

Received:

23 July 2017

Revised:

20 December 2017

Accepted:

12 January 2018

Seasonal changes in surface ozone over South Korea

Cite as: Hyun-Chae Jung,
Byung-Kwon Moon,
Jieun Wie. Seasonal changes in
surface ozone over South
Korea.

Heliyon 4 (2018) e00515.

doi: [10.1016/j.heliyon.2018.e00515](https://doi.org/10.1016/j.heliyon.2018.e00515)

Hyun-Chae Jung, Byung-Kwon Moon*, Jieun Wie

Division of Science Education, Institute of Fusion Science, Chonbuk National University, Jeonju 54896, South Korea

* Corresponding author.

E-mail address: moonbk@jbnu.ac.kr (B.-K. Moon).



Abstract

Recently, the surface ozone concentration in the Korean peninsula has been increasing more rapidly than in the past, and seasonal changes are appearing such as increases in the number of ozone alerts in springtime. We examined changes in the timing of annual maximum South Korean O₃ levels by fitting a sine function to data from 54 air-quality monitoring sites over a 10-year period (2005–2014). The analytical results show that the date of maximum ozone concentration at 23 points in the last 10 years has been advanced by about 2.1 days per year (E-sites), while the remaining 31 points have been delayed by about 2.5 days per year (L-sites). We attribute these differences to seasonal O₃ changes: E-sites show a larger increase in O₃ level in March–April (MA) than in June–July (JJ), while L-sites show a larger increase in JJ than in MA. Furthermore, these shifts are significantly larger in magnitude than those reported for Europe and North America. We also examined one possible reason for these seasonal differences: the relationship between O₃ and precursors such as NO₂ and CO. E-sites showed a rapid decrease in NO₂ (NO) concentration in MA over the last decade. As a result, the ozone concentration at E-sites seems to have increased due to the absence of ozone destruction by NO_x titration in early spring. In L-Sites, the concentrations of ozone precursors such as NO₂ and CO in JJ showed a smaller decrease than those at other sites. Therefore, in L-sites, relatively large amounts of ozone precursors were distributed in JJ, implying that more ozone was generated. We suggest that shifts in the South Korean O₃ seasonal cycle are due to changes in early spring and summer NO₂ (NO) and CO levels; this should be tested further by modeling studies.

Keywords: Earth sciences, Atmospheric science, Environmental science

1. Introduction

Surface ozone (O_3) plays a central role in the Earth's climate system as the primary source of OH radicals that control the atmospheric oxidizing capacity [1, 2]. It is both a greenhouse gas [3, 4] and an air pollutant, causing respiratory disease and an increased risk of premature death [5, 6, 7]. The level of O_3 is controlled by photochemical reactions involving precursors emitted by various natural and anthropogenic sources [8, 9] or net transport from the stratosphere [10, 11, 12].

Background O_3 concentrations have increased over polluted areas in the Northern Hemisphere during the last few decades [13, 14, 15]. This is presumed to be due to an increase of pollutants from rapid economic growth and industrialization, particularly in East Asia [16, 17, 18], and the influence of climate change from global warming [19, 20]. South Korea is also experiencing a gradual rise in O_3 concentrations and high- O_3 events despite efforts to regulate emissions of precursors [21, 22]. As a consequence, the occurrence of severe O_3 episodes has increased in recent decades during spring and summer [23, 24] along with an increase in socioeconomic damage [25]. Previous studies link these patterns to the downward transport of O_3 and its precursors [26, 27, 28]. Other studies show that an increase in O_3 concentrations is a result of climate change due to global warming [29, 30, 31].

Thus, most previous studies on tropospheric ozone in the Korean peninsula investigated the causes of increased ozone concentration in terms of pollutant transport and climate change. However, in order to prepare measures against direct damage from O_3 and minimize impacts, it is important to examine the variability in ozone concentrations in South Korea. Studies regarding the seasonal fluctuations of O_3 concentrations in the Northern Hemisphere have already been conducted in other countries. For example, Parrish et al. [32] studied the annual cyclic fluctuations of O_3 in Europe and North America by fitting a sine function to monthly average data from background sites. They showed a shift in the seasonal cycle such that the timing of the annual O_3 maximum appears earlier in the year, a common pattern across all continental regions in the Northern Hemisphere.

We applied the methodology of Parrish et al. [32] to examine seasonal shifts in ground-level O_3 concentrations in South Korea and to suggest a possible explanation for such fluctuations. Sections 2 and 3 present the data and analysis methods used in this study, Section 4 analyzes the annual cyclic fluctuation of surface O_3 concentrations over South Korea, Section 5 discusses the results, and Section 6 presents our conclusions.

2. Materials

We acquired hourly O_3 , NO_2 , and CO data for South Korea during the 10 years from 2005 to 2014 from the website of the Korea Environment Corporation [33].

This resource provides hourly data for O₃, NO₂, and CO mixing ratios in ppbv, measured by the ultraviolet photometric and chemiluminescent methods, respectively. We selected 54 urban air-quality monitoring sites (Table 1) based on data availability and statistical significance (a 90% or better confidence level for the linear trends for the seasonal maximum date) and converted each site's data into monthly average values. We also analyzed season-averaged O₃, NO₂, and CO areas to investigate potential reasons for shifts in the dates of annual O₃ maximums.

3. Methods

We estimated the date of the highest O₃ value for each station using the sine function equation described by Parrish et al. [32] (Fig. 1):

$$y = y_0 + A \sin(x + \emptyset) \quad (1)$$

where y_0 is the annual average O₃, A is the amplitude of the seasonal cycle, x is the month (where 12 months corresponds to 2π), and \emptyset refers to the phase shift of the seasonal cycle. Since the average ozone concentration y_0 for 5 years can be calculated in advance, it is treated as a constant in Eq. (1). Three-parameter regressions to Eq. (1) produced results in close (statistically not significantly different) agreement with the two-parameter fits, but the latter gave somewhat more precise determinations of the A and \emptyset parameters [32].

We fitted Eq. (1) to the 5-year running O₃ concentration by the least-squares method after removing the linear trend during the entire period. Since the surface ozone concentration of the Korean Peninsula is continuously increasing, we tried to eliminate the noise generated when approximating the sine function as much as possible by eliminating the linear trend. With the estimated phase shift (\emptyset), the date of the annual O₃ peak can be given by:

$$(\pi/2 - \emptyset) \times 365/2\pi. \quad (2)$$

As a result, we obtained a total of six O₃ maximum dates per observation site for 2005–2014. We then estimated the linear trend for these O₃ peak dates (Fig. 3) and defined E-sites as those where the trend in O₃ peak dates was negative (the sites where O₃ maximum dates are becoming earlier), and L-sites as those where the trend in O₃ peak dates was positive (the sites where O₃ maximum dates are becoming later). Fig. 2 indicates the spatial distribution of E- and L-sites, where shades of red indicate E-sites and shades of blue indicate L-sites.

4. Results

The highest O₃ concentrations for all sites in South Korea occurred between May 1 (Julian Day 122.3) and June 25 (Julian Day 177.1) over the ten-year study period

Table 1. Averaged O₃ concentration and trend of seasonal maximum date at 54 sites over South Korea for the period of 2005–2014.

Site Number	Site Name	Avg. O ₃ (ppbv)	Trend (day/year)	Site Number	Site Name	Avg. O ₃ (ppbv)	Trend (day/year)
111123	Jongno	19.60	-1.70	221233	Yongsu	32.23	-4.42
111153	Dongdaemun	12.46	-2.15	221251	Bugok	25.50	2.96
131111	Sinpung	21.24	2.79	238112	Bongam	25.96	1.09
131124	Soonae	19.68	1.21	238374	Nongso	24.96	-1.01
131141	Anyang 6-dong	21.67	-1.21	324115	Seoseok	22.99	-1.88
131144	Hogye	18.67	1.34	324121	Nongseong	24.09	2.28
131161	Cheolsan	19.65	0.89	324134	Unam	16.82	-1.97
131193	Bono	21.33	1.08	324155	Juwol	23.01	-1.36
131194	Wongok	21.59	2.26	335115	Jungang	24.53	5.78
131197	Gojan	21.97	-1.76	336352	Jung	29.18	-1.54
131202	Gwacheon	19.10	-2.90	336354	Jinsang	30.14	-2.41
131211	Gyomun	20.08	-2.16	339111	Ido	36.11	-3.23
131222	Bugok	18.73	0.43	422161	Manchon	22.00	-1.64
131231	Jeongwang	21.81	1.16	422201	Hyeonpung	26.79	3.03
131232	Sihwagongdan	23.80	-0.94	437153	Hyeonggok	27.71	2.96
131233	Daeya	20.91	2.27	437161	Hyucheon	24.36	-1.84
131341	Bijeon	21.55	1.43	525151	Dacheung	14.60	2.53
131382	Jeongbalsan	19.87	4.69	525171	Jeongnim	22.21	3.20
131383	Madu station	15.43	-2.67	534112	Baekseok	21.91	5.46
131442	Changjeon	20.64	2.15	534422	Dongmun	25.47	1.80
131501	Dang	20.97	3.21	534431	Nanjido	29.74	2.68
131531	Osan	20.32	2.47	632121	Jungang	20.96	1.73
131552	Hyangnam	24.65	0.58	632122	Myeongnyun	22.95	-1.04
221112	Gwangbok	23.22	5.15	632151	Cheongok	28.08	-2.41
221152	Jeonpo	23.36	-2.81	735123	Gaejeong	24.78	3.74
221162	Oncheon	14.46	4.69	823652	Geomdan	23.46	-2.17
221212	Noksan	30.99	1.39	831154	Wonjong	18.62	-2.42

Surface O₃ Concentration [ppbv]

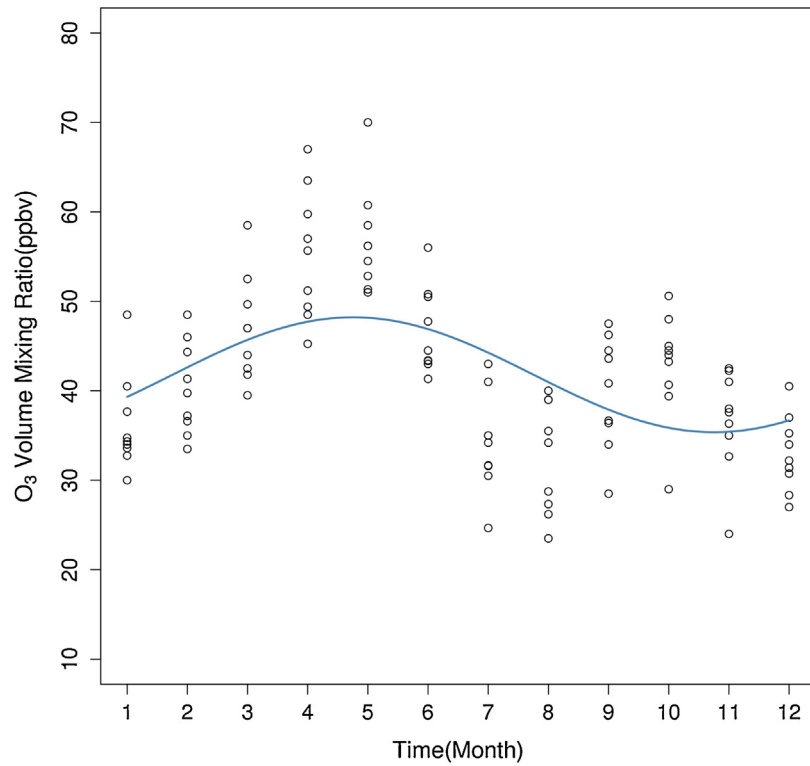


Fig. 1. Monthly averaged surface O₃ concentrations in the South Korea (circles) over 10 years (2005–2014) and its fitted curve (line) to a sine function.

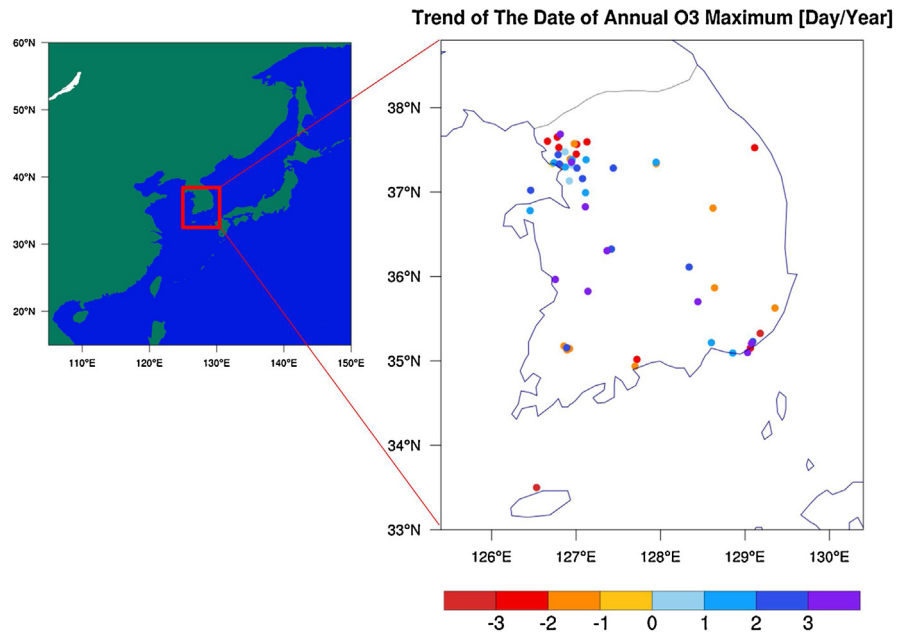


Fig. 2. Linear trends of the date of annual peak of O₃ concentrations for 54 observational sites in South Korea during 10-year period (2005–2014). Unit is in day year⁻¹.

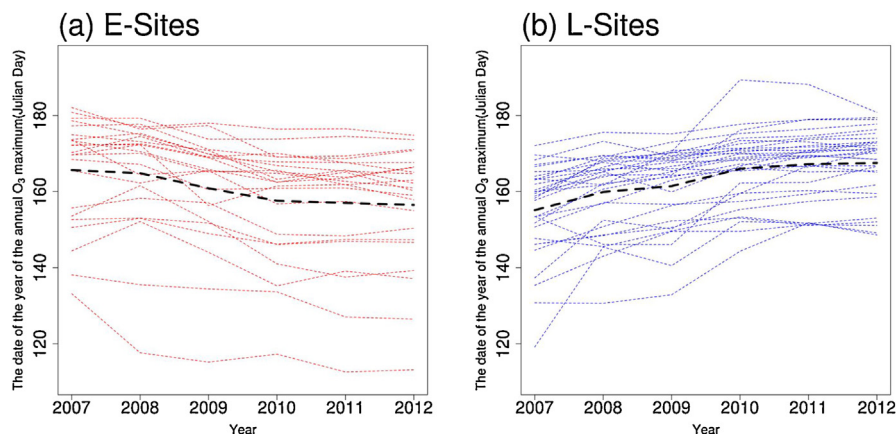


Fig. 3. Time series of the date of O_3 maximum for (a) E-sites and (b) L-sites. The thick dashed lines show the averaged values.

(Fig. 3). However, O_3 maximum dates appeared earlier at 23 locations (E-sites) and later at 31 locations (L-sites). Table 1 shows trends in average ozone concentrations and O_3 maximum dates over a 10-year period at all sites. Here, points with a negative trend for 10-year O_3 maximum dates are the E-sites, and points with a positive trend are the L-sites. O_3 maximum dates were found in a range of -4 days to 5 days. Although the date of ozone peak concentration sometimes appears to shift earlier or later, this seems to have no relation to the scale of ozone concentration. The distribution of E-sites and L-sites is spatially inhomogeneous (Fig. 2), which hinders the understanding of processes leading to shifts in O_3 maximum dates. This pattern indicates that the trend in O_3 maximum dates is related to the local characteristics at each site (local emission of ozone precursors) rather than the effects of the synoptic weather field. Fig. 3 shows the time series of O_3 maximum dates obtained from fitting a sine function to running 5-year periods, indicating the temporal evolution of O_3 seasonal cycles from E-sites and L-sites. The averaged temporal linear trend of the O_3 maximum date at the 23 E-sites and 31 L-sites is -2.1 days year^{-1} and $+2.5$ days year^{-1} , respectively. In this study, we excluded all points where the confidence level was less than 90% when performing statistical analysis.

Fig. 4a and b shows the anomalies and linear trend lines for the ozone concentrations in E- and L-sites in March–April (MA) and June–July (JJ) from 2005 to 2014; Fig. 4c shows the difference in ozone concentration between MA and JJ. Any linear slope with a statistical confidence level of 90% or higher was marked with an asterisk. In the last 10 years, the ozone concentration at E-sites in MA has increased by more than three times than that of L-sites in the same period. On the contrary, the ozone concentration at L-sites in JJ has increased 1.5 times more than that of E-Sites in the same period. As a result, E-sites show an increasing

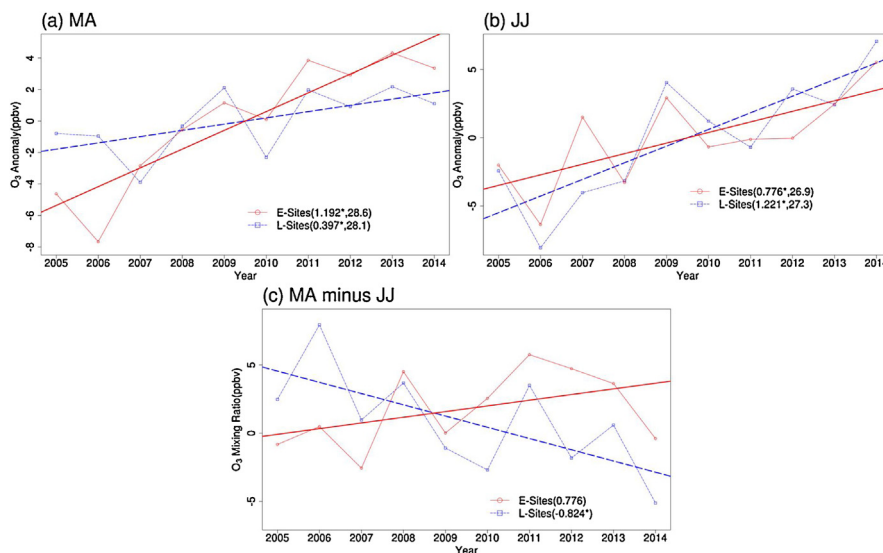


Fig. 4. Seasonal time series of anomalous O₃ concentrations and their corresponding linear regression lines for (a) MA and (b) JJ. (c) Time series of the O₃ difference between MA and JJ and linear regression lines. The values in parentheses are linear trends (ppbv year⁻¹) and averaged O₃ concentrations (ppbv).

difference in ozone concentration between MA and JJ as opposed to a decrease for L-Sites (Fig. 4c). These changes in O₃ trends cause a shift in the seasonal cycle toward the beginning or end of the calendar year for E-sites and L-sites, respectively.

We examined the corresponding changes in seasonal cycle by comparing the long-term variation for two periods: 2005–2007 (as a beginning period) and 2012–2014 (as an ending period), as shown in Fig. 5. As expected, the largest increase in surface O₃ occurred in MA for E-sites but in JJ for L-sites (Fig. 5a). Note that the annual peaks of O₃ concentration occur in May for both types of site. Therefore, we conclude that O₃ maximum dates change due to changes in ozone concentrations during spring and summer.

Next, we tried to find the cause of these changes by considering ozone precursors. Fig. 5b and c shows the time series of NO₂ and CO concentrations and their differences over the two periods. NO₂ decreased rapidly at E-Sites in MA, while in JJ, the concentrations of NO₂ and CO decreased more at E-sites than in L-sites. Fig. 6a and b shows anomalies and linear trend lines for NO₂ concentrations in E- and L-sites from 2005 to 2014 in MA and JJ; Fig. 6c shows CO in JJ. NO₂ concentrations at E-sites decreased rapidly in MA, while NO₂ and CO concentrations at E-sites decreased more than in L-sites in JJ. All the linear regression lines shown in Fig. 6 had a statistical reliability of more than 90%.

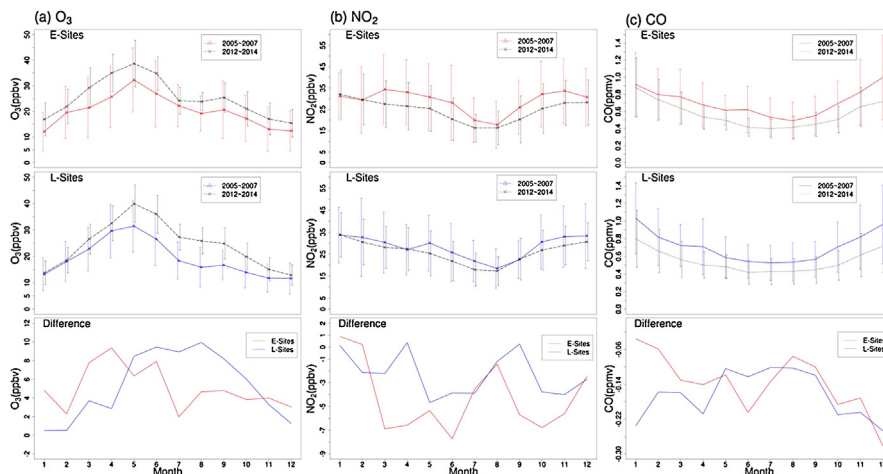


Fig. 5. (a) Annual cycle of O_3 concentration for two periods (2005–2007 and 2012–2014) and their differences (2012–2014 minus 2005–2007). (b), (c) Same as (a) but for NO_2 concentration and CO concentration, respectively. Vertical bars indicate $\pm\sigma$ ranges.

5. Discussion

The surface O_3 concentrations in South Korea for both E- and L-sites have generally increased for all seasons during the last 10 years at a rate of $+0.68$ ppbv $year^{-1}$ from 2005 to 2014, greater than the increasing trend of $+0.26$ ppbv $year^{-1}$ reported over 46 South Korean cities from 1999 to 2010 [21]. The recent increasing trend of surface O_3 levels is quite common in East Asia, including a $+1.1$ ppbv $year^{-1}$ rise in Beijing from 2001 to 2006 [34] and a $+0.18$ ppbv $year^{-1}$ rise in populated Japanese areas from 1996 to 2005 [35]. This rise in surface O_3 over East Asia is mainly caused by recent increases in anthropogenic precursor emissions [36] along with long-term changes in meteorological conditions including insolation and temperature [35].

The magnitudes of the increasing or decreasing trends in the O_3 peak date over South Korea are much larger than those observed at remote sites in Europe (-0.57 days $year^{-1}$) and North America (-1.4 days $year^{-1}$) [32]. Potential reasons for this include the proximity of the South Korean sites in this study to relatively polluted regions and the location of South Korea on the eastern boundary of the Asian continent such that the downward transport of O_3 by prevailing westerlies affects the O_3 values [28]. However, the mechanisms driving these differences remain unclear and need to be investigated further.

In order to consider possible mechanisms for this shift in seasonal cycles, we investigated whether the seasonal shift of O_3 maximum is linked to O_3 precursors by analyzing the seasonal time series of surface NO_2 and CO. These concentrations have generally decreased over the last 10 years. As previously noted, the O_3 trend for E-sites shows the greatest increase in MA and has contributed to changing

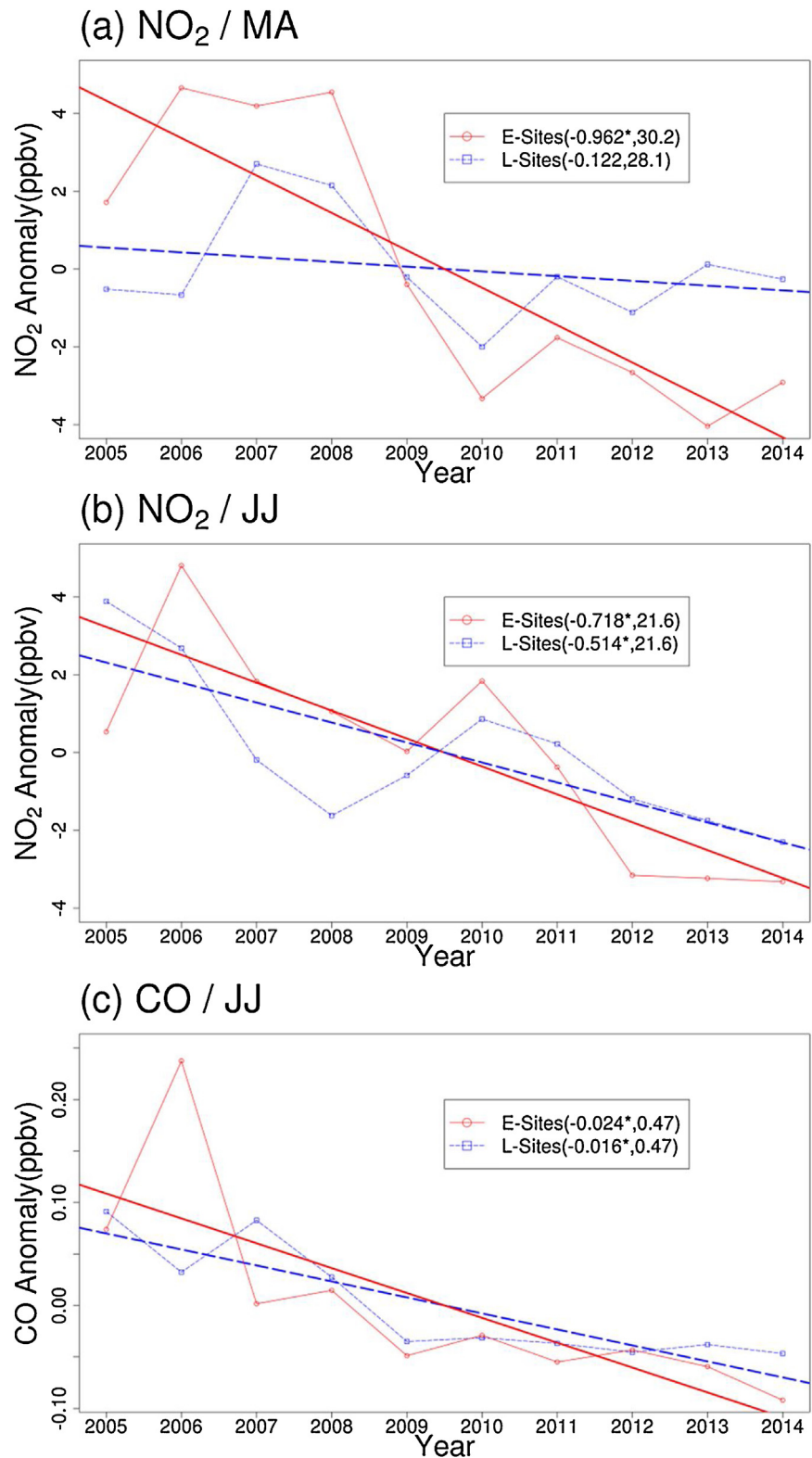


Fig. 6. Time series of anomalous NO_2 concentration and their corresponding linear regression lines in (a) MA and (b) JJ. (c) Same as (b), but for CO concentration. The values in parentheses are linear trends (ppbv year^{-1}) and averaged concentrations (ppbv).

seasonality. In contrast, for E-sites, the largest decrease in NO₂ concentration is evident in MA. This indicates that the recent increase in early spring O₃ at E-sites is consistent with decreasing NO₂. At the same time, decreasing NO₂ may have led to lower loss of O₃ via NO_x titration [37, 38], resulting in increasing early springtime O₃ concentration at E-sites. It is worth noting that relatively higher O₃ regions are well-correlated with relatively lower NO₂ regions, and vice versa (see Fig. 3 in [21]), which suggests that many regions in South Korea are volatile-organic-compound-limited [39]. Therefore, we argue that one of the main driving mechanisms responsible for the early spring increase of O₃ at E-sites is the decrease in NO_x titration associated with NO₂ reduction.

A similar mechanism may also play a role in the shift of the O₃ seasonal cycle toward the year's end for L-sites. In this case, the NO₂ temporal changes in MA are small during the 10-year period (Fig. 6a). Thus it seems that NO_x-driven depletion of O₃ (i.e., NO_x titration) prevents a considerable increase of O₃ in early spring, so that the differences between the two periods are relatively small during spring, as shown in Fig. 5a. However, a significant increase of O₃ is evident in the summer season (June–July), probably due to enhanced photochemical production of O₃ with accumulated NO₂ and CO. These different changes in O₃ for early spring and summer thus cause a shift in the seasonal cycle of L-sites to later in the year.

6. Conclusions

We estimated the temporal changes in the annual South Korean O₃ peak by fitting a sine function to 5-year running O₃ data from 54 monitoring sites for a ten-year period (2005–2014). At 23 sites, the annual peak moved earlier by 2.1 days year⁻¹ (E-sites), but at 31 sites this peak was delayed by 2.5 days year⁻¹ (L-sites). O₃ concentrations at the E-sites substantially increased in early spring (MA) over the study period, while NO₂ (NO) simultaneously decreased, indicating that the O₃ increase was driven by less depletion of O₃ via NO_x titration. Consequently, the O₃ annual cycle has shifted toward the beginning of the year, resulting in the observed shift of the O₃ maximum.

Conversely, in early spring, NO₂ concentrations for the L-sites did not show a large change during the study period. Thus the O₃ concentrations in early spring show a relatively small increase, indicating that NO₂ (NO) is contributing to the depletion of O₃ due to NO_x titration. Since the O₃ in summer (JJ) showed a large increase, the date of the O₃ annual peak has shifted toward the end of the year. This increase in summer O₃ concentration is probably due to elevated photochemical formation in the presence of NO₂ and CO.

While we focus on the NO_x titration effect as the reason for the observed changes in the O₃ seasonal cycle, several other factors may be involved, including changes in meteorological variables (such as temperature and humidity), emissions, and

ozone photochemistry. More detailed chemistry-climate model simulations are necessary in order to explain to what degree such factors might impact the observed changes in the South Korean O₃ seasonal cycle. Furthermore, our findings are useful for evaluating the performance of chemistry-climate models in a changing climate.

Declarations

Author contribution statement

Hyun-Chae Jung: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Byung-Kwon Moon: Conceived and designed the experiments; Wrote the paper.

Jieun Wie: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Competing interest statement

The authors declare no conflict of interest.

Funding statement

This work was supported by the Korea Ministry of Environment (MOE) as “Climate Change Correspondence Program”.

Additional information

Data associated with this study is available at: <http://www.airkorea.or.kr>.

References

- [1] H. Levy, Normal atmosphere: large radical and formaldehyde concentrations predicted, *Science* 173 (1971) 141–143.
- [2] J.R. Ziemke, S. Chandra, Seasonal and interannual variabilities in tropical tropospheric ozone, *J. Geophys. Res.* 104 (1999) 21425–21442.
- [3] D.G. Shindell, G. Faluvegi, A. Lacis, J. Hansen, R. Ruedy, E. Aguilar, Role of tropospheric ozone increases in 20th-century climate change, *J. Geophys. Res. Atmos.* 111 (2006) D08302.
- [4] IPCC (Intergovernmental Panel on Climate Change), *Climate Change, The Physical Scientific Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*,

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

- [5] K. Knowlton, J.E. Rosenthal, C. Hogrefe, B. Lynn, S. Gaffin, R. Goldberg, C. Rosenzweig, K. Civerolo, J.Y. Ku, P.L. Kinney, Assessing ozone-related health impacts under a changing climate, *Environ. Health Perspect.* 112 (15) (2004) 1557–1563.
- [6] A.K. Nawahda, K. Yamashita, T. Ohara, J. Kurokawa, K. Yamaji, Evaluation of premature mortality caused by exposure to PM_{2.5} and ozone in East Asia: 2000, 2005, 2020, *Water Air Soil Pollut.* 223 (2012) 3445–3459.
- [7] H.K. Kim, Y. Lyu, J.-H. Woo, S.-C. Hong, D.-R. Kim, J. Seo, M. Shin, S.-K. Kim, Impact of future Chinese emissions on ozone air quality and human health in Northeast Asia, *J. Clim. Change Res.* 7 (4) (2016) 451–463.
- [8] P.J. Crutzen, M.G. Lawrence, U. Pöschl, On the background photochemistry of tropospheric ozone, *Tellus Ser. A–B* 51 (1999) 126–146.
- [9] D.J. Jacob, *Introduction to Atmospheric Chemistry*, Princeton University Press, 1999, pp. 206–217.
- [10] E. Danielsen, Stratospheric source for unexpectedly large values of ozone measured over the Pacific Ocean during Gametag, August 1977, *J. Geophys. Res.* 85 (C1) (1980) 401–412.
- [11] L.W. Uccellini, D. Keyser, K.F. Brill, C.H. Wash, The presidents day cyclone of 18–19 February 1979: influence of upstream trough amplification and associated tropopause folding on rapid cyclogenesis, *Mon. Weather Rev.* 113 (1985) 962–988.
- [12] W.K. Kim, Y.S. Moon, S.K. Song, I.B. Oh, Case study of surface ozone enhancement due to vertical transport of tropospheric ozone, *J. Korean Meteor. Soc.* 38 (2002) 307–317.
- [13] R.J. Allen, S.C. Sherwood, J.R. Norris, C.S. Zender, Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone, *Nature* 485 (2012) 350–355.
- [14] O.R. Cooper, R.-S. Gao, D. Tarasick, T. Leblanc, C. Sweeney, Long-term ozone trends at rural ozone monitoring sites across the United State, 1990–2010, *J. Geophys. Res. Atmos.* 117 (D22307) (2012).
- [15] D.D. Parrish, J.-F. Lamarque, V. Naik, L. Horowitz, D.T. Shindell, J. Staehelin, R. Derwent, O.R. Cooper, H. Tanimoto, A. Volz-Thomas, S. Gilge, H.-E. Scheel, M. Steinbacher, M. Fröhlich, Long-term changes in lower tropospheric baseline ozone concentrations: comparing chemistry-climate

- models and observations at northern midlatitudes, *J. Geophys. Res. Atmos.* 119 (2014) 5719–5736.
- [16] D.H. Jaffe, H. Price, D. Parrish, A. Goldstein, J. Harris, Increasing background ozone during spring on the west coast of North America, *Geophys. Res. Lett.* 30 (2003) 1613.
- [17] T. Wang, X.L. Wei, A.J. Ding, C.N. Poon, K.S. Lam, Y.S. Li, L.Y. Chan, M. Anson, Increasing surface ozone concentrations in the background atmosphere of Southern China, 1994–2007, *Atmos. Chem. Phys.* 9 (2009) 6217–6227.
- [18] J.I. Jeong, R.J. Park, Effects of the meteorological variability on regional air quality in East Asia, *Atmos. Environ.* 69 (2013) 46–55.
- [19] D.J. Jacob, D.A. Winner, Effect of climate change on air quality, *Atmos. Environ.* 43 (2009) 51–63.
- [20] J.T. Kurokawa, T. Ohara, L. Uno, M. Hayasaki, H. Tanimoto, Influence of meteorological variability on interannual variations of the springtime boundary layer ozone over Japan during 1981–2005, *Atmos. Chem. Phys.* 9 (2009) 6287–6304.
- [21] J. Seo, D. Youn, J.Y. Kim, H. Lee, Extensive spatiotemporal analyses of surface ozone and related meteorological variables in South Korea for the period 1999–2010, *Atmos. Chem. Phys.* 14 (2014) 6395–6415.
- [22] J. Susaya, K.H. Kim, Z.H. Shon, R.J.C. Brown, Demonstration of long-term increases in tropospheric O₃ levels: causes and potential impacts, *Chemosphere* 92 (11) (2013) 1520–1528.
- [23] Y.S. Ghim, H.S. Oh, Studies of high-ozone episodes in the Greater Seoul area between 1990 and 1997, *J. Korean Soc. Atmos. Environ.* 15 (3) (1999) 267–280 (in Korean with English abstract).
- [24] J.H. Han, H.Y. Kim, M.H. Lee, S.Y. Kim, S.W. Kim, Photochemical air pollution of Seoul in the last three decades, *J. Korean Soc. Atmos. Environ.* 29 (2013) 390–406 (in Korean with English abstract).
- [25] KEI, Climate Change and Air Pollution Effects on Environmentally Related Disease – Interactive Effects of Temperature and Ozone on Environmentally Related Disease, KEI/2010/RE-06, 2010 (in Korean with English abstract).
- [26] H.S. Kim, Y.S. Chung, On surface O₃ associated with long-range transport in the Yellow Sea region, *Water Air Soil Pollut.* 165 (2005) 95–112.
- [27] V.R. Kotamarthi, G. Carmichael, The long range transport of pollutants in the Pacific Rim region, *Atmos. Environ.* 24A (6) (1990) 1521–1534.

- [28] I.B. Oh, Y.K. Kim, M.K. Hwang, C.H. Kim, S. Kim, S.K. Song, Elevated ozone layers over the Seoul Metropolitan Region in Korea: evidence for long-range ozone transport from eastern China and its contribution to surface concentrations, *J. Appl. Meteorol. Clim.* 49 (2010) 203–220.
- [29] Y.M. Jeong, H.W. Lee, S.H. Lee, H.J. Choi, W.B. Jeon, Numerical study on the impact of regional warming on the meteorological field and ozone concentration over the south-eastern part of the Korean Peninsula, *J. Environ. Sci.* (2010) 1431–1445 (in Korean with English abstract).
- [30] H.-J. Park, B.-K. Moon, J. Wie, Characteristics of summer tropospheric ozone over East Asia in a chemistry-climate model simulation, *J. Korean Earth Sci. Soc.* 38 (5) (2017) 345–356.
- [31] J. Wie, B.-K. Moon, Seasonal relationship between meteorological conditions and surface ozone in Korea based on an offline chemistry-climate model, *Atmos. Pollut. Res.* 7 (2016) 385–392.
- [32] D.D. Parrish, K.S. Law, J. Staehelin, R. Derwent, O.R. Cooper, H. Tanimoto, A. Volz-Thomas, S. Gilge, H.-E. Scheel, M. Steinbacher, E. Chan, Lower tropospheric ozone at northern midlatitudes: changing seasonal cycle, *Geophys. Res. Lett.* 40 (2013) 1631–1636.
- [33] Korea Environment Corporation, <http://www.airkorea.or.kr>.
- [34] G. Tang, X. Li, Y. Wang, J. Xin, X. Ren, Surface ozone trend details and interpretations in Beijing, 2001–2006, *Atmos. Chem. Phys.* 9 (2009) 8813–8823.
- [35] S. Chatani, K. Sudo, Influences of the variation in inflow to East Asia on surface ozone over Japan during 1996–2005, *Atmos. Chem. Phys.* 11 (2011) 8745–8758.
- [36] H. Tanimoto, T. Ohara, I. Uno, Asian anthropogenic emissions and decadal trends in springtime tropospheric ozone over Japan: 1998–2007, *Geophys. Res. Lett.* 36 (2009) L23802.
- [37] Y.S. Ghim, Y.S. Chang, Characteristics of ground-level ozone distributions in Korea for the period of 1990–1995, *J. Geophys. Res. Atmos.* 105 (D7) (2000) 8877–8890.
- [38] J.E. Jonson, D. Simpson, H. Fagerli, S. Solberg, Can we explain the trends in European ozone level? *Atmos. Chem. Phys.* 6 (2006) 51–66.
- [39] L. Jin, S.-H. Lee, H.-J. Shin, Y.P. Kim, A study on the ozone control strategy using the OZIPR in the Seoul Metropolitan Area, *Asian J. Atmos. Environ.* 6 (2012) 111–117.