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# Atmospheric Pollution Research

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## Long-term trend analysis of CO in the Yongsan district of Seoul, Korea, between the years 1987 and 2013



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### ARTICLE INFO

#### Article history:

Received 18 February 2017

Received in revised form

26 March 2017

Accepted 26 March 2017

Available online 25 April 2017

#### Keywords:

Carbon monoxide

Long-term analysis

Temporal

Air pollution

Yongsan

Seoul

### ABSTRACT

In this study, the long-term trend in atmospheric carbon monoxide (CO) concentration was analyzed using the CO levels measured (intermittently) at an air quality monitoring (AQM) station in Seoul, Korea, between the years 1987 and 2013. Temporal trends in CO were analyzed on an annual and seasonal basis in reference to other important air pollutants such as methane (CH<sub>4</sub>), particulate matter (PM<sub>10</sub>), sulfur dioxide (SO<sub>2</sub>), nitrogen monoxide (NO), nitrogen dioxide (NO<sub>2</sub>), mercury (Hg), and ozone (O<sub>3</sub>). The annual mean of CO for the entire period was  $0.93 \pm 0.22$  ppm. CO levels were reduced by 83% from  $3.25 \pm 0.78$  ppm (1987) to  $0.51 \pm 0.31$  ppm (2013). Its relative reduction was compared over three periods chosen arbitrarily as period 1 (fast reduction, 1987–1988), period 2 (intermediate reduction, 1999–2000), and period 3 (slow reduction, 2004–2013). The concentrations of CO were strongly correlated with others (e.g., SO<sub>2</sub>, NO, NO<sub>2</sub>, O<sub>3</sub>, and Hg), suggesting the effects of similar source processes (e.g., fuel combustion). The reduction in its level was marginally consistent with the decreasing trend in the total CO column concentration in Seoul by the Measurements of Pollution in the Troposphere (MOPITT) satellite between 2000 and 2013, indicating decreasing anthropogenic CO emissions (despite increasing anthropogenic CO<sub>2</sub> emissions). The rapid relative reduction of CO in period 1 and the subsequent slower but moderate reduction thereafter appear to reflect the effects of both enforcement of administrative regulations and advances in emissions control technologies.

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### 1. Introduction

Carbon monoxide (CO) is an important trace pollutant in the troposphere and stratosphere (Cicerone and Oremland, 1988; Waibel et al., 1999; Wuebbles and Hayhoe, 2002). CO is well known as a colorless, odorless, and tasteless gas. It is notoriously poisonous to animals that use hemoglobin for oxygen transport due to the fact that it causes decreased oxygen delivery to cells (Choi

et al., 2014; Kim et al., 2015; Weaver, 2009). The major sources of CO are diverse and include incomplete combustion of carbonaceous fuels, biomass burning, and oxidation of methane and other hydrocarbons (Meszaros et al., 2005; Nguyen et al., 2010; Zhang et al., 2001).

The increasing energy demand in South Korea (from fossil fuels, especially from petroleum) is the main source of national anthropogenic CO emissions (Kim et al., 2013b; Yoo et al., 2015). Although CO<sub>2</sub> emissions from fossil fuels in South Korea have greatly increased since 1990, co-emissions of pollutants like CO have decreased sharply (EIA, 2015). Approximately 91% (194,795 ton yr<sup>-1</sup>) of the total anthropogenic CO emissions in South Korea were estimated to be derived from on-road mobile sources (Lee et al., 1999). The number of registered vehicles in the Republic of Korea increased by a factor of ~10 from 1988 (2,000,000) to 2014

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Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.

(20,000,000); in contrast, the annual CO emission decreased by ~50% from 1990 to 1998 and remained relatively constant ( $820 \pm 68$  kt/y) from 1999 to 2012 due to stricter emission standards (Kim et al., 2015). The transport sector was estimated to be responsible for 80% of CO emissions in Delhi, India while being projected to increase up to 3-fold from 2011 to 2020 (Nagpure et al., 2016).

In light of recent global policies related to climate change, both national and local air quality regulations have focused on reducing transportation emissions (e.g., CO<sub>2</sub> and NO<sub>x</sub>) in the environment by using substitute fuels (e.g., compressed natural gas) and more thermally efficient engines with better pollution control (Argüelles et al., 2006; Iglesias and Apsimon, 2004). To monitor air pollution levels of CO and other pollutants at both urban and suburban locations, a network of air quality monitoring (AQM) stations has been established and operated by the Korean Ministry of Environment (KMOE); these are comparable to those of other Organization for Economic Co-operation and Development (OECD) countries, including Japan, the USA, Netherlands, and Germany (Kim et al., 2015).

In this study, the concentration data on CO and selected air pollutants collected at an urban location in Yongsan, Seoul, Korea, were examined for the period between 1987 and 2013. The CO concentration data, along with other environmental parameters, were analyzed on various temporal scales (i.e., daily, monthly, seasonally, and annually) over the three arbitrary periods defined above. The results of our analysis, determined by focusing on the significant correlations with other airborne pollutants, sources of emission (briquette and fossil fuel usage), and comparisons with the background level emissions on a regional basis, were evaluated. As such, our study will help improve air regulation standards and reduce CO emissions by establishing systematic strategies and policies.

## 2. Methodology

### 2.1. Characteristics of the study area

The study area of Yongsan (YS) in Seoul, Korea, has previously been studied for other pollutants (Ahmed et al., 2015) and is geographically located north of the Han River ( $37^{\circ}32'18''\text{N}$  and  $126^{\circ}57'56''\text{E}$ ), as shown in Fig. 1. Yongsan is a densely populated area with about 250,000 residents. In addition, the official significance of Yongsan is enhanced by the presence of the Ministry of National Defense Headquarters, specifically the Yongsan Garrison (a U.S. military base). Moreover, the presence of commercial/industrial activities (e.g., corporate headquarters, Yongsan Electronics market, Haebangchon and Itaewon commercial districts, KOSPI 200 companies, Hyundai Development Company, Orion Confectionery, Cheil Worldwide, and Amore Pacific) contribute to making Yongsan an important commercial area. In addition, the historical Yongsan Station building has landmark status (Yongsan-district, 2016).

### 2.2. Data processing

The CO concentration was measured and recorded at hourly intervals at the YS air quality monitoring station. For detailed analysis, the CO concentration data were evaluated over different temporal intervals including hourly, daily, weekly, monthly, seasonally, and annually. The criteria used for such analyses have been described elsewhere (Vellingiri et al., 2015). The YS station is part of a national monitoring network operated by the KMOE, and monitoring stations are found in other major cities of South Korea (Kim et al., 2015). Table 1 lists the instrumentation used for

data acquisition of pollutant species and meteorological parameters (Ahmed et al., 2015; Nguyen and Kim, 2005, 2006).

The acquisition of raw CO data was made by a CO analyzer unit (response time = 60 s) using on-line air quality measurement system (Maxsam-series, Kimoto, Japan). The minimum detectable sensitivity of CO was 0.05 ppm with a precision of 0.5–2%. As shown in Table 1, other criteria pollutants were also monitored concurrently. The measurements of Hg at the site were also made as total gaseous mercury (TGM) which is generally predominated by gaseous elementary mercury (GEM). The emission patterns of CO were reported to be reflected by a number of trace components like atmospheric mercury (Hg) (Kim et al., 2016). Furthermore, the behavior of particulate matter (PM) was also monitored mainly in terms of PM<sub>10</sub> due to the unavailability or discontinuity of PM<sub>2.5</sub> at the study site.

The smallest daily data collection window of CO was 79 (120) days in the latter part of 1987 (i.e., 79 days over a period of four months), and the largest daily collection window was 363 days in 2011 (i.e., 363 days over a period of one year). The annual average concentration for the 1987–2013 period was  $0.93 \pm 0.22$  ppm, with a range of 0.1–8.64 ppm, ( $N = 3989$  daily measurements from a maximum possible total of 9862 days). The lowest annual CO concentration ( $0.35 \pm 0.13$  ppm,  $N = 358$  daily averages) was measured in 2004, and the highest annual CO concentration ( $3.25 \pm 0.78$  ppm,  $N = 79$  daily averages) was noted in 1979 (Table 2). It should be noted that data were only collected on 3989 of the total 9862 days during the 27-year period (1987–2013). The missing data (40% of the total) were caused by instrumentation malfunctions, lack of representative samples, and fiscal constraints. The daily average data were calculated if there were at least  $N = 16$  valid hourly measurements. Missing data or measurements that failed quality control measures are shown in the tables as 'not measured (NM)'.

The long-term (2000–2014) satellite-based record of atmospheric CO obtained from the Measurements of Pollution in the Troposphere (MOPITT) on board the NASA Earth Observing System Terra spacecraft was used to investigate the long-term trend in CO loading in the target area (Seoul) (MOPITT, 2016). We used the monthly level 3 daytime column data from the version 5 thermal infrared (TIR) product, which has negligible drift in the bias over time (Deeter et al., 2013). The level 3 data are a gridded product and include the a priori and averaging kernel data for each grid box. Long-term (decadal scale and deseasonalized) trends in CO for the target city were estimated using 12-month moving averages. For truncating the end-points, the data from the first and last six months were not used to calculate the trend because these data could introduce a dependence on the smoothing method or incur spurious results (Worden et al., 2013). In addition, to calculate the 12-month moving averages, a cubic spline interpolation was performed over the gaps in the monthly averages due to halted instrument operation. A linear least-squares fit to the 12-month moving averages was used to compute the linear trends.

## 3. Results and discussion

### 3.1. General temporal pattern of the CO levels in the study area

The study data were analyzed over different timescales (i.e., daily, monthly, seasonally, and annually). The obtained results were used to examine the effectiveness of abatement strategies.

The discontinuous CO concentration and other environmental data were grouped into three periods: period 1 (1987–1988), period 2 (1999–2000), and period 3 (2004–2013), as summarized in Table 3. The mean CO level of each period can be classified



Fig. 1. Data collection site in the Yongsan district of Seoul (1987–2013).

**Table 1**  
List of analytical instruments and measurement systems used in the current research.

Target pollutant	Measurement instrument
SO <sub>2</sub>	UV fluorescence (PUF)
NO <sub>x</sub>	NA-623 Japan/KIMOTO (chemiluminescence)
CO	ZRF Japan/FUJI (NDIR)
O <sub>3</sub>	OA-683 Japan/KIMOTO (ultraviolet spectroscopy)
CH <sub>4</sub>	HA-675 Japan/KIMOTO (HFID)
PM <sub>10</sub> <sup>a</sup>	FH62 C-14 Thermo-Electric Corporation (β-rays absorption) methods
Meteorological parameter	Measurement instrument
Ambient temp <sup>b</sup>	High-altitude mast (MHP45A, VAISALA Co., Finland)
UV <sup>c</sup> and SR <sup>d</sup>	Pyranometer (LI200SZ, LI-COR Biosciences, USA)
WS <sup>e</sup>	Wind monitor sensor (Model WM0513, R.M. Yong Company, USA)

<sup>a</sup> Coarse particulate matter.  
<sup>b</sup> Temperature.  
<sup>c</sup> Ultraviolet radiation.  
<sup>d</sup> Solar radiation.  
<sup>e</sup> Wind speed.

further as follows: (1) high ( $3.25 \pm 0.78$  ppm) in period 1, (2) intermediate to low in period 2 (i.e.,  $2.26 \pm 0.79$  ppm in 1998 and lower in 1999 ( $1.24 \pm 0.13$  ppm) and in 2000 ( $1.11 \pm 0.11$  ppm)), and (3) quasi-static in period 3 between 2004 ( $0.35 \pm 0.13$  ppm) and 2013 ( $0.51 \pm 0.31$  ppm). Similar temporal reductions (high, intermediate, low, and quasi-static) were noted for other pollutants, including SO<sub>2</sub>, NO, and Hg. The average CO concentrations observed during periods 1, 2, and 3 were  $2.52 \pm 1.86$  ppm,

$1.15 \pm 0.50$  ppm, and  $0.51 \pm 0.06$  ppm, respectively. The average CO concentration reduction was 54% (period 1 to period 2) and 56% (period 2 to period 3), while the overall reduction was about 80% from period 1 ( $2.52 \pm 1.86$  ppm) to period 3 ( $0.51 \pm 0.06$  ppm).  
The monthly trend analysis in CO concentration is shown in Fig. 2a. The peak CO concentrations occurred in the last and first months of each year, i.e., December and January (winter).

**Table 2**

Statistical summary of CO and relevant environmental parameters determined from the YS site over the period between 1987 and 2013.

	Year														
	1987	1988	1999	2000	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Mean (1987–2013)
<b>A. Pollutant species</b>															
CO	3.25 ± 0.78 <sup>a</sup> 0.48–8.64 <sup>b</sup>	2.26 ± 0.79 0.31–8.24	1.24 ± 0.13 0.32–3.56	1.11 ± 0.11 0.46–2.75	0.35 ± 0.13 0.20–1.00	0.43 ± 0.17 0.20–1.40	0.49 ± 0.27 0.20–2.10	0.61 ± 0.34 0.10–2.20	0.49 ± 0.23 0.10–1.70	0.59 ± 0.30 0.13–1.63	0.48 ± 0.27 0.10–1.91	0.57 ± 0.22 0.24–1.64	0.55 ± 0.23 0.10–1.54	0.51 ± 0.31 0.10–1.96	0.93 ± 0.22 0.10–8.64
(ppm)	(N = 79)	(N = 252)	(N = 96)	(N = 180)	(N = 358)	(N = 359)	(N = 243)	(N = 292)	(N = 351)	(N = 360)	(N = 360)	(N = 363)	(N = 362)	(N = 361)	(N = 3989) <sup>c</sup>
CH <sub>4</sub>	1.84 ± 0.07	2.07 ± 0.14	2.35 ± 0.01	2.28 ± 0.12	2.07 ± 0.28	2.10 ± 0.19	2.03 ± 0.16	2.04 ± 0.14	– <sup>d</sup>	–	–	2.21 ± 0.16	–	–	2.11 ± 0.08
(ppm)	(N = 110)	(N = 105)	(N = 100)	(N = 150)	(N = 347)	(N = 331)	(N = 309)	(N = 248)	–	–	–	(N = 362)	–	–	(N = 2062)
SO <sub>2</sub>	7.07 ± 1.31	5.66 ± 1.20	4.95 ± 0.44	6.52 ± 0.37	4.57 ± 2.06	5.89 ± 3.62	5.29 ± 2.79	5.77 ± 3.06	4.90 ± 2.43	5.53 ± 2.58	5.56 ± 1.90	4.75 ± 2.11	4.37 ± 1.94	5.84 ± 1.47	5.48 ± 0.93
(ppb)	(N = 110)	(N = 127)	(N = 103)	(N = 179)	(N = 354)	(N = 358)	(N = 285)	(N = 299)	(N = 366)	(N = 356)	(N = 364)	(N = 361)	(N = 361)	(N = 361)	–3984
NO	84.8 ± 7.69	51.8 ± 8.11	58.2 ± 12.1	32.3 ± 5.44	38.0 ± 41.0	33.1 ± 37.8	22.9 ± 25.1	25.2 ± 23.8	28.7 ± 25.6	24.3 ± 24.0	23.4 ± 22.7	18.5 ± 21.5	17.7 ± 18.3	21.3 ± 22.1	34.3 ± 10.4
(ppb)	(N = 112)	(N = 247)	(N = 102)	(N = 180)	(N = 321)	(N = 344)	(N = 287)	(N = 299)	(N = 366)	(N = 360)	(N = 364)	(N = 362)	(N = 362)	(N = 361)	(N = 4067)
NO <sub>2</sub>	15.6 ± 3.43	24.0 ± 2.53	41.0 ± 1.35	44.5 ± 9.72	40.3 ± 18.2	32.8 ± 16.4	35.1 ± 13.1	37.8 ± 14.8	42.6 ± 15.5	39.1 ± 14.5	37.6 ± 12.9	33.6 ± 14.6	33.4 ± 12.2	36.3 ± 14.2	35.3 ± 5.40
(ppb)	(N = 112)	(N = 248)	(N = 102)	(N = 180)	(N = 321)	(N = 344)	(N = 287)	(N = 299)	(N = 366)	(N = 360)	(N = 364)	(N = 362)	(N = 362)	(N = 361)	(N = 4068)
NO <sub>x</sub>	100.1 ± 6.72	75.7 ± 7.72	99.2 ± 11.7	76.8 ± 12.0	78.2 ± 55.6	65.8 ± 48.1	58.0 ± 36.3	63.0 ± 35.4	71.3 ± 38.0	63.4 ± 36.0	61.0 ± 32.5	52.1 ± 34.2	51.1 ± 28.1	57.6 ± 34.3	69.5 ± 14.9
(ppb)	(N = 112)	(N = 247)	(N = 102)	(N = 180)	(N = 321)	(N = 344)	(N = 287)	(N = 299)	(N = 366)	(N = 360)	(N = 364)	(N = 362)	(N = 362)	(N = 361)	(N = 4067)
THC	2.63 ± 0.19	2.71 ± 0.24	3.10 ± 0.07	2.78 ± 0.13	2.50 ± 0.35	2.53 ± 0.26	2.39 ± 0.30	2.37 ± 0.23	–	–	–	2.49 ± 0.28	–	–	2.61 ± 0.09
(ppm)	(N = 110)	(N = 114)	(N = 103)	(N = 150)	(N = 347)	(N = 331)	(N = 309)	(N = 248)	–	–	–	(N = 362)	–	–	(N = 2074)
NMHC	0.79 ± 0.17	0.63 ± 0.18	0.77 ± 0.08	0.50 ± 0.12	0.44 ± 0.26	0.43 ± 0.19	0.37 ± 0.19	0.33 ± 0.15	–	–	–	0.28 ± 0.16	–	–	0.50 ± 0.05
(ppm)	(N = 110)	(N = 114)	(N = 100)	(N = 150)	(N = 347)	(N = 331)	(N = 309)	(N = 248)	–	–	–	(N = 362)	–	–	(N = 2071)
O <sub>3</sub>	6.91 ± 3.03	11.1 ± 2.91	9.65 ± 2.17	19.8 ± 1.66	13.6 ± 8.29	13.7 ± 8.20	17.1 ± 11.0	17.1 ± 10.3	15.6 ± 9.30	20.1 ± 11.5	18.0 ± 11.0	20.4 ± 11.1	19.4 ± 10.2	19.7 ± 12.0	15.9 ± 3.85
(ppb)	(N = 106)	(N = 242)	(N = 105)	(N = 180)	(N = 350)	(N = 351)	(N = 278)	(N = 298)	(N = 366)	(N = 360)	(N = 359)	(N = 361)	(N = 364)	(N = 361)	(N = 4081)
Hg	15.7 ± 1.80	14.8 ± 2.57	4.95 ± 0.43	5.32 ± 1.36	3.15 ± 1.71	3.88 ± 1.73	3.21 ± 1.25	3.34 ± 1.37	3.43 ± 1.12	4.02 ± 1.49	4.08 ± 1.09	3.08 ± 1.50	2.12 ± 0.59	2.57 ± 0.79	5.26 ± 0.55
(ng m <sup>–3</sup> )	(N = 31)	(N = 66)	(N = 34)	(N = 68)	(N = 243)	(N = 261)	(N = 292)	(N = 321)	(N = 344)	(N = 360)	(N = 356)	(N = 364)	(N = 359)	(N = 365)	(N = 3464)
PM <sub>10</sub>	–	–	–	73.3 ± 16.4	62.1 ± 34.4	63.5 ± 34.6	57.5 ± 74.6	63.2 ± 47.4	54.9 ± 34.7	56.2 ± 36.1	50.0 ± 30.6	48.9 ± 34.7	40.1 ± 21.2	43.8 ± 23.5	55.8 ± 15.5
(μg m <sup>–3</sup> )	–	–	–	(N = 101)	(N = 350)	(N = 355)	(N = 304)	(N = 319)	(N = 365)	(N = 363)	(N = 365)	(N = 360)	(N = 364)	(N = 363)	(N = 3609)
<b>B. Meteorological parameter<sup>e</sup></b>															
Temp	10.9 ± 8.17	15.9 ± 11.2	–	–	12.8 ± 9.69	11.7 ± 10.8	14.0 ± 10.3	12.9 ± 10.4	12.9 ± 10.0	13.1 ± 10.1	12.5 ± 10.9	12.9 ± 10.6	12.2 ± 11.4	12.6 ± 11.0	12.9 ± 0.86
(°C)	(N = 103)	(N = 246)	–	–	(N = 361)	(N = 361)	(N = 320)	(N = 317)	(N = 366)	(N = 360)	(N = 365)	(N = 365)	(N = 361)	(N = 365)	(N = 3890)
UV	15.1 ± 9.57	41.1 ± 21.1	–	–	0.05 ± 0.03	0.05 ± 0.04	0.15 ± 0.10	0.29 ± 0.24	0.38 ± 0.19	0.37 ± 0.21	0.37 ± 0.20	0.28 ± 0.20	0.39 ± 0.21	0.39 ± 0.21	4.91 ± 6.40
(mW cm <sup>–2</sup> )	(N = 96)	(N = 98)	–	–	(N = 352)	(N = 284)	(N = 275)	(N = 307)	(N = 366)	(N = 360)	(N = 365)	(N = 365)	(N = 361)	(N = 365)	(N = 3594)
WS	0.74 ± 0.47	0.70 ± 0.43	–	–	0.76 ± 0.32	0.83 ± 0.35	1.02 ± 0.47	1.28 ± 0.62	2.21 ± 0.52	2.41 ± 0.63	2.46 ± 0.59	1.43 ± 0.58	2.53 ± 0.69	2.52 ± 0.61	1.57 ± 0.12
(m s <sup>–1</sup> )	(N = 103)	(N = 197)	–	–	(N = 361)	(N = 361)	(N = 320)	(N = 320)	(N = 366)	(N = 360)	(N = 365)	(N = 365)	(N = 361)	(N = 365)	(N = 3844)
SR	–	–	–	–	125 ± 64.8	123 ± 59.4	133 ± 79.5	113 ± 65.0	147 ± 74.6	145 ± 79.2	138 ± 77.6	133 ± 77.1	148 ± 77.0	146 ± 78.4	135 ± 7.32
(W m <sup>–2</sup> )	–	–	–	–	(N = 361)	(N = 361)	(N = 320)	(N = 307)	(N = 366)	(N = 360)	(N = 365)	(N = 365)	(N = 361)	(N = 365)	(N = 3531)

<sup>a</sup> Mean±SD (standard deviation).<sup>b</sup> Range (min – max), N = Number of daily data.<sup>c</sup> N = Number of total data (1987–2013).<sup>d</sup> NM (not measured).<sup>e</sup> Abbreviations used for meteorological parameters: Temp = temperature, UV = ultraviolet, WS = wind speed, and SR = solar radiation.

**Table 3**

A statistical summary of CO and relevant environmental parameters determined from the YS site for period 1 to period 3.

Period	Period 1 (1987–1988)	Period 2 (1999–2000)	Period 3 (2004–2013)	All periods (1987–2013)
<b>A. Pollutant species</b>				
CO (ppm)	2.52 ± 1.86 <sup>a</sup> (N = 331) R = 0.31–9.60 <sup>b</sup>	1.15 ± 0.50 (N = 276) R = 1.62–3.56	0.51 ± 0.06 (N = 3409) R = 0.10–2.20	1.39 ± 0.94 (N = 4016) <sup>c</sup> R = 0.10–9.60
CH <sub>4</sub> (ppm)	1.97 ± 0.40 (N = 208)	2.31 ± 0.31 (N = 250)	2.09 ± 0.03 (N = 1597)	2.12 ± 0.20 (N = 2055)
SO <sub>2</sub> (ppb)	6.57 ± 4.29 (N = 237)	6.30 ± 2.44 (N = 282)	5.25 ± 0.63 (N = 3465)	6.04 ± 1.83 (N = 3984)
NO (ppb)	61.8 ± 35.6 (N = 350)	43.3 ± 33.8 (N = 282)	25.3 ± 7.30 (N = 3426)	43.4 ± 17.0 (N = 4058)
NO <sub>2</sub> (ppb)	83.8 ± 39.1 (N = 351)	41.3 ± 17.4 (N = 282)	36.9 ± 1.76 (N = 3426)	33.4 ± 8.03 (N = 4059)
NO <sub>x</sub> (ppb)	83.8 ± 39.1 (N = 350)	84.6 ± 46.4 (N = 282)	62.1 ± 8.04 (N = 3426)	76.9 ± 20.4 (N = 4058)
THC (ppm)	2.59 ± 0.69 (N = 208)	2.92 ± 0.62 (N = 253)	2.46 ± 0.04 (N = 1597)	2.66 ± 0.36 (N = 2058)
NMHC (ppm)	0.62 ± 0.50 (N = 208)	0.62 ± 0.41 (N = 250)	0.37 ± 0.04 (N = 1597)	0.54 ± 0.24 (N = 2055)
O <sub>3</sub> (ppb)	10.2 ± 8.96 (N = 338)	15.8 ± 5.51 (N = 285)	17.5 ± 1.31 (N = 3448)	14.5 ± 3.83 (N = 4071)
Hg (ng m <sup>-3</sup> )	14.6 ± 6.35 (N = 97)	5.33 ± 2.59 (N = 102)	3.29 ± 0.38 (N = 3265)	7.74 ± 3.02 (N = 3464)
PM <sub>10</sub> (μg m <sup>-3</sup> )	— <sup>d</sup>	66.1 ± 37.6 (N = 101)	54.0 ± 15.0 (N = 3508)	60.0 ± 16.0 (N = 3609)
<b>B. Meteorological parameters<sup>e</sup></b>				
Temp (°C)	14.4 ± 9.92 (N = 349)	—	12.8 ± 0.59 (N = 3541)	13.6 ± 6.60 (N = 3890)
UV (mW cm <sup>-2</sup> )	28.2 ± 18.6 (N = 194)	—	0.27 ± 0.08 (N = 3400)	14.2 ± 12.7 (N = 3594)
WS (m s <sup>-1</sup> )	0.71 ± 0.37 (N = 300)	—	1.74 ± 0.12 (N = 3544)	1.23 ± 0.17 (N = 3844)
SR (W m <sup>-2</sup> )	—	—	135 ± 8.47 (N = 3531)	135 ± 8.47 (N = 3531)

<sup>a</sup> Mean±SD (standard deviation).<sup>b</sup> Range (min - max), N = Number of daily data.<sup>c</sup> N = Number of total data (1987–2013).<sup>d</sup> NM (not measured).<sup>e</sup> Abbreviations used for meteorological parameters: Temp = temperature, UV = ultraviolet, WS = wind speed, and SR = solar radiation.

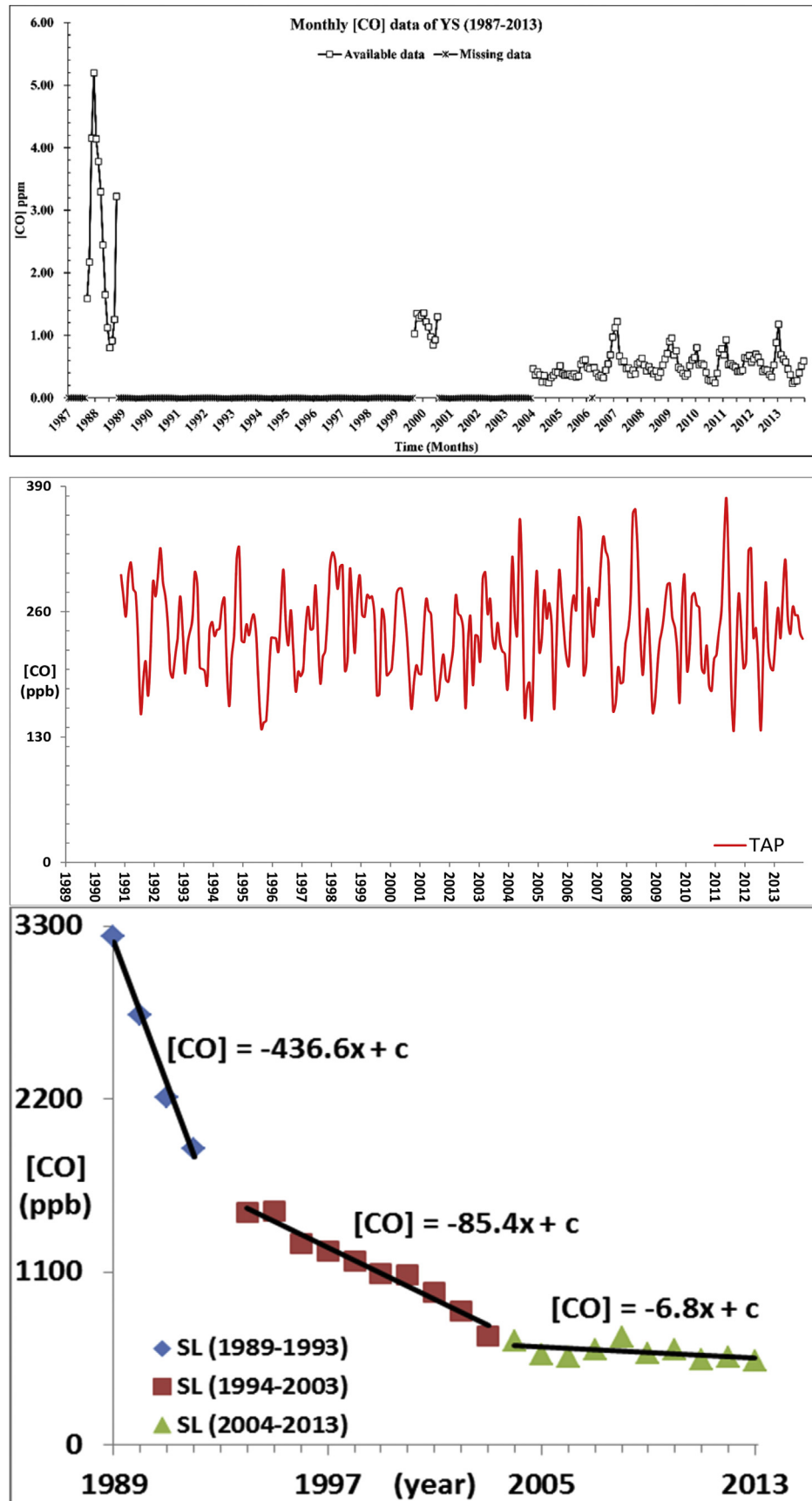
Alternatively, low concentrations occurred in the middle of the year (May, June, or July – late spring and summer). The monthly concentration of CO (YS, Seoul) of 1.30 ppm (during mid-summer: July 2000) was 5.4 times higher than the background level of CO (0.24 ppm) at the Tae-Ahn Peninsula (TAP), as shown in Fig. 2b (Kim et al., 2015). In contrast, the YS CO concentration (1.35 ppm) was 6.5 times higher than the CO concentration of 0.20 ppm at the TAP during mid-winter (January 2000). The CO concentration data is shown in Table 1S. The average seasonal concentrations within a period follow the seasonal pattern of winter > fall > spring > summer, with an inter-period pattern of period 1 > period 2 > period 3.

The annual mean CO concentration reduction over the three periods at Yongsan is classified as high, low, or quasi-static, i.e., 3.25 ppm–2.26 ppm (1987–1988), 1.24 ppm–1.11 ppm (1999–2000), and 0.35 ppm–0.51 ppm (2004–2013), respectively (Fig. 2a). The annually averaged CO concentration for the Seoul (SL) metropolitan area is shown in Fig. 2c (Kim et al., 2015). The background CO level in South Korea was about 0.25 ppm for the 1989–2015 period (measured at the TAP observatory located 120 km SW of Seoul on the coast) (TAP, 2016). The YS CO level (0.35 ppm) in 2004 was only 1.4 times greater than the background level (0.25 ppm), while that (3.25 ppm) in 1988 (period 1) was 13 times higher than the background level (0.25 ppm). The

daily statistical analysis of CO level for each period is shown in Table 2S. Little variations in the concentration data were observed between weekdays and weekends.

The [CO] data (Fig. 2a,c) are qualitatively similar for both the Yongsan site (located within the Seoul metropolitan area, Fig. 1) and other areas in Seoul (Kim et al., 2015). The monthly mean [CO] values for January to August for the full study period are shown in Fig. 1S(a). Likewise, the results for September to December are also plotted in Fig. 1S(b). The results thus indicate strong seasonal effects on anthropogenic [CO] emissions. Overall, a significant decrease in [CO] over the whole study period can be confirmed from the comparison of monthly data sets. For example, [CO] in January 1988 (Mid-winter: 4.1 ppm) decreased more than 3-fold in January 2013 (1.2 ppm) while there are 4-, 3-, and 5 folds changes in mid-spring, mid-summer, and in mid-fall, respectively. The hourly data for the concentrations of CO and other relevant pollutants during period 1 were also analyzed on a seasonal basis (Table 3S). The hourly CO concentrations of period 1 were higher during spring mornings (3.50 ± 2.98 ppm) and lower (0.70 ± 0.47 ppm) during summer evenings. Similarly, the CO concentrations were higher (6.49 ± 5.17 ppm) during winter mornings but lower (1.04 ± 0.73 ppm) during fall afternoons.





**Fig. 2.** (a) Monthly [CO] at Yongsan from 1987 to 2013, (b) monthly [CO] at an NOAA monitoring network site (Tae-Ahn peninsula, Korea), and (c) yearly [CO] for the Seoul metropolitan area from 1989 to 2013 (Kim et al., 2015).

### 3.2. CO seasonal trends

The seasonal CO mean concentrations are shown in Table 1S; these represent the average monthly data, as follows: spring (March to May), summer (June to August), fall (September to November), and winter (December to February). The mean seasonal CO concentrations over all three periods were as follows: winter ( $1.53 \pm 0.84$  ppm), fall ( $1.02 \pm 0.59$  ppm), spring ( $0.98 \pm 0.49$  ppm), and summer ( $0.60 \pm 0.12$  ppm). The seasonal average CO concentration decreased from period 1 to period 3 and was most significant in the winter season: ~83.8% (winter), ~78.7% (spring), ~60.3% (summer), and ~80.4% (fall). Similar trends were also observed in other major cities of South Korea (i.e., Seoul, Busan, Daegu, Incheon, Daejeon, Gwangju, and Ulsan) (Kim et al., 2015). The maximum CO concentration in winter might result from the mixed effects of a low atmospheric boundary layer (caused by atmospheric inversions due to persistent anti-cyclonic weather in winter) (Ray and Kim, 2014), higher coal use (especially in period 1) (Kim et al., 2015), and possible long-range transport from China (see Fig. 2 in (Worden et al., 2013)).

In Fig. 2S, the seasonal comparison of CO concentrations indicates a variation in the order of period 1 > period 2 > period 3. However, in every period, the seasonal CO level was highest in winter and lowest in summer. Also, other environmental pollutants, such as SO<sub>2</sub>, NO, NO<sub>2</sub>, total hydrocarbon (THC), and non-methane hydrocarbon (NMHC) concentrations, showed similar seasonal trends to those of CO with solar irradiance, UV level, and temperature cycle. This behavior has been previously noted (Ahmed et al., 2015).

### 3.3. Correlation of airborne CO level with other pollutants

To analyze the statistical significance of annual and seasonal trends, Pearson correlation analysis was carried out to identify correlations between CO and other relevant environmental parameters. The annual and seasonal mean correlations are shown in Table 4S. A strong positive correlation was found between CO and some pollutants (e.g., SO<sub>2</sub>, NO, NMHC, THC, Hg, PM<sub>10</sub>, and UV), while a negative correlation was found for others (e.g., CH<sub>4</sub>, O<sub>3</sub>, and WS). A positive correlation indicates that the pollutants may have a common source, e.g., fossil fuel combustion in power stations (CO, SO<sub>2</sub>, and Hg) (Kim et al., 2015; Marković et al., 2008; Ray and Kim, 2014). Airborne carbon compound emission/production sources include both natural and anthropogenic sources (Guenther et al., 2000; Song et al., 2007). High CO anthropogenic emissions from the road transportation sector are due to combustion of gasoline and diesel fuels (Singh et al., 2008). Moreover, the local temperature can increase the concentration of ozone in the atmosphere (Wang et al., 2008).

### 3.4. Long-term trend analysis of CO level in Yongsan

The mean annual concentrations of CO are summarized in Table 2. The CO level decreased sharply between periods 1 and 2 and then decreased less noticeably between periods 2 and 3, i.e.,  $3.25 \pm 0.78$  ppm in 1987 to  $0.35 \pm 0.13$  ppm in 2004. In period 3, the CO reduction was less distinctive across the period:  $0.35 \pm 0.13$  ppm in 2004 to  $0.61 \pm 0.34$  ppm in 2007 to  $0.51 \pm 0.31$  ppm in 2013. A significant reduction of 84% was observed from 1987 to 2013. Overall, between 2004 and 2013, a slow increase in the annual CO mean concentration was observed. The high CO concentration in 1987 may reflect the effect of rapid industrialization and the high demand for coal in period 1, while the lower CO concentration after 1999 may be indicative of the falling demand for coal briquettes and stricter policies regarding fuel type usage enacted by the South

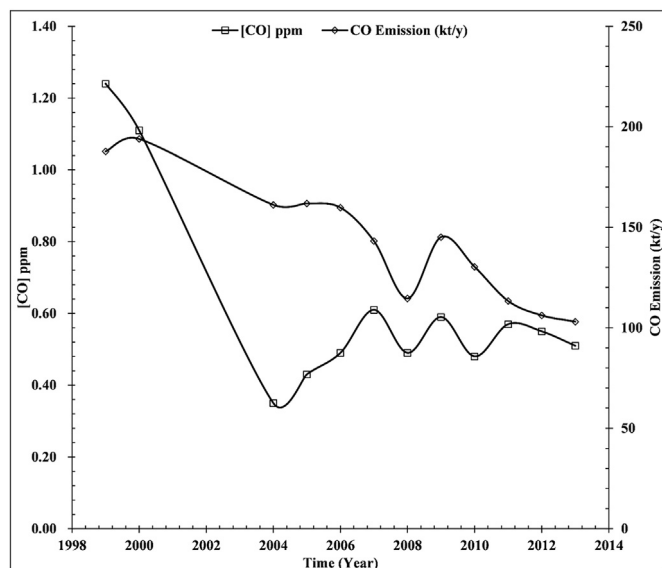


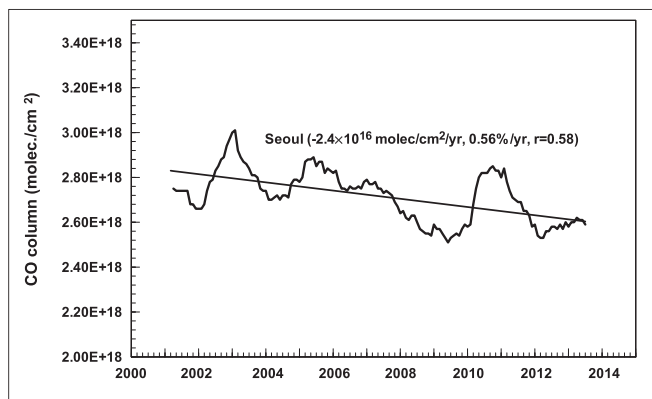
Fig. 3. Comparison of annual airborne CO concentration (Yongsan) and emission (Seoul) during the 1999–2013 period.

Korean government (Kim et al., 2015; Lee et al., 1999). The average annual pollutant concentrations in Yongsan were found in the following order: THC ( $2610 \pm 90$  ppb) > CH<sub>4</sub> ( $2100 \pm 80$  ppb) > CO ( $930 \pm 220$  ppb) > NMHC ( $500 \pm 50$  ppb) > NO<sub>x</sub> ( $96.5 \pm 14.9$  ppb) > NO<sub>2</sub> ( $35.3 \pm 5.40$  ppb) > NO ( $34.3 \pm 10.4$  ppb) > O<sub>3</sub> ( $15.9 \pm 3.85$  ppb) > Hg ( $6.40 \pm 0.67$  ppb) > SO<sub>2</sub> ( $5.48 \pm 0.93$  ppb) > PM<sub>10</sub> ( $0.94 \pm 0.26$  ppb).

The seasonal concentration of CO, as shown in Table 1S, decreased significantly from period 1 to period 3 in spring (2.40–0.51 ppm), summer (0.98–0.36 ppm), fall (2.40–0.47 ppm), and winter (4.26–0.69 ppm). The higher CO concentrations in the winter compared to the summer are due to the higher fossil fuel consumption for domestic and commercial heating purposes as well as to the weather conditions (Kim et al., 2015). A similar trend was observed for CO concentration in the Seoul metropolitan area (Fig. 2c):  $-0.44$  ppm yr<sup>-1</sup> (1989–1993),  $0.084$  ppm yr<sup>-1</sup> (1993–2004), and  $-0.007$  ppm yr<sup>-1</sup> (2004–2013) (Kim et al., 2015).

The concentration and emission levels of CO in Seoul, for the period between 1999 and 2013, are compared in Fig. 3. A significant 45% reduction in CO emissions (NAPES, 2016) with a 59% reduction in [CO] levels were observed. These reduced emissions clearly demonstrate the effectiveness of the strong mitigation policies along with other factors including the high urbanization (83%) of the RoK (UNdata, 2011), the 6.5-fold higher fossil fuel usage in the winter compared to the summer (KMOE, 2016), and the increasing economic development. The estimated CO emission rate from the estimated 2,000,000 cars in Seoul (population 10,000,000) is about 40 kt.CO.yr<sup>-1</sup>, assuming a Euro 4 emission factor of 1.0 g.CO.km<sup>-1</sup> and 20,000 km per year per car; this can be compared to the total CO emission rate in 2012 for Seoul (107 kt.CO.yr<sup>-1</sup>). However, the weekly concentration pattern of CO and other relevant environmental data (Fig. 3S) show no significant difference between the weekday and weekend data (Yoo et al., 2015) in the urban area (Yongsan district) for any of the periods.

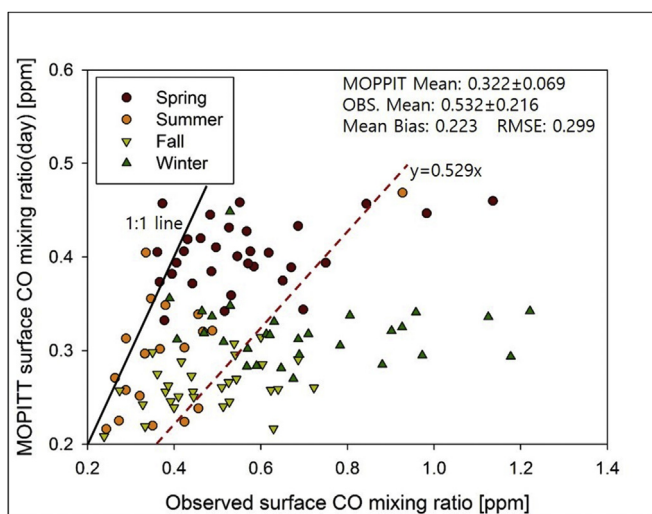
Fig. 4 shows the 12-month moving averages and linear fits for 14-yr trends with the MOPITT CO total column data for the target city (37.5°N, 127.5°E). The 12-month moving average time series of the total column CO shows only a weak reduction in CO levels over Seoul (see Fig. 2c for a more pronounced reduction). The small downward trend in CO total column density was  $-2.4 \times 10^{16}$



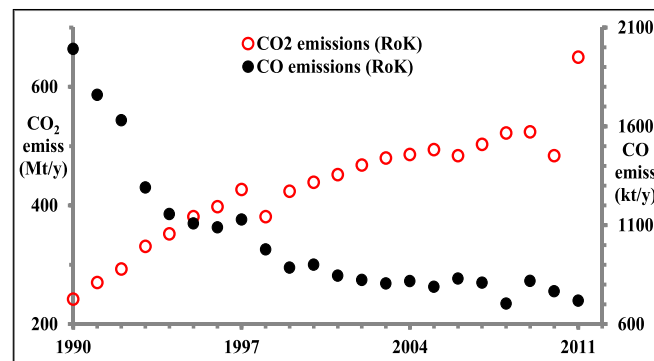
**Fig. 4.** MOPITT long-term trend in total CO column change per year. Time series with a 12-month moving average and the corresponding linear trend are indicated by the line and slope in molecules/cm<sup>2</sup>/yr, respectively.

molec.cm<sup>-2</sup> yr<sup>-1</sup> (0.56% yr<sup>-1</sup>,  $r = 0.58$ ), which was smaller than that over China ( $1.6 \pm 0.5\%$  yr<sup>-1</sup>) (Worden et al., 2013). Compared to the downward trend observed for CO concentrations and emissions, the downward trend in total column CO was significantly weaker due to the effects of long-range transport and the long atmospheric lifetime of CO (about two months). In addition, the correlation between MOPITT surface CO mixing ratio and surface CO observed at the site was not significant ( $r = 0.278$ , Fig. 5). The ratio of MOPITT CO to observed CO was 0.65, suggesting underestimation of observed CO. For the entire column (assuming 287 K, an equivalent mixing depth (EMD) of 1.65 km atm and a CO column density of  $\sim 2.8 \times 10^{18}$  molec.cm<sup>-2</sup>), the average CO concentration would be 0.66 ppm, which was within the range of the surface CO concentrations (0.35–1.1 ppm) during 2000–2013. In this calculation, the EMD can be viewed as the height of an atmospheric column that contains all CO mass (Chen et al., 1999); it was calculated using the ratio of EMD to boundary layer height ( $2.07 \pm 0.32$ ) derived from Chen et al. (1999) and the boundary layer height of  $\sim 800$  m (Kim et al., 2013a).

The diurnal pattern for [CO] in period 1, along with the other pollutants and environmental parameters, are shown in Fig. 4S. The pollutant levels for CO and other relevant pollutants (e.g., SO<sub>2</sub>, NO,



**Fig. 5.** Comparison of MOPITT surface CO mixing ratio (day) and observed surface CO mixing ratio at the site.



**Fig. 6.** Annual anthropogenic CO and CO<sub>2</sub> emissions in the Republic of Korea (RoK) from 1990 to 2012 (data from: [www.eia.gov/beta/international/data](http://www.eia.gov/beta/international/data), accessed June 2015).

and THC) are higher in early morning (2–8 a.m.) in the winter season and lower in early afternoon (1–4 p.m.) in the summer season. A street-level CO sensor network in the Da-an district (population density – 9800 persons/per km<sup>2</sup>) of Taipei City, Taiwan, showed a maximum CO level ( $\sim 5$  ppm) during the morning and evening rush hours; this decreased to  $\sim 0.5$  ppm during quieter traffic periods (Wen et al., 2013). In contrast, the CH<sub>4</sub> level showed an inverse trend relative to CO (e.g., higher in summer and lower in winter). The O<sub>3</sub> concentration in the winter season is lower in the early morning and higher in the afternoon. Ozone levels were lowest between 12 and 9 a.m. and between 8 and 12 p.m., and they were highest around midday (between 11 a.m. and 5 p.m.) due to the photochemical effects of maximum solar irradiance (Wang et al., 2008). The meteorological diurnal behavior (e.g., wind speed) was lowest between 12 and 8 a.m. and between 8 and 12 p.m. and highest around midday (between 11 a.m. and 2 p.m.) due to maximum solar irradiance warming (Pettersson et al., 2010; Thimmaiah et al., 2009). In spite of the increasing fossil fuel CO<sub>2</sub> emissions, the accompanying CO emissions were reduced sharply, showing the effectiveness of CO mitigation policies (see Fig. 6).

#### 4. Conclusions

A long-term (1987–2013) trend analysis of CO and other pollutant concentrations at an AQM station in the Yongsan district of Seoul, Korea, was carried out. Overall, significant decreases were observed in the atmospheric levels of CO and other relevant pollutants from 1987 to 2013, despite the fact that the population of Yongsan increased by a factor of four over that period. The large decreases in CO and other pollutant atmospheric concentrations since 1988 are the result of the implementation of the South Korean government's strategic mitigation rules and policies related to fuel switching from coal to natural gas for both domestic and commercial purposes. The higher CO levels observed during winter and the lower CO levels observed during summer show the important role of meteorological conditions and fuel consumption patterns.

#### Acknowledgements

This study was supported by a grant from the National Research Foundation (NRF) of Korea funded by the Ministry of Science, ICT and Future Planning (No. 2016R1E1A1A01940995). This research was also supported by the Korea Agency for Infrastructure Technology Advancement grant (16SCIP-B07689-03).



## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.apr.2017.03.006>.

## References

- Ahmed, E., Kim, K.-H., Shon, Z.-H., Song, S.-K., 2015. Long-term trend of airborne particulate matter in Seoul, Korea from 2004 to 2013. *Atmos. Environ.* 101, 125–133.
- Argüelles, M., Benavides, C., Junquera, B., 2006. The impact of economic activity in Asturias on greenhouse gas emissions: consequences for environmental policy within the Kyoto Protocol framework. *J. Environ. Manag.* 81, 249–264.
- Chen, G., Davis, D., Kasibhatla, P., Bandy, A., Thornton, D., Blake, D., 1999. A mass-balance/photochemical assessment of DMS sea-to-air. *J. Geophys. Res.* 104, 5471–5482.
- Choi, Y.-R., Cha, E.S., Chang, S.-S., Khang, Y.-H., Lee, W.J., 2014. Suicide from carbon monoxide poisoning in South Korea: 2006–2012. *J. Affect. Disord.* 167, 322–325.
- Cicerone, R.J., Oremland, R.S., 1988. Biogeochemical aspects of atmospheric methane. *Glob. Biogeochem. Cycles* 2, 299–327.
- Deeter, M., Martínez-Alonso, S., Edwards, D., Emmons, L., Gille, J., Worden, H., Pittman, J., Daube, B., Wofsy, S., 2013. Validation of MOPITT Version 5 thermal-infrared, near-infrared, and multispectral carbon monoxide profile retrievals for 2000–2011. *J. Geophys. Res.* 118, 6710–6725.
- EIA (Energy Information Administration, 2015). [www.eia.gov/beta/international/data](http://www.eia.gov/beta/international/data) (Accessed on Jun, 2015).
- Guenther, A., Geron, C., Pierce, T., Lamb, B., Harley, P., Fall, R., 2000. Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America. *Atmos. Environ.* 34, 2205–2230.
- Iglesias, M., Apsimon, H., 2004. Alternative vehicle technologies and fuels in scenarios for atmospheric emissions in London. *J. Environ. Assess. Policy Manag.* 6, 213–243.
- Kim, C.H., Hun, W.J., Kim, S.-T., Park, R., Jeong, J.-I., Lee, S.-M., Seong-deuk, C., Seo, Y.-S., Jong-jae, L., Ki-Pyo, N., Kang, J.-E., Gu, K.W., Hwa, R.K., Kim, M.-J., Sung, C.D., Hong, S.-K., Kwon, H.-A., Lee, S.-I., Cho, C.-H., Sun, M., Chang, H., Kim, E.H., Kim, J.-W., Hyeon-ok, K., Yoon-se, L., Jin, Y., 2013a. Final Report, National Environmental Science Institute: Study on Mutual Effect of National Air Pollution in Northeast Asia (1). NIER-sp2013-187. <http://webbook.me.go.kr/DLI-File/NIER/06/020/5567971.pdf> (Accessed on 26 March 2017).
- Kim, K.-H., Brown, R.J., Kwon, E., Kim, I.-S., Sohn, J.-R., 2016. Atmospheric mercury at an urban station in Korea across three decades. *Atmos. Environ.* 131, 124–132.
- Kim, K.-H., Sul, K.-H., Szulejko, J.E., Chambers, S.D., Feng, X., Lee, M.-H., 2015. Progress in the reduction of carbon monoxide levels in major urban areas in Korea. *Environ. Pollut.* 207, 420–428.
- Kim, N.K., Kim, Y.P., Morino, Y., Kurokawa, J.-i., Ohara, T., 2013b. Verification of NOx emission inventory over South Korea using sectoral activity data and satellite observation of NO2 vertical column densities. *Atmos. Environ.* 77, 496–508.
- KMOE (Ministry of Environment, Korea, 2016). <http://eng.me.go.kr/eng/web/main.do> (Accessed on 08 April 2016).
- Lee, H.S., Kang, C.-M., Kang, B.-W., Kim, H.-K., 1999. Seasonal variations of acidic air pollutants in Seoul, South Korea. *Atmos. Environ.* 33, 3143–3152.
- Marković, D.M., Marković, D.A., Jovanović, A., Lazić, L., Mijić, Z., 2008. Determination of O3, NO2, SO2, CO and PM10 measured in Belgrade urban area. *Environ. Monit. Assess.* 145, 349–359.
- Meszaros, T., Haszpra, L., Gelencser, A., 2005. Tracking changes in carbon monoxide budget over Europe between 1995 and 2000. *Atmos. Environ.* 39, 7297–7306.
- MOPITT (MEASUREMENTS OF POLLUTION IN THE TROPOSPHERE, 2016). <https://www2.acom.ucar.edu/mopitt> (Accessed 22 December 2016).
- Nagpure, A.S., Gurjar, B., Kumar, V., 2016. Estimation of exhaust and non-exhaust gaseous, particulate matter and air toxics emissions from on-road vehicles in Delhi. *Atmos. Environ.* 127, 118–124.
- NAPES (National Air Pollutants Emission Service, Korea, 2016). <http://airemiss.nier.go.kr/mbshome/mbshome/airemiss/index.do> (Accessed on July 21 2016).
- Nguyen, H.T., Kim, K.-H., 2005. Changes in SO2 concentration from major cities and provinces in Korea: a case study from 1998 to 2003. *J. Korean Soc. Atmos. Environ.* 21, 95–105.
- Nguyen, H.T., Kim, K.-H., 2006. Evaluation of SO2 pollution levels between four different types of air quality monitoring stations. *Atmos. Environ.* 40, 7066–7081.
- Nguyen, H.T., Kim, K.-H., Ma, C.-J., Cho, S.-J., Sohn, J.R., 2010. A dramatic shift in CO and CH4 levels at urban locations in Korea after the implementation of the Natural Gas Vehicle Supply (NGVS) program. *Environ. Res.* 110, 396–409.
- Pettersson, E.R., Lindmark, F., Ohman, M., Nordin, A., Westerholm, R., Boman, C., 2010. Design changes in a fixed-Bed pellet combustion device: effects of temperature and residence time on emission performance. *Energy & Fuels* 24, 1333–1340.
- Ray, S., Kim, K.-H., 2014. The pollution status of sulfur dioxide in major urban areas of Korea between 1989 and 2010. *Atmos. Res.* 147, 101–110.
- Singh, A., Gangopadhyay, S., Nanda, P.K., Bhattacharya, S., Sharma, C., Bhan, C., 2008. Trends of greenhouse gas emissions from the road transport sector in India. *Sci. Total Environ.* 390, 124–131.
- Song, Y., Shao, M., Liu, Y., Lu, S., Kuster, W., Goldan, P., Xie, S., 2007. Source apportionment of ambient volatile organic compounds in Beijing. *Environ. Sci. Technol.* 41, 4348–4353.
- TAP, S.K. ([http://www.esrl.noaa.gov/gmd/dv/site/site\\_table.html](http://www.esrl.noaa.gov/gmd/dv/site/site_table.html) accessed, Nov16, 2016, 2016). [http://www.esrl.noaa.gov/gmd/dv/site/site\\_table.html](http://www.esrl.noaa.gov/gmd/dv/site/site_table.html) (accessed on Nov16 2016).
- Thimmaiah, D., Hovorka, J., Hopke, P.K., 2009. Source apportionment of winter submicron Prague aerosols from combined particle number size distribution and gaseous composition data. *Aerosol Air Qual. Res.* 9, 209–236.
- UNdata (United Nation (Population Division), 2011). <http://www.un.org/en/development/desa/population/publications> (accessed on).
- Vellingiri, K., Kim, K.-H., Ma, C.-J., Kang, C.-H., Lee, J.-H., Kim, I.-S., Brown, R.J.C., 2015. Ambient particulate matter in a central urban area of Seoul, Korea. *Chemosphere* 119, 812–819.
- Waibel, A., Fischer, H., Wienhold, F., Siegmund, P., Lee, B., Ström, J., Lelieveld, J., Crutzen, P., 1999. Highly elevated carbon monoxide concentrations in the upper troposphere and lowermost stratosphere at northern midlatitudes during the STREAM II summer campaign in 1994. *Chemosphere-Global Change Sci.* 1, 233–248.
- Wang, Y., McElroy, M.B., Munger, J.W., Hao, J., Ma, H., Nielsen, C., Chen, Y., 2008. Variations of O3 and CO in summertime at a rural site near Beijing. *Atmos. Chem. Phys.* 8, 6355–6363.
- Weaver, L.K., 2009. Carbon monoxide poisoning. *N. Engl. J. Med.* 360, 1217–1225.
- Wen, T.-H., Jiang, J.-A., Sun, C.-H., Juang, J.-Y., Lin, T.-S., 2013. Monitoring street-level spatial-temporal variations of carbon monoxide in urban settings using a wireless sensor network (WSN) framework. *Int. J. Environ. Res. Public Health* 10, 6380–6396.
- Worden, H., Deeter, M., Frankenberg, C., George, M., Nichitiu, F., Worden, J., Aben, I., Bowman, K., Clerbaux, C., Coheur, P.-F., 2013. Decadal record of satellite carbon monoxide observations. *Atmos. Chem. Phys.* 13, 837–850.
- Wuebbles, D.J., Hayhoe, K., 2002. Atmospheric methane and global change. *Earth-Sci. Rev.* 57, 177–210.
- Yongsan-district 2016). [https://en.wikipedia.org/wiki/Yongsan\\_District](https://en.wikipedia.org/wiki/Yongsan_District) (accessed on March 31, 2016).
- Yoo, J.-M., Jeong, M.-J., Kim, D., Stockwell, W., Yang, J.-H., Shin, H.-W., Lee, M.-I., Song, C.-K., Lee, S.-D., 2015. Spatiotemporal variations of air pollutants (O3, NO2, SO2, CO, PM10, and VOCs) with land-use types. *Atmos. Chem. Phys.* 15, 10857–10885.
- Zhang, R., Wang, M., Ren, L., 2001. Long-term trends of carbon monoxide inferred using a two-dimensional model. *Chemosphere-Global Change Sci.* 3, 123–132.