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Seasonal trends and Caline4 predictions of carbon monoxide over Madurai city, India

Tennyson Daniel[1], Rajesh Kumar.M[2]
[1]*Regional Test Centre (Solar Thermal), School of Energy, Environment and Natural Resources, Madurai Kamaraj University, Madurai-625 021, Tamil Nadu, India.*
[2]*Department of Solar Energy, School of Energy, Environment and Natural Resources, Madurai Kamaraj University, Madurai –625 0 21, Tamil Nadu India*

Abstract: *Concentrations of carbon monoxide (CO) in the atmospheric environment have been measured periodically for a year at six sampling sites in Madurai City, the second largest and most densely populated city in the state of Tamil Nadu.The recorded CO concentrations vary from 0.03 ppm to 6.39 ppm and are mostly below the Indian air quality standards. The seasonal averages of CO concentrations are calculated and it is found that the minimum concentrations (0.03 ppm) are in summer season and the maximum concentrations (6.396 ppm) are in winter season. The CO levels are explained in terms of sources, seasons and suitable statistical analysis in this research paper. The CALINE4 model is validated simultaneously and a good agreement is found to exist between the estimated and CALINE4-predicted values. The generated database of the present investigation pertaining to the status, seasonal trend and theoretical prediction of CO in the atmospheric environment of Madurai city may be effectively used for air quality management, air pollution abatement and further related research investigations.*
Keywords: *Air quality, CALINE4, Carbon monoxide, Madurai city, Seasonal trends*

I. Introduction

Carbon monoxide (CO), a toxic gaseous pollutant, is emitted during the combustion of conventional fuels and is currently drawing strong research interest because of its importance in causing adverse effects especially on human health [15]. It is a poisonous inhalant and when inhaled, it passes through lungs and diffuses into the blood. The combination of CO with hemoglobin leads to formation of carboxyhaemoglobin (COHb). The affinity of hemoglobin to absorb CO is 240 times more than that of oxygen. Therefore, CO can be absorbed into the blood instead of oxygen, which reduces the ability of hemoglobin to carry oxygen to the tissues. Due to lack of oxygen (asphyxiation) sometimes even death can occur [13,17]. The estimation of CO in the atmospheric environment of urban areas is beneficial in air quality management, air pollution abatement and epidemiological perspectives [19,7]. With these perspectives, we have monitored and modeled the dispersion of CO over Madurai, the second largest city in the state of Tamil Nadu of India. The concentrations were measured for a period of one year viz. January 2013 to December 2013. To investigate the dispersion of the pollutant over Madurai city, we have used CALINE4 model developed by California department of transportation. The results obtained from monitoring and modeling of CO are presented in this investigation.

II. Study area

Madurai city (9° 54’ N, 78° 84’ E and 100 m MSL), one of the ancient cities in Tamil Nadu, dating all the way back to the pre Christian era, is now a bustling city and a major commercial centre. The 4000 year old city is now the second largest city of Tamil Nadu with modern and progressive developments having a surface area of 140Km^2 and a population of 1.28 million in 2011. The ambient air quality of the city is being deteriorated like other cities of India due to combustion of fossil fuels in stationary and mobile sources [20,12]. To study the distribution of CO over Madurai city, measurements have been carried out at six different sampling sites. The selection of these sites has been made based on the existing anthropogenic activities occurring at these sites, which are mainly responsible for atmospheric pollution. These anthropogenic activities include the varying density of road traffic, industrialization and domestic activities within the urban limits of the city. Concentrations of CO in the atmospheric environment have been measured periodically for one year duration. A description of the land use, nature of activities and likely sources of pollution in the vicinity of the sites are given below:

2.1 Site 1: Periyar bus stand

This is the main bus station situated at the heart of the city. The area of this bus station is very limited and is surrounded by narrow roads. Therefore, there are traffic jams at this site, which in turn leads to congestions that cause slow movement of traffic. The contribution to air pollution at this site is mainly due to the emissions from personal, commercial and public transportation like two wheelers, auto-rickshaws, buses and trucks. There is accumulation and photochemical processing of air pollutants at this site due to the presence of tall roadside shops, houses and buildings.

2.2 Site 2: Goripalayam

This is a very busy commercial site located in the northern part of the city. In addition to some Government establishments such as Government Rajaji Hospital (the biggest hospital in southern Tamil Nadu region), colleges and schools, a large number of shops, restaurants and workshops are situated near this site. Although the roads are relatively wider than those in the central part of the city, the movement of traffic is highly congested and slow due to high density of vehicles and encroachment on the roadsides.

2.3 Site 3: Palanganatham

This site is surrounded by many cottage and small scale industries mostly related to furniture, grill works, plastic, rubber and lathe works. There are also electroplating units, rice mills and residential colonies in this area. Continuous traffic flow can be observed at this site. Besides the emission from automobiles, emissions from commercial and domestic sectors also contribute to the total air pollution load at this site.

2.4 Site 4: Kochadai

This is an industrial site of Madurai city, where two major industries are situated. The National Highway (NH-47) extension passing near this site has substantial flow of traffic. Hence, the emissions from the industries and automobiles are the major sources of air pollution in this region. There are also some residential colonies at this site.

2.5 Site 5: Pudur

Pudur is a fast emerging extension area of the city with many residential colonies. There are also a number of Government offices, educational institutions and commercial establishments in this area of study. Traffic flow consists mainly of light tonnage vehicles especially two wheelers and heavy tonnage vehicles mainly public buses. Since the roads are narrow and their conditions are poor, traffic emissions are substantial. An industrial estate is situated in the outskirts of Pudur, which may also contribute by means of background concentrations.

2.6 Site 6: SreeMeenakshi Temple

Having a large number of temples, Madurai is popularly referred to as the Temple city of south India. SreeMeenakshi temple, the landmark of the city, is located at the central part of the city. Around the temple, there are many commercial establishments. This causes the site to be over-crowded with traffic flow almost round the clock. The emissions from the automobiles, commercial establishments and residences contribute to the air pollution load of this sampling site.

III. Topographical features of Madurai city

The topography of Madurai city slightly increases in all directions as one moves away from the heart of the city except in the south direction. A gently sloping terrain surrounds this city. There are no hills in the region of Madurai corporation limit. Therefore, the existing topography of this city experiences horizontally homogeneous wind flow and more or less steady state meteorological conditions. Such condition does not allow the accumulation of pollutants [3]. However, at the central regions of the city, building geometry on both sides of the narrow roads is an important parameter for characterizing the transport and dispersion of pollutants. This geometry can be treated as a tunnel, which is open at the top. The elevated pollutant concentrations at some of the sampling sites, which are located in the central parts of the city, may also be determined by this parameter [6, 5].

IV. Materials and Methods

4.1 Measurement of CO

A personal, portable, single gas monitor having a microprocessor controlled electrochemical diffusion type sensor, is utilized for quantifying CO concentrations at different sites. The instrument has a range of 0 – 1500 ppm, with a resolution of 1 ppm and an accuracy of 1%. Once turned on, the instrument monitors continuously. The atmosphere being sampled gets into the sensors by diffusion through the vents in the sensor compartment cover. Normal air movements are enough to carry the sample to the sensors. The electrochemical sensor detects the amount of electric charges produced by oxidation/reduction of target gas and electronic signals are generated. These signals are converted to gas concentration through the on board microprocessor.

The ambient concentrations are recorded at time duration of one minute during morning and evening peak hours at all the sampling sites and the averages for eight hours are calculated.

4.2 Meteorological observations

Meteorology plays a crucial role in air pollution studies. In fact, there is a strong seasonality in the meteorological factors, which modulates the air quality levels [9, 14]. The important meteorological variables having influence on the levels of the pollutants over Madurai are wind (speed and direction), rainfall (amount and duration), air temperature, and relative humidity[18]. The analysis of the meteorological observations during the period of January 2013 to December 2013 shows a maximum solar radiation of 986.4 W/m^2. Amaximum atmospheric temperature of 39.6 °C is recorded during the summer season (mid February to mid June). It is observed that the velocity of wind is maximum during the months of August (7.85 m/s), followed by June (6.00 m/s) and September (5.88 m/s) and ranges between 0.08 and 7.85 m/s. The predominant wind velocity is observed in the southwest monsoon season. In the summer months, the observed wind speed is relatively lower than those in the winter season and varies from 0.11 to 6.00 m/s. The predominant wind directions during the period of this study are northeast, north, southwest, and west. The maximum number of rainy days (38) and the average maximum rainfall (534 mm) is noticed in the month of October followed by November due to the presence of the northeast monsoon. The variation of relative humidity shows a steep decrease from winter to summer (66.8% to 49.8%) and then a slow increase in the rainy season (56.3% to 62.4%).

4.3 Modeling of air quality

The California Line Source model (CALINE4) developed by the California Board of transportation is evaluated for the pollutant CO at six sampling locations in Madurai city. CALINE4 model divides individual highway links into a series of elements, from which incremental concentrations are then computed and summed up to form a total concentration estimate for a particular receptor location. The receptor distance is measured along a perpendicular from the receptor to the link centerline. Each element is modeled as an equivalent finite line source (FLS) positioned normal to the wind direction and centered at the element midpoint. The emissions occurring within an element are assumed to be released along the FLS representing the element. CALINE4 computes receptor concentrations as a series of incremental contributions from each element FLS. The total receptor concentration (C) from a particular roadway link is computed as follows:

$$C = \frac{1}{\sqrt{2\pi U}} \times \sum_{i=1}^{n} \left\{ \frac{1}{SGZ_i} \times \sum_{k=-CNT}^{CNT} \left[\exp\left(\frac{-(Z - H + 2 \times K \times L)^2}{2 \times SGZ_i^{\,2}} \right) + \exp\left(\frac{-(Z + H + 2 \times K \times L)^2}{2 \times SGZ_i^{\,2}} \right) \right] \times \sum_{j=1}^{6} \left(WT_j \times QE_i \times PDi_j \right) \right\} \qquad \text{---- (1)}$$

Where, n = Total number of elements , CNT = Number of multiple reflections required for convergence,U = Wind speed, L = Mixing height,SGZ_i = σ_z as f(x) for i^{th} element, QE_i = Central sub-element lineal source strength for i^{th} element, WT_j = Source strength weighting factor for j^{th} FLS segment.

CALINE4 treats the region directly over the highway as a zone of uniform emissions and turbulence. This is designated as the mixing zone and is defined as the region over the traveled way plus three meters on either side. The additional width accounts for the initial horizontal dispersion imparted to pollutants by the vehicle wake. CALINE4 permits the specification of up to 20 links and 20 receptors within an X-Y plane. The location of the link is specified in terms of X, Y and Z coordinates. Thus CALINE4 can be used to model multiple sources and receptors, curved alignments or roadway segments with varying emission factors.

CALINE4 is capable of predicting concentrations of pollutants within 500m of a roadway. Meteorology (eg. wind speed, wind direction, mixing height, stability class, temperature, background concentrations), source strength (eg. vehicles per hour, vehicle emission factor) and geometry (eg. roadway height, receptor locations and heights, number of links, surface roughness, mixing zone width) are required input parameters for the model. In addition to its application to roadways, special options allow the model to be applied to intersections, street canyons and parking lots.

4.4 Inputs to the model

4.4.1 Traffic inputs

A traffic survey is conducted from 6 a.m. to 22 p.m. so as to cover both forenoon and afternoon peak hours of traffic at the selected six traffic points by visual counting. The number of vehicles per hour is calculated from the database generated through the traffic survey and the emission factors of the vehicles are computed subsequently.

4.4.2 Meteorological inputs

The major meteorological inputs required for the model predictions include wind speed, wind direction, mixing height, stability class, ambient temperature and background concentrations. Stability class is obtained using wind speed and solar radiation measurements in conjunction with the table given by Pasquill. Hourly mixing heights are estimated from measured changes in temperature with altitude and are assumed to be the height of the lowest inversion.

4.4.3. Geometric inputs

The geometric inputs required for the model predictions include roadway height, receptor locations and heights, number of links, surface roughness and mixing zone.

All the required traffic, meteorological and geographic parameters are collected and used as inputs to CALINE4 air quality model.

V. Results and discussion

Urban air quality is a dynamic and complex environmental phenomenon exhibiting temporal and spatial variations, which are mainly due to changes in the rate of emission from sources, variations in the meteorological and topographical conditions and dissimilarities in the rate of removal of pollutants from the atmosphere [10, 16, 21]. The ambient air quality data of Madurai city under all weather and meteorological conditions is evaluated. In addition, CALINE4 air quality model is validated. These databases are beneficial (i) to define inter-relationship among the sources of pollution, atmospheric parameters and measurable manifestations for evaluating the character and the magnitude of the existing problem, (ii) to obtain knowledge and understanding necessary for developing preventive and corrective measures and urban planning and to evaluate the efficiency of existing abatement measures, if any, (iii) to appraise risk to health and well being of urban population and (iv) to validate air quality models[22, 2, 8, 4, 1].

5.1 Status of CO concentrations

While observing the overall level of pollutant of current concern recorded at all the sampling sites and for all seasons, it is found that the CO concentrations range between 0.03 to 6.39 ppm. This indicates that CO levels in some parts of the city are exceeding the permissible limits set by Central Pollution Control Board (CPCB), India. There is no major industrial source like power plant, which produces high CO emissions. However, a few industries, which are spread sporadically all over the city, emit CO into the atmosphere, but not in substantial quantities. The estimated CO source strength in domestic and commercial sectors of the city shows that the combustion of firewood, dung, peat and other bio mass fuels besides charcoal, kerosene and LPG contribute considerably to the CO pollution load.

The present traffic survey shows that there is an abundant increase in the number of vehicles on the roads, while comparing the data of past two decades in Madurai city. While comparing the growth of the number of two wheelers with other type of vehicles in the past two decades, it is studied that it is quite high. Presently, the number of two wheelers is relatively higher than that of all other vehicles.CO pollution in Madurai city is mostly due to the mixing of vehicular emissions with clean air masses and undoubtedly vehicular source is the major source like most other cities of India.The length, width and quality of the roads in Madurai city have not increased commensurately with the growth of vehicles and these lead to the increased instances of extreme congestion, traffic bottlenecks and long waits at traffic signals particularly in the central parts of the city. All these cause poor and random urban driving conditions. These in turn cause more CO emissions. Hence, CO pollution in the city can be directly correlated with the number of automobiles and the related parameters. It is worth mentioning that the topography of this city does not allow the accumulation of pollutants. But in the central parts of the city, the roads are narrow, with tall buildings on either side, which give them a canyon-like appearance. The elevated pollutant concentrations at some of the sampling sites can be correlated with these parameters.

5.2 Seasonal variation in CO concentrations

The overall concentrations of CO throughout the year at the six sampling sites are presented in Table 1. The monthly variations of the concentrations of CO are depicted in Fig 1 to 6. From the figures, it is observed that the month of December shows the highest recorded CO levels in all the sites, whereas the lowest concentration can be observed in the month of June.

To understand the seasonal variability of the concentrations of the pollutant, seasonal distribution has been calculated and it has been presented in Table 2. The meteorological parameters recorded during the period of study are given in Table 3 and Table 4. It is observed from Table 2 that CO has the maximum concentrations in the winter season (mid November to mid February) and minimum concentrations during summer season (mid

March to mid June). The recorded concentrations are found to cross the tolerance limits set by CPCB mostly during winter season, but they are found to be within the permissible limits mostly during the summer season.

The enhanced concentrations during winter can be correlated with the meteorological conditions like weak wind speed, low temperature, high humidity and feeble solar radiation available in the season. In addition, the mixing height can be associated, as it was low due to small values of sensible heat flux and a large lapse rate owing to the long stable surface layer due to radiative cooling. All these factors cause poor dispersion conditions and favour the occurrence of high concentrations of this pollutant. As the rate of homogeneous conversion of this gaseous pollutant by photochemical radicals is very low, reduction in the ambient concentrations in this way is negligible in this season.

The reduced concentrations during summer can be attributed with the strong influence of CO on hydroxyl (OH) and hydroperoxy radical (HO_2) processes. The hydroxyl governs the atmospheric chemistry during the day since its formation depends on the radiation from the sun.The high solar flux in addition to high ambient temperature during the summer season exerts a quite definite action on transformation rates and promotes the efficiency of atmospheric chemical reactions, leading to greater conversion of CO to CO_2. The summer season is also associated with relatively higher wind speed, lower relative humidity and rare inversions. The higher wind speed with lower relative humidity causes rapid dispersion, transport and dilution of the gaseous pollutant of current concern.

5.3 Comparison of estimated and CALINE4-predicted CO concentrations

The concentrations of CO are predicted using CALINE4 model equation. The estimated and predicted concentrations are presented in Table 5.

The observed and predicted concentrations in the present study range from 1.5 to 4.3 ppm and 2.1 to 5.5 ppm respectively. High observed and predicted concentrations of CO are obtained at the receptor points of Site-1 and Site-2. This is comparable with the traffic emissions in these sampling sites. Wind speed determines the extent to which pollutants are initially diluted with ambient air at the point of release. Since wind speeds are mostly lower than 2 m/s, there are excessively high predicted concentrations, compared with the measured CO levels. It is noted that the model performance deteriorates for situations with lower wind speeds. Over-prediction can also result due to parallel-to-road wind conditions. The model also over-predicts at wind directions from approximately 280º to 300º. These can be the reasons for the observed variation in the predicted and estimated concentrations.

A statistical analysis is done for the CALINE4 model validation and it is presented in Table 6. It is observed from the statistical analysis that difference between the predicted and observed mean concentration is > 1 ppm for the gaseous pollutant CO. The calculated correlation measures show that there is a good correlation between the observed and predicted concentrations. As for as the difference measures are concerned, it is noted that the values of systematic error is close to zero and the value of the unsystematic error nearly approaches the value of the overall root mean square error. The index of agreement (d) between the observed and predicted concentrations is calculated. A perfect agreement between the measured and predicted values would result in an index of agreement value of 1.0. For all data in Table 5, the value of d is 0.82. The value corresponds to a fairly good agreement between the measured and predicted values. CALINE4 model may be utilized for the quick assessment of air quality in increased spatial as well as temporal coverage of Madurai city.

Table 1: Summary of CO concentrations at six sites of Madurai city

Sl. No.	Site	CO concentrations in $\mu g/m^3$						
		Percentile			Maximum	Mean	Minimum	S.D
		25^{th}	50^{th}	75^{th}				
1	Site-1	1428.6	2845.8	4326.0	7317.8	3033.7	34.4	2025.9
2	Site-2	1606.1	2908.8	4111.2	7260.5	3229.7	68.7	1898.4
3	Site-3	1357.1	2158.7	3309.6	5760.3	2408.4	297.8	1328.8
4	Site-4	747.2	1202.5	2098.6	4557.9	1502.4	114.5	1502.4
5	Site-5	612.7	1276.9	2230.3	5588.5	1573.8	68.7	1218.6
6	Site-6	658.5	1465.8	2135.8	3733.3	1513.2	114.5	968.4

Table 2: Seasonal variations of CO concentrations in Madurai city

Sl.No	Site	CO concentrations in $\mu g/m^3$			
		Winter	Summer	SW monsoon	NE monsoon
1	Site-1	5497.9	1685.3	1776.8	4260.1
2	Site-2	5262.2	1641.5	3664.6	3067.9
3	Site-3	3642.7	1874.9	1342.5	3369.4
4	Site-4	2369.6	857.0	1770.7	1249.5
5	Site-5	2587.2	891.3	1053.6	2338.7
6	Site-6	2177.8	1359.0	820.1	1936.7

Table 3: Seasonal meteorological conditions of Madurai city (Part 1)

Sl.No	Season	Temperature (°C)			Relative humidity (%)		
		Min	Mean	Max	Min	Mean	Max
1	Winter	22.4	26.4	30.8	42.2	66.8	81.5
2	Summer	29.9	35.0	39.6	32.4	49.8	70.0
3	SW monsoon	23.5	30.4	36.7	45.8	56.3	69.7
4	NE monsoon	25.8	31.5	36.2	48.3	62.4	76.1

Table 4: Seasonal meteorological conditions of Madurai city (Part 2)

Sl.No	Season	Wind speed (m/sec)			Solar radiation (W/m^2)		
		Min	Mean	Max	Min	Mean	Max
1	Winter	0.08	2.26	5.39	518.1	690.1	814.7
2	Summer	0.11	2.66	6.00	727.9	879.9	1010.4
3	SW monsoon	0.21	4.21	7.85	567.1	725.5	824.5
4	NE monsoon	0.10	2.87	5.88	626.1	713.4	825.6

Table 5: CALINE4-predicted and observed concentrations of CO in Madurai city

Receptor points	CO concentrations (ppm)							
	Winter		Summer		SW monsoon		NE monsoon	
	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed
Site 1	5.2	4.8	1.9	1.5	1.8	1.6	5.5	3.7
Site 2	5.5	4.6	1.8	1.4	2.0	1.7	5.2	4.2
Site 3	3.9	2.6	1.5	1.1	1.3	1.2	3.8	2.9
Site 4	3.0	2.1	1.1	0.8	1.1	0.9	2.3	1.9
Site 5	3.2	2.3	1.0	0.8	1.2	0.9	3.6	2.9
Site 6	2.3	1.9	0.9	0.7	1.4	0.9	2.4	1.7

Table 6: Statistical analysis of model validation (CALINE4)

Sl No.	Statistical measures	Winter	Summer	SW monsoon	NE monsoon
1	**Average measures**				
	Observed mean (O)	3.1	1.1	1.2	2.9
	Predicted mean (P)	3.9	1.4	1.5	3.8
2	**Correlation measures**				
	Slope (B)	0.99	0.79	0.96	0.70
	Intercept (A)	-0.74	-0.03	-0.21	0.23
	Correlation coefficient (γ)	0.96	0.99	0.93	0.97
3	**Difference measures**				
	Observed deviation	1.19	0.31	0.34	0.89
	Predicted deviation	1.16	0.39	0.32	1.23
	Bias	1.60	0.63	0.53	1.83
	Fractional Bias	0.23	0.26	0.20	0.27
	Normalised mean square error (NMSE)	0.05	0.07	0.04	0.08
	Mean square error – systematic (MSEs)	0.80	0.33	0.27	1.00
	Mean square error – unsystematic (MSEu)	0.32	0.04	0.12	0.23
	Total mean square error (RMSE)	0.86	0.33	0.29	1.02
4	**Degree measures**				
	Index of agreement (D)	0.88	0.82	0.82	0.80

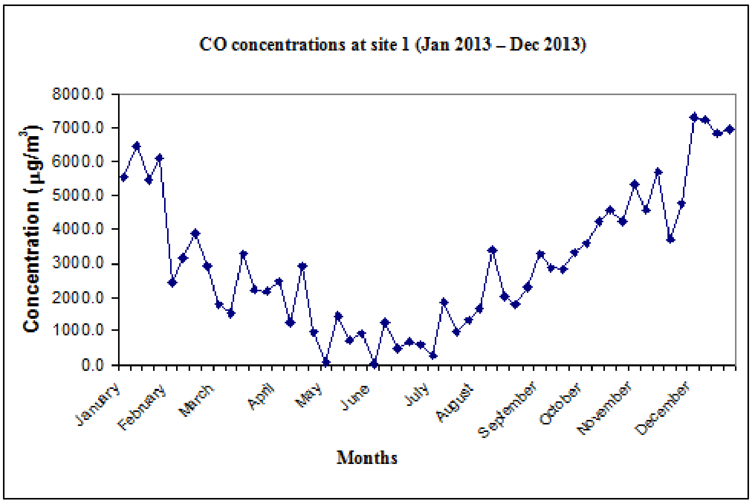

Fig 1: Concentrations of CO at Site 1: Periyar Bus Stand

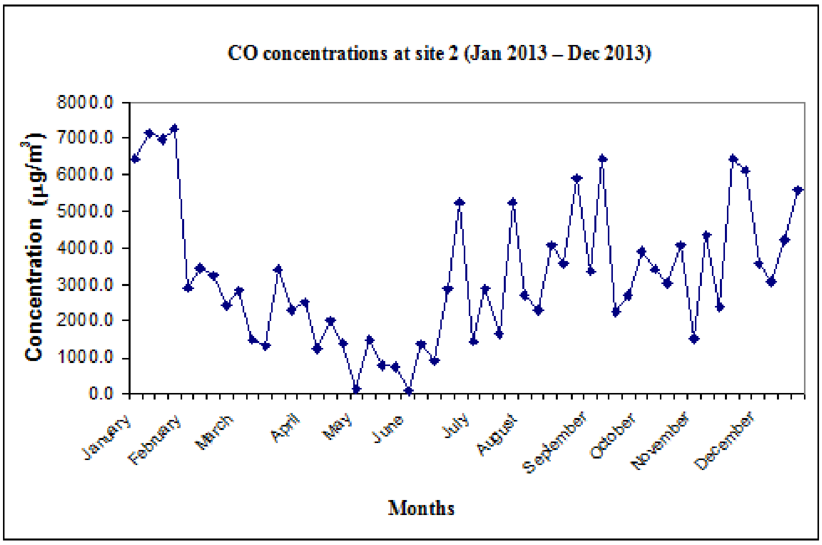

Fig 2: Concentrations of CO at Site 2: Palanganatham

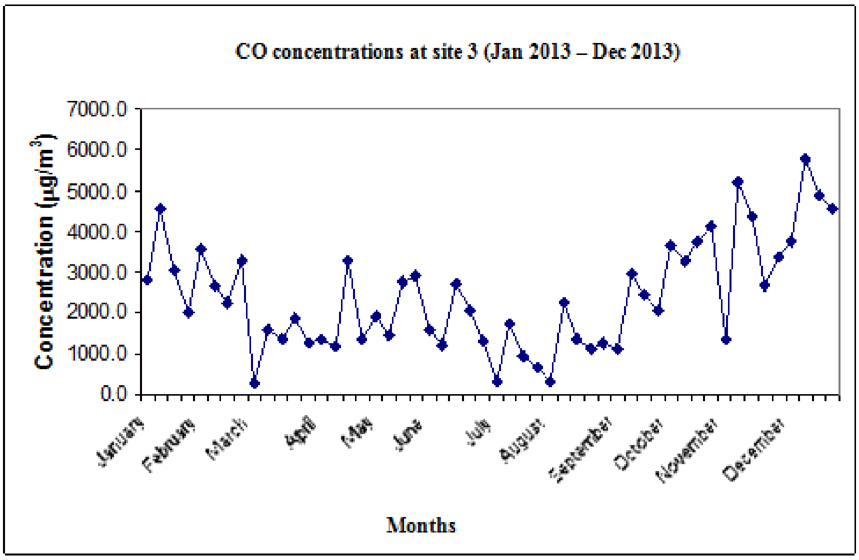

Fig 3: Concentrations of CO at Site3: Goripalayam

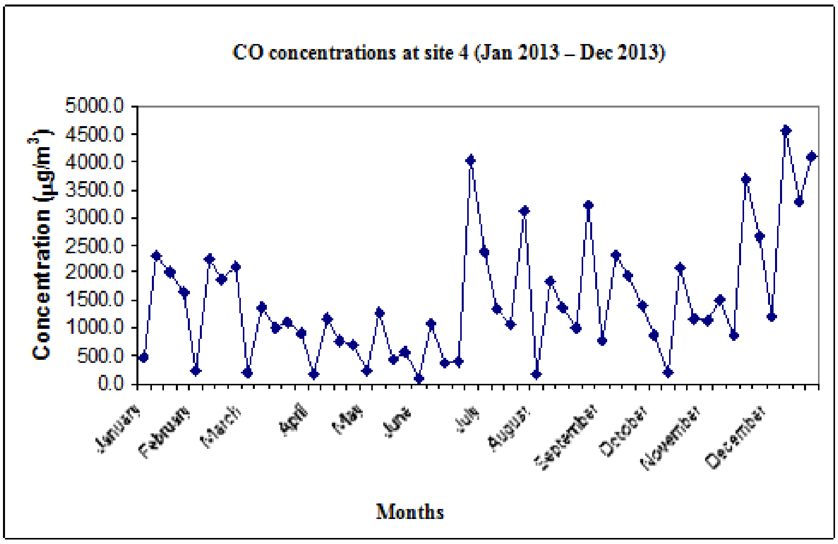

Fig 4: Concentrations of CO at Site 4: Kochadai

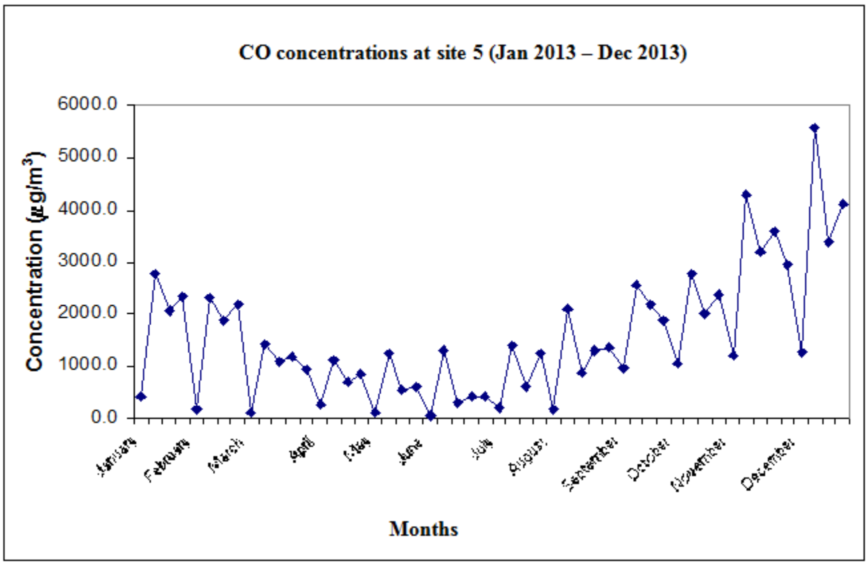

Fig 5: Concentrations of CO at Site 5: Pudur

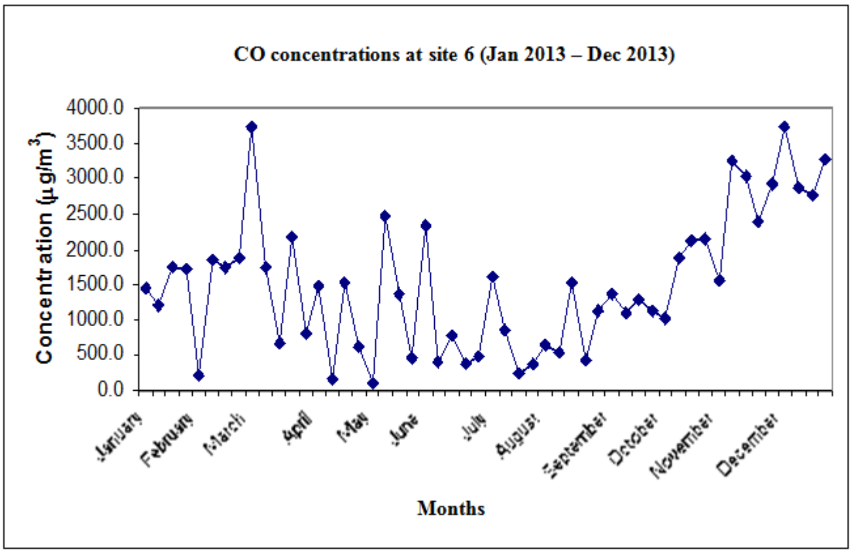

Fig 6: Concentrations of CO at Site 6: SreeMeenakshi Temple

VI. Conclusion

It is found that the concentrations cross the permissible limits at some of the sampling sites during the monitoring period. As the population, traffic, industrialization and per capita energy consumption will increase in future, it will simultaneously increase the emission load, which in turn will increase the ambient air pollution substantially over a period of time. If the atmosphere is polluted in this range, it is certain that it will have long-range adverse effects on the health and social wealth of the people living in this city. In this connection, strict implementation of adequate abatement measures and environmental regulations are necessary for the pleasant present and the sustainable future.

In the case of modeling of CO, a statistical measure namely index of agreement is calculated between the measured and CALINE4-predicted concentrations of CO and it is found to be 0.82. The value indicates that a good agreement exists between the observed and predicted values. Therefore CALINE4 can be used to simulate pollutant concentrations for Madurai city.

Continuous monitoring of the pollutant concentrations, simultaneous recording of meteorological variables, assessment of traffic density and generation of extensive emission inventory may be carried out periodically not only to evaluate the existing air quality management strategies but also to implement air pollution abatement strategies.

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