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Statistical analysis of Seoul air quality to assess the efficacy of emission abatement strategies since 1987

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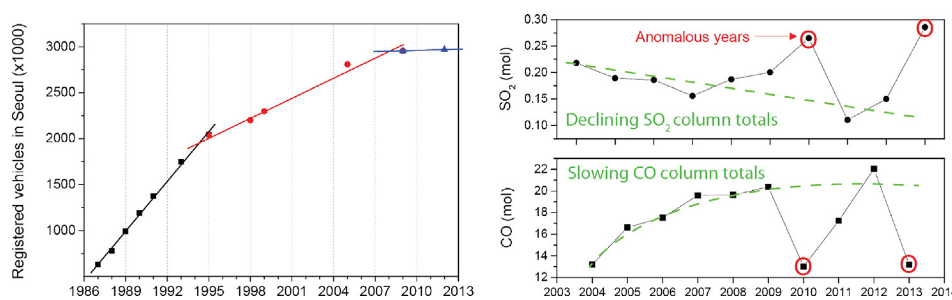
HIGHLIGHTS

- Improved long-term analysis of urban air quality in the central Seoul region.
- We demonstrate the existence, magnitude, and temporal changes of ambient air pollutants.
- Improved analysis techniques for investigating long-term changes in urban air pollution.
- Clearly demonstrate the efficacy of mitigation measures on Seoul air quality since 1987.
- Identify causes of large inter-annual variability in Seoul air quality in summer.

GRAPHICAL ABSTRACT



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ABSTRACT

The combined influences of recent mitigation measures on urban air quality have been assessed using hourly observations of the criteria air pollutants (NO, NO_2, O_3, CO, and SO_2) made from the Yongsan district of Seoul, Korea, over 26 years (1987 to 2013). A number of data selection criteria are proposed in order to minimize variability associated with temporal changes (at diurnal, weekly, and seasonal timescales) in source strengths, their spatial distribution, and the atmospheric volume into which they mix. The temporal constraints required to better characterize relationships between observed air quality and changes in source strengths in Seoul were identified as: (i) a 5-hour diurnal sampling window (1300–1700 h), (b) weekday measurements (Monday to Friday only), and (c) summer measurements (when pollutant fetch is mostly Korea-specific, and mean wind speeds are the lowest). Using these selection criteria, we were able to closely relate long-term trends identified in criteria pollutants to a number of published changes to traffic-related source strengths brought about by mitigation measures adopted over the last 10–15 years.

1. Introduction

As the global population continues to increase, power, transportation, and industrial demands necessarily follow suit (Andres et al., 1997; Guttikunda et al., 2001; Streets et al., 2003; Mills, 2007; Hu et al., 2014; Miranda et al., 2015). Other factors being equal, concentrations of primary

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and secondary air pollutants associated emissions from these three key sources will also rise; most notably, within and downwind of major urban centres and industrial facilities (Huebert et al., 2003; Martin et al., 2003; Svirejeva-Hopkins et al., 2004; Naja and Akimoto, 2004; Richter et al., 2005; Begum et al., 2011). Among the immediate challenges to be overcome to ensure a sustainable future are: (1) the limited reserves of fossil fuels – presently still the primary energy source for the power, transportation, and industrial sectors, (2) pollution-related changes to local and global climate (Action for Air, 2005; Metz et al., 2007; Lawrence et al., 2007), and (3) human health effects of gaseous and particulate pollutants in urban centres (Gurjar et al., 2008; Shi et al., 2011; Chen et al., 2012; Martins et al., 2012; Li et al., 2015; Lu et al., 2015; EEA, 2015; WHO, 2016), where it has been estimated that 60 to 80% of the global population will reside within the coming decade (Mirzaei and Haghighat, 2010; Bassett et al., 2016).

It has long been recognized that mitigation measures are required for emissions arising from the power, transportation, and industrial sectors in many parts of the developed and developing world (e.g. Nguyen and Kim, 2006; Miranda et al., 2016), whether in the form of exploring alternative energy sources, improving engine or fuel use efficiency (Kim et al., 2015; Ribeiro et al., 2016), capturing and cleaning exhaust gases, or, ideally, all of the above. As recognized by many researchers, the implementation of a nationwide clean-up activity (the Natural Gas Vehicle Supply (NGVS) program) and emission control retrofits in Korea provide a good reference point from which to evaluate the direct effect of air quality control measures (Bergmann et al., 2009; Biswas et al., 2009; Nguyen et al., 2010). Among the various attempts made to improve Korean air quality, NGVS is considered one of the largest movements to replace the entire fleet of diesel-powered city buses with natural gas buses in most large cities with fuel switching policies. Improvements have also been made in the quality of fuel (e.g. reduced sulphur content). The effect of these programs has been sufficient to induce a ubiquitous shift in key pollutant species (e.g., PM, SO_2, and CO) in all target urban areas (e.g. Kim and Shon, 2011). Regardless of the combination of mitigation measures adopted, a key part of their development and implementation is a demonstrated ability to accurately quantify their efficacy. Unnecessarily large variability in results introduced by overly simplistic or inappropriate analysis methods can complicate such efforts.

Identifying the need for, and assessing the efficacy of, atmospheric pollution mitigation measures requires statistically robust results. Production of robust results requires high-quality (consistent and high precision) long-term measurements, and consistent, well-considered data quality control and analysis procedures. Of paramount importance to data analysis procedures is the recognition that many factors influence near-surface concentrations of pollutants, including, although not necessarily limited to: source characteristics (strength and spatio-temporal distribution), chemical interactions, and meteorology (e.g. Li et al., 2014; Grundstrom, 2015; Williams et al., 2016; Chambers et al., 2016). Because source strengths are the primary concern of mitigation measures, the effect of these key variables need to be well understood.

The main aim of the present study is to demonstrate, and develop techniques to account for, (a) the temporal distribution of urban pollution sources, and (b) the key meteorological influences on urban pollutant concentrations, in Seoul, Korea. Having done so, brief commentary will be provided on efficacy of pollution mitigation measures in Seoul over the past 25 years. Since the focus of this study is on demonstrating the required data analysis *techniques* to best characterize long-term changes in air quality, it will focus only on a *single* representative site, and only on a selected number of pollutants, for the sake of brevity. The particular pollutants examined here include NOx ($NO + NO_2$) and CO, SO_2 and O_3, chosen as representative examples of transport-related sources (e.g. Kim and Shon, 2011), power and industrial sources (Ray and Kim, 2014), and secondary pollutants.

The power, transportation, and industrial emissions within and around urban centres are intimately related to the weekly workday cycle. Consequently, to reduce the risk of under-representing "typical" urban emissions, and to reduce the variability of relationships derived between source strengths and observed concentrations when assessing the efficacy of mitigation measures, it is important to distinguish between weekday (Monday to Friday) and weekend (Saturday and Sunday) periods when deriving long-term summary statistics.

Regarding potential meteorological influences, there are a range of location-specific temporal influences on observed atmospheric pollution concentrations that need to be assessed properly prior to passing judgment on the efficacy of the mitigation measures implemented in a given area. Seasonal changes in large-scale air mass fetch, as may be associated with monsoonal circulations or migration of the subtropical jet-stream, can substantially alter the relative contributions of local and remote sources to pollution observed in a particular urban centre (Huebert et al., 2003; Chambers et al., 2016). This is particularly significant in Europe and Southeast Asia, where political boundaries may be close enough so that trans-boundary influences from regions subject to different pollution mitigation strategies may be significant. On shorter timescales, changes in air mass fetch associated with the passage of synoptic weather systems can have a similar effect (e.g. Galmarini, 2006), albeit usually less pronounced. On diurnal timescales, changes in the atmospheric mixing depth can have a profound influence on hourly observations of near-surface pollutant concentrations (e.g. Chambers et al., 2015), as well as significantly bias daily average or daily integrated observations (e.g. Chambers et al., 2016).

Specifically, this study will demonstrate the existence, magnitude, and temporal changes of the "weekday effect" on atmospheric pollution concentrations in Seoul between 1987 and 2013. Diurnal influences on key pollutant concentrations will be characterized. A restricted diurnal sampling window will be proposed to minimize the influences of changing atmospheric mixing depth. A seasonal analysis will then be performed on weekday pollutant concentrations observed within the proposed diurnal sampling window in order to better characterize seasonal changes in large-scale air mass fetch on observed pollutant concentrations. Lastly, based on the improved understanding of contributing factors, average seasonal pollution concentrations in Seoul will be compared from 1989 to 2013 and related to dominant source strengths to assess the efficacy of mitigation measures adopted prior to 2014.

2. Methods

2.1. Background and study region

Following swift economic growth in Korea throughout the mid-twentieth century, the need to monitor levels of atmospheric pollution and to develop abatement strategies for curbing the detrimental effects of air pollution was recognized (Nguyen and Kim, 2005). This realisation led to a network of urban and suburban air quality monitoring stations being established and operated by the Korean Ministry of Environment (KMOE). As a result, air quality has been routinely monitored throughout Korea since 1970 (Nguyen and Kim, 2006; Ray and Kim, 2014). The extensive, and growing, database of information provided by this monitoring network provides an ideal platform for the analysis of long-term changes in the behaviour and concentrations of many airborne chemical species since identified as key anthropogenic (or criteria) atmospheric pollutants. Observations employed in this study were taken from an urban air quality monitoring station in Yongsan district of Seoul, Korea (37°32′18″N, 126°57′56″E). Although the urban air quality in Seoul is presently monitored by a network of around 30 stations, Yongsan, the station chosen for this study, is one of the most representative and longest-running sites, having been operated since the 1980s (Kim and Kim, 2002). The Yong-san district is located north of the Han River, under the shadow of the popular Seoul tower, and represents a densely populated area containing about 250,000 residential homes. The Yong-san district also contains the

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