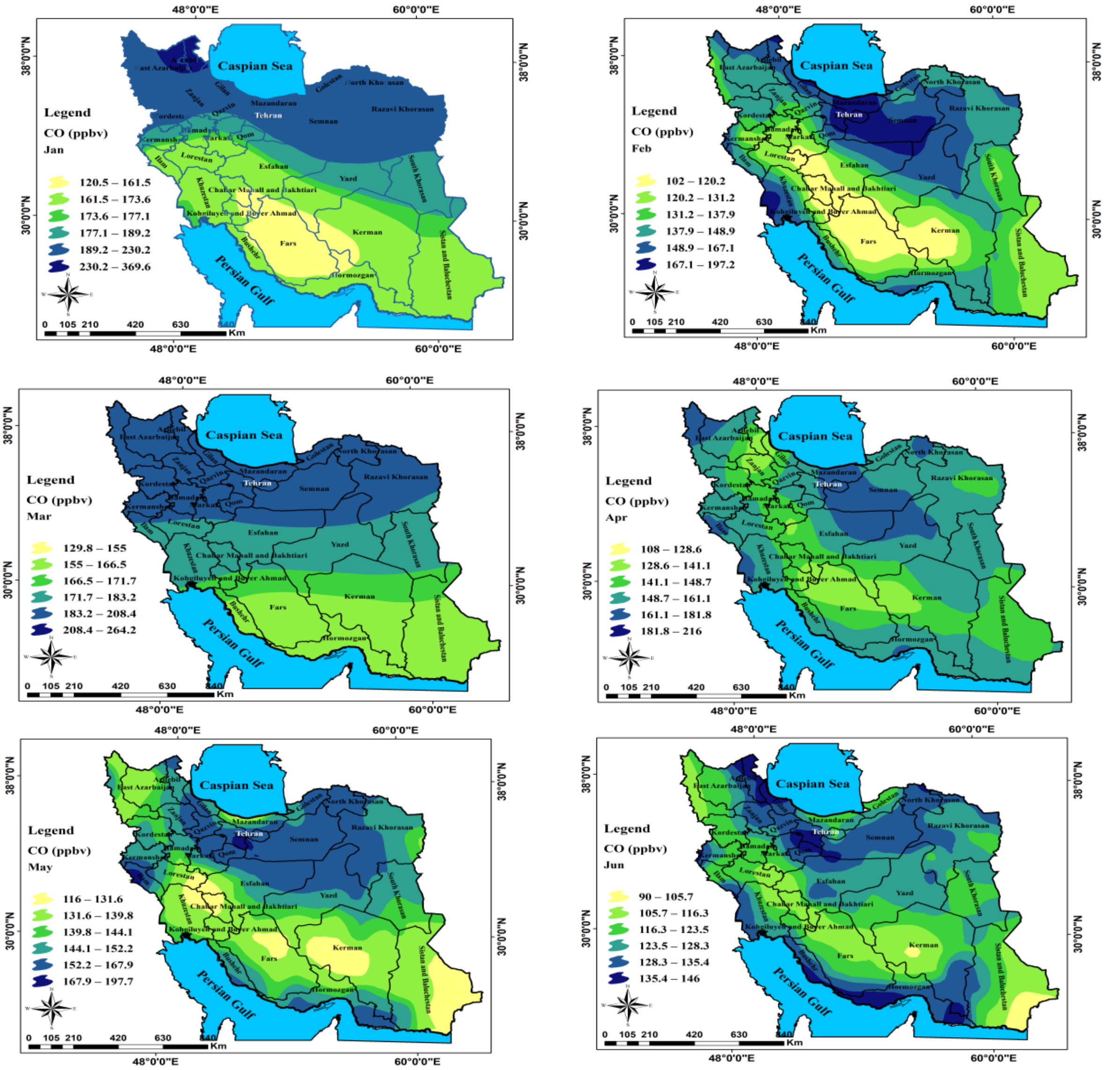


Fig. 4. Average Multispectral CO Mixing Ratio monthly ppbv for Jan, Feb, Mar, Apr, May, Jun months for 2000-Apr to 2020-Feb, Iran area.

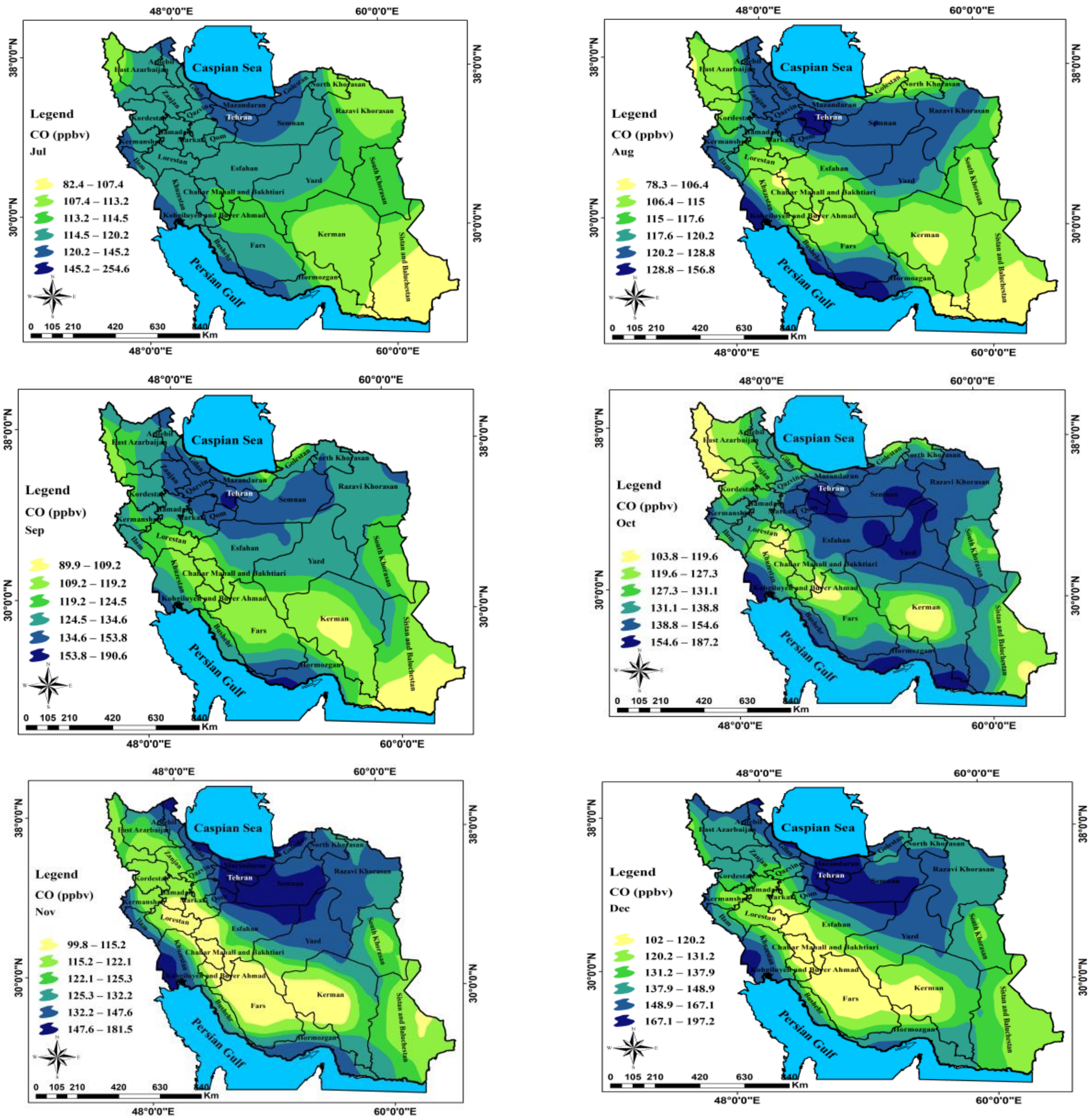


Fig. 5. Average Multispectral CO Mixing Ratio monthly ppbv for Jul, Aug, Sep, Oct, Nov, Dec months for 2000-Apr to 2020-Feb, Iran area.

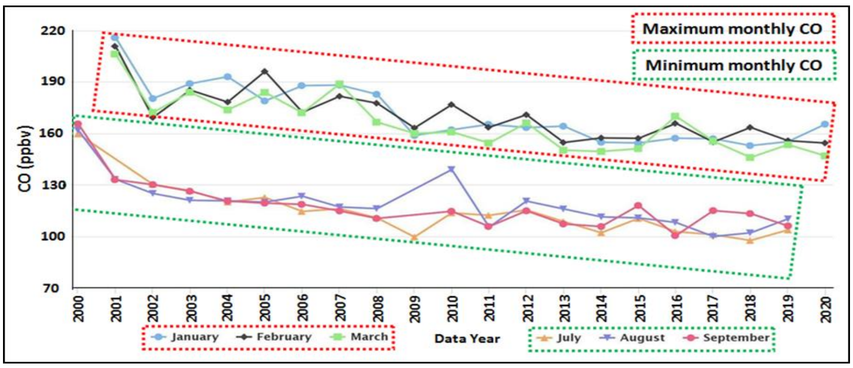


Fig. 6. Inter-annual time series Average Multispectral CO Mixing Ratio max and min monthly. ppbv for 2000-Apr to 2020-Feb, Iran area.

Analysis of CO in the four seasons of Iran showed the highest and lowest amounts in winter (December, February and July) and summer (June, July and August), respectively (Fig. 7). One of the most important climatic (geographic) factors affecting the increase in the CO value during the cold period is the temperature inversions that can be observed both in the form of radiation and synoptic. Radiant inversions occur due to intense ground coolness and synoptic inversions are mainly due to the establishment of sustained atmospheric pressure systems, both of which are the main characteristics of the cold period of the year. Other factors affecting the increase in the CO value during the cold season can be high traffic volumes (due to the openness of schools, universities and offices), increased use of fossil fuels for heating residential, office, educational and health spaces. These results are consistent with the maximum and minimum values of CO in the global zone. Fig. 8 show the CO value for the seasons of winter, spring, summer and autumn. Based on these figures, CO levels in order of the highest to the lowest seasonal value, includes winter, spring, autumn and summer, respectively. In different seasons of spatial distribution, the amount of CO in the Iranian atmosphere is different. So that the highest concentration of CO in the first place over Tehran and the northern coastal area and in the next priority over the southern coastal area to southwestern of Iran. The lowest levels of CO were estimated in the Zagros Mountains and southeastern Iran.

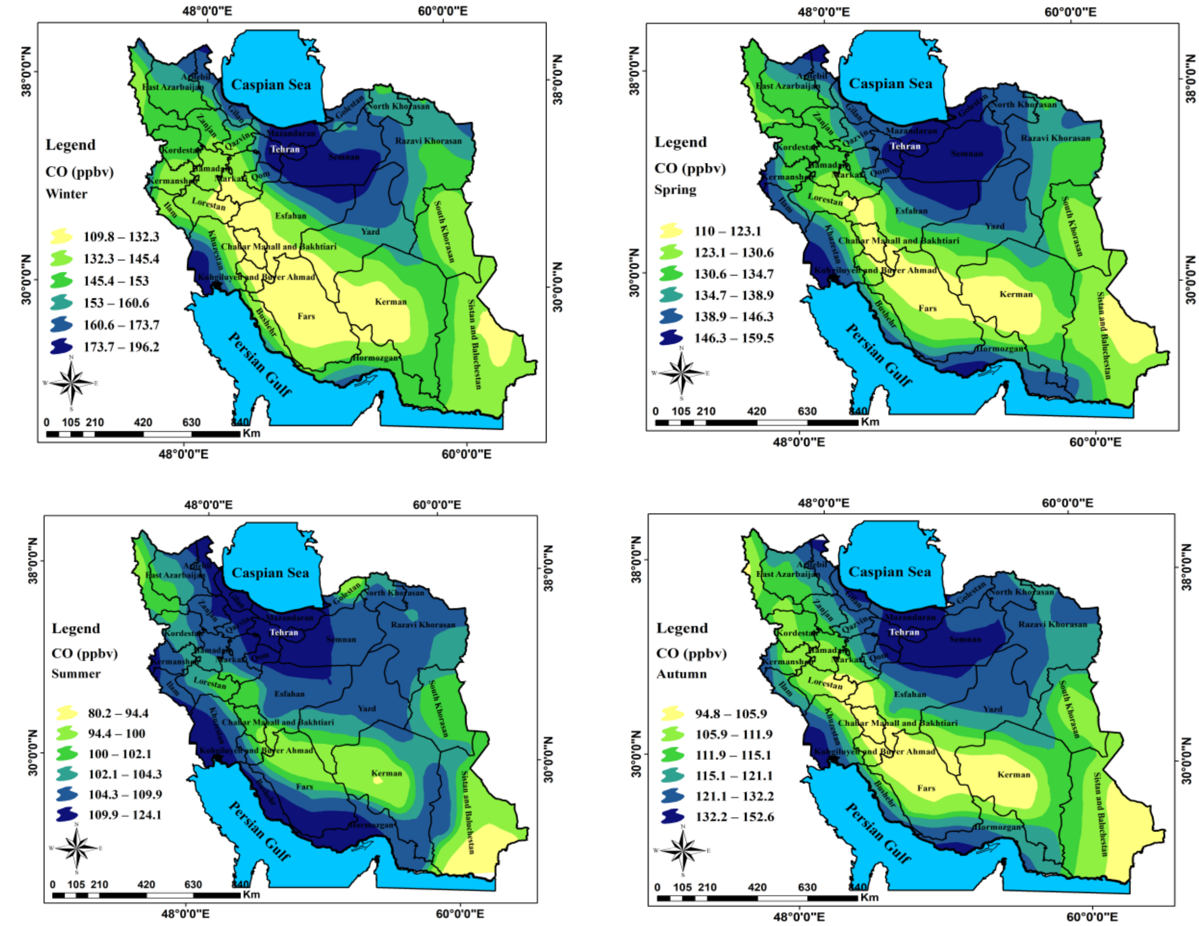


Fig. 7. Average Multispectral CO Mixing Ratio Seasonal ppbv for Winter, Spring, Summer and Autumn seasons for 2000-Apr to 2020-Feb, Iran area

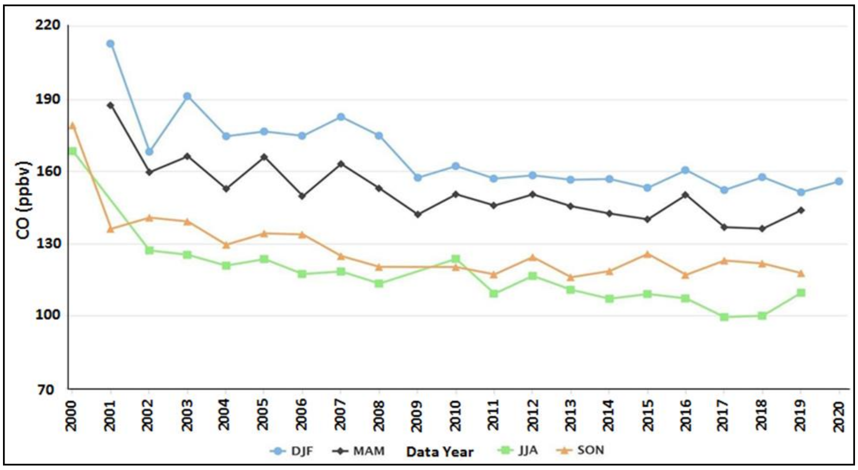


Fig. 8. Inter-annual time series Average Multispectral CO Mixing Ratio Seasonally. ppbv for 2000-Apr to 2020-Feb, Iran area.

Measurement of vertical CO, which determines the vertical distribution of CO in the troposphere, has been determined using vertical profiles along latitude and longitude. The results of vertical atmospheric survey clearly explain the vertical distribution and changes of CO in the troposphere of Iran. Fig. 9 represents the vertical distribution of carbon monoxide along the latitude and 14 levels of pressure in hPa (1000 to 1hPa level). According to this figure, the maximum concentration of CO is concentrated at altitudes between 1000 hpa and 150 hpa (below the black dashed line), and above that the value of CO is reduced to a minimum. Meanwhile, the highest concentration of CO in the 1000hPa level is observed at the latitude of 36 degrees north, which corresponds to the latitude of Tehran (the largest metropolis in Iran). The vertical distribution of CO in the Iran's troposphere along the longitude also indicates the concentration of CO at the lower levels of the troposphere (the area under the black dashed line) which shows approximately the same situation with the distribution along latitude (Fig. 10). Meanwhile, the maximum concentration of CO corresponds to the longitude of Tehran's metropolitan area (Fig.11). Also, the vertical survey of CO during the studied period is well illustrated by the gradual reduction of CO levels, as the highest value of CO was observed in the first 6 years of the statistical period (2000-2005) and approaching to the last years of the statistical period, the concentration of the CO layer is reduced (Fig. 12).

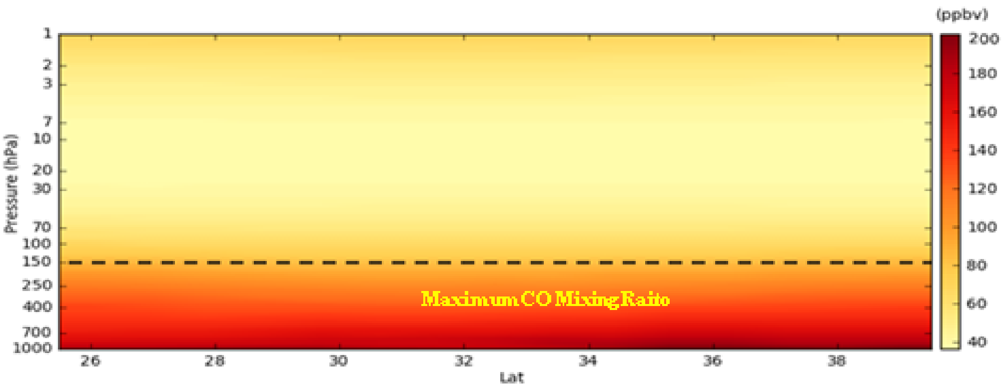


Fig. 9. Cross Section, latitude-Pressure of Multispectral CO Mixing Ratio profile monthly. [MOPITT MOP03JM v008] ppbv for 2000-Apr to 2020-Feb, Iran area.

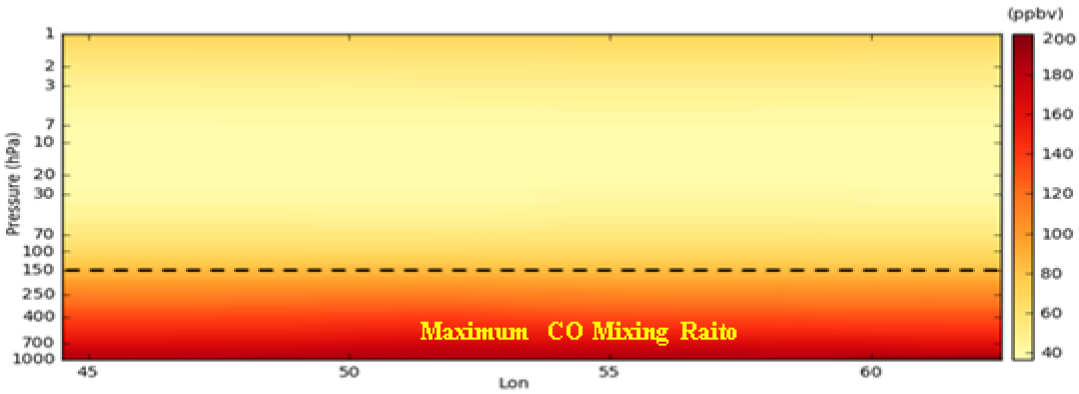


Fig. 10. Cross Section, longitude-Pressure of Multispectral CO Mixing Ratio profile monthly. [MOPITT MOP03JM v008] ppbv for 2000-Apr to 2020-Feb, Iran area.

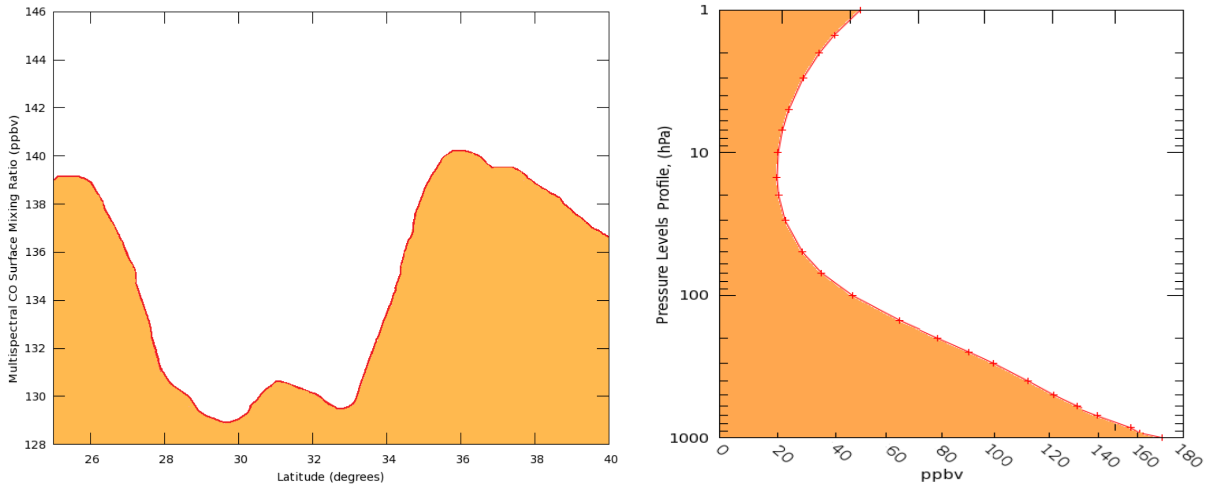


Fig. 11. Zonal Mean of Multispectral CO Mixing Ratio profile ppbv over 2001-Jan - 2017-Dec & Vertical Profile of Multispectral CO Mixing Ratio profile ppbv for 2000-Apr to 2020-Feb, Iran area.

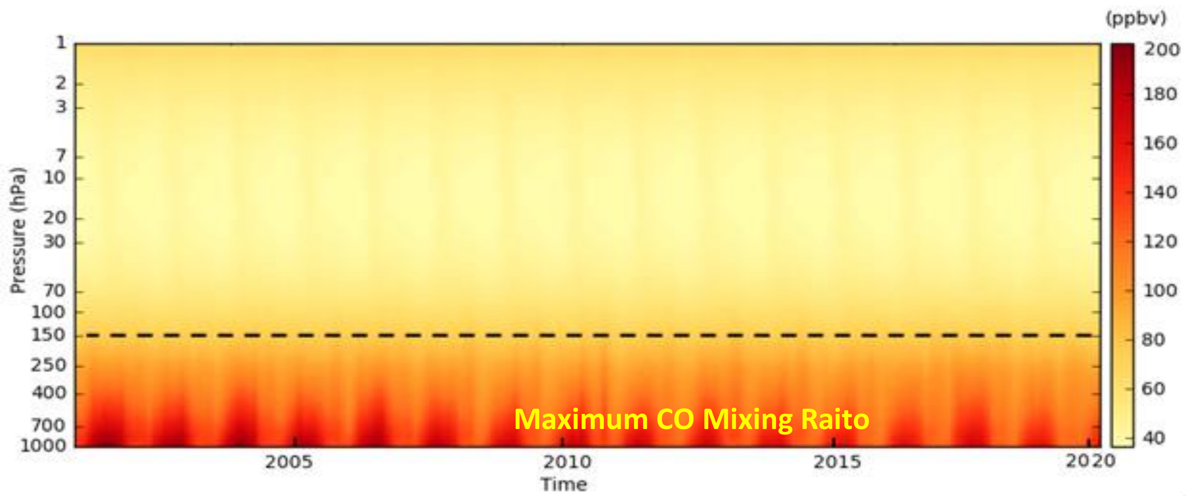


Fig. 12. Cross Section, Time Pressure of Multispectral CO Mixing Ratio profile monthly. [MOPITT MOP03JM v008] ppbv for 2000-Apr to 2020-Feb, Iran area.

CONCLUSION

This study has been conducted on the basis of MOPITT sensor measurements, as a hyperspectral sensor that can be used to study CO and specially designed to detect changes in atmospheric CO. The results clearly show an understanding of the status of CO in the surface and vertical direction of the troposphere of Iran. According to the monthly CO value during the 20 years statistical period (for 2000-Apr to 2020-Feb) over Iran, the average CO value varies from more than 150 over the Tehran and northern coast of Iran to less than 110 on the Zagros Mountains. In this statistical period, the average CO value in Iran’s troposphere was 133.5 ppbv (5.5 ppbv less than the global mean CO), with a maximum total column CO of 595.9 ppbv and minimum of 59.9 ppbv. The average monthly total CO in the troposphere of Iran has significant differences. The highest and lowest CO value was observed in cold and hot months, respectively. Seasonally, it was also cleared that the highest and lowest CO value is in winter and summer, respectively. Three-dimensional presentation (vertical presentation) of the changes of CO in the troposphere of Iran along latitude and longitude indicate the maximum CO concentration at lower levels of the troposphere, so that the maximum CO concentration in Iran's troposphere has been expanded up to 150 hPa but in particular, the highest concentration of the CO layer is evident from a surface level up to 1000 hPa. This layer consists of the lower troposphere, which is strongly influenced by the physical characteristics of the ground and planetary boundary layer. The results also indicate the decreasing trend of CO in the troposphere of Iran, as in the last years of the statistical period, in comparison with the first years of the statistical period, about 30% of the CO value in the troposphere of Iran has decreased. This situation well illustrates the decreasing trend of surface carbon monoxide levels in Iran's surface troposphere during the statistical period. Equipment of transportation network, increasing fuel quality, plans for traffic control and promotion of heating systems, promotion of industrial fuels and factories are the reasons for reducing the level of surface carbon monoxide. But unlike the declining trend of CO during the study period, CO_2 emissions have been on the rise. So that the amount of CO_2 has increased from 373 ppm in 2002 to 411 ppm in 2020. Accordingly, the average emission of CO decreased by about 42 ppbv during the statistical period, but the rate of emission of CO_2 increased by about 38 ppm. This situation is a good indication of the inverse correlation between the CO and CO_2.

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The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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