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Process analysis of the impact of atmospheric recirculation on consecutive high-O_3 episodes over the Seoul Metropolitan Area in the Korean Peninsula

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HIGHLIGHTS

► We clarify the impact of atmospheric recirculation on consecutive high-O_3 cases.
► Precursors behavior due to atmospheric recirculation can vary ozone formation.
► High-O_3 concentration was more sensitive to VOCs concentration than NO_x in Seoul.

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ABSTRACT

Episodes of exceptionally high surface ozone (O_3) levels were measured in the Seoul Metropolitan Area (SMA) from July 6 to July 8. During the episode period, the 1-h average O_3 concentration exceeded the daily maximum of 80 ppb over three consecutive days. In order to understand the mechanisms behind the increased O_3 concentrations on consecutive days, several numerical experiments were conducted using the atmospheric dynamic model WRF for assessing the atmospheric flow as well as CMAQ for the estimation of the amount of photochemical ozone.

Gradually increasing ozone concentration during episode period in SMA depends not only on the variation of meteorological conditions and the emission rate of precursors but also on the accompanying precursors within the air mass recirculation that are emitted from the SMA and its surrounding areas. The impact from the recirculation of precursors responsible for the increased ozone concentration was clarified for numerical studies using the particle dispersion model FLEXPART. Results obtained from our experimental model also demonstrated that recirculated O_3 precursors such as nitrogen oxide (NO_x) and volatile organic compounds (VOCs) significantly influenced O_3 levels. During the episode period, NO_x and VOCs concentrations in the PBL increased by an average of 2.9% and 19.7%, respectively, through recirculation. The recirculated precursors also are involved in the activation of photochemical reactions responsible for the formation of O_3, leading to an average increase in the local O_3 production of 10.9 ppb. And overall effect due to recirculation is dependent on the actual path and direction of recirculation.

1. Introduction

Surface ozone (O_3) is one of the most hazardous photochemical oxidants in the lower troposphere. High levels of O_3 within this layer of the atmosphere often lead to severe air pollution resulting in harmful effects to human health. For example, exposure to high levels of O_3 can impair lung function and cause respiratory disease including asthma and bronchitis (Mauzerall et al., 2005; Sicard et al., 2011). High-O_3 concentrations are more frequently found near urban areas, especially in locations downwind of cities, as compared to rural areas primarily due to denser emission levels of potential precursors of O_3 from the cities (Vizuete et al., 2008; Ying et al., 2009). As a consequence of rapid industrial development and urbanization, the concentration of the secondary pollutant O_3, which is derived from nitrogen oxides (NO_x) and volatile organic carbons (VOCs), has increased as well, thereby posing a serious threat to the environment (Zhang et al., 2008).

The majority of high-O_3 episodes have occurred in large urban areas, such as metropolitan cities, and appear to be a direct result of the widespread distribution of emitted precursors of O_3. However, these high-O_3 episodes may appear as particular types as a result of several conditions including complicated terrain

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features, meteorological conditions, or particular regional circulations (Andronopoulos et al., 2000; Ding et al., 2004; Lee et al., 2008; Tie et al., 2009). O_3 formation is a complex process that is dependent on several factors including NO_x and VOCs emissions, meteorological conditions, chemical reactions, and other physical and chemical processes, all of which are important variables involved in the activation of the photochemical reaction that produces O_3 or results in the transport and movement of O_3 to different areas (Kleinman et al., 2000; Yin et al., 2009). In addition, each of these factors influences the overall O_3 concentration to some extent and is also dependent on topographical features. For example, several reports in the literature demonstrate that high-O_3 episodes occurred more frequently in areas with complex terrain (Lee et al., 2011; Xu et al., 2008). In general, atmospheric conditions including sufficiently high temperatures and solar radiation as well as decreased wind speed, lead to high levels of O_3 in the atmosphere (Banta et al., 2011). However, O_3 in the lower atmosphere is rapidly lost through nitric oxide (NO) titration and surface deposition processes that occur during the night (Morris et al., 2009), and high-O_3 levels are not easily sustained for consecutive periods of time. Previous studies have assessed high-O_3 episodes and how these increased levels correlated with the level and direction of recirculation (Levy et al., 2008; Boucouvala et al., 2003). In this study, we investigated a specific high-O_3 episode that occurred over consecutive days in the Seoul Metropolitan Area (SMA) using numerical models and also evaluate the impact of precursors released several days prior to the initiation of the episode on the overall concentration of ozone within this particular urban area.

2. Domain and time-frame of the episode

The SMA consists of a large population of 10.58 million people, as reported in 2010, as well as urbanized industrial complexes that are located in the central part of the Korean Peninsula with the Yellow Sea to the west (Fig. 1). The SMA is surrounded by several mountains including Bukhan (837 meters (m) elevation above sea level), Dobong (740 m), Surak (640 m), Bulam (510 m), Acha (287 m), Geomdan (657 m), Cheonggye (618 m), Nam (262 m) and Gwanak (632 m). Together these mountains provide a basin-like topography with a single outlet channel resulting in one major opening to the sea on the west side of the mountains (Lee et al., 2008). The complex terrain, surrounding and within the SMA, leads to landscape-induced mesoscale circulation from land-sea breezes, and mountain-valley winds, coupled with increased temperatures originating from the effects of the urban heat island (Sarrat et al., 2006; Chen et al., 2008).

We analyzed the ozone levels that were collected from the SMA during July of 2007 through observation data and numerical experiments. We focused our attention on a specific episode over several days that began on July 6, due to the observed ozone concentration measured and averaged over a 1 h period from 15 Air Quality Monitoring Stations (AQMSs) in the SMA, which was over the standard regulation level of 80 ppb. During this episode period, precipitation did not occur; however, slightly cloudy weather conditions prevailed as a result of a low-pressure system located over the western region of the Korean Peninsula (data not shown). Data obtained including the daily minimum, average, and maximum values of the observed temperature, wind speed, and

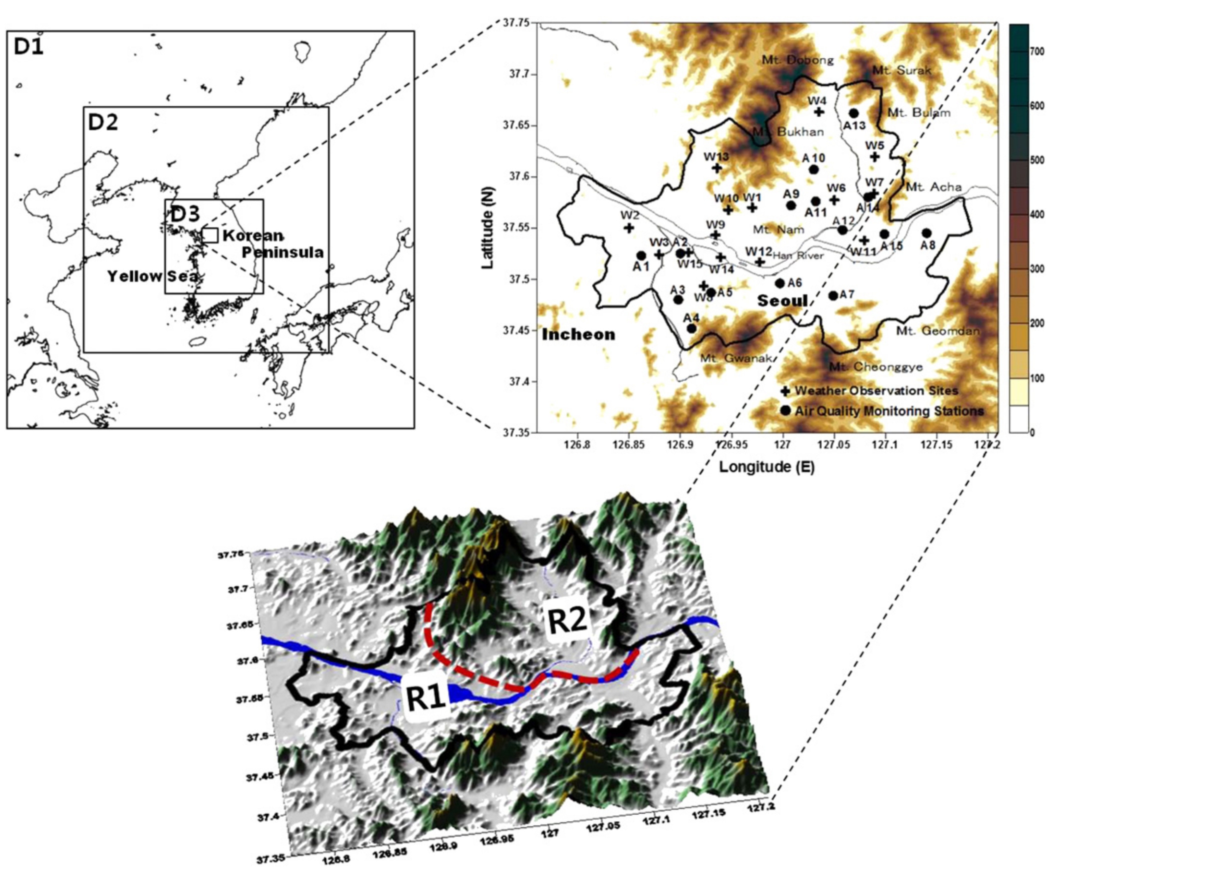

Fig. 1. Domain settings of the WRF (left) and detailed topography of the SMA (right and bottom). Domain D3 (left) provides meteorological fields to the CMAQ. Incheon metropolitan area is adjacent to SMA. The right figure shows the locations of fifteen observational sites (+) and air quality monitoring stations (●), which are used in this study. The two divisions of the SMA are shown (bottom), the area below the dashed line is defined as R1, and the area above the line is defined as R2.